Towards a Taxonomy of Technological Change

Vers une taxonomie du changement technique

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Abstract

The paper presents an approach towards a taxonomy of technological change focusing on the dynamic processes of technological diffusion. The objective of the approach is to develop a synthetic measure of the transformation of the diffusion characteristics during the very process of diffusion of a technological innovation. The elaboration of such a measure is based on a methodology of graphical representation of structural changes in a multidimensional space as proposed by Herman and Montroll. This synthetic measure constitutes a first step towards the identification of structural similarities between processes of diffusion of various (different) technologies, and thus a first step for their classification for developing a taxonomy of technological change. This approach to represent dynamic processes leads to a new interpretation of structural similarities of processes of technological change as reflected for instance in traditional diffusion parameters.

Résumé

L'approche proposée porte sur les processus dynamiques de diffusion des technologies comme elements de base d'une taxonomie du changement technique. Il s'agit de confectionner une mesure synthétique permettant de rendre compte de la façon dont les caractéristiques mêmes de la diffusion sont susceptibles de changer au cours de la diffusion d'une innovation technologique. La confection d'une telle mesure synthétique est basée sur la méthodologie de representation graphique des changements structurels d'un espace multidimensionel developpé par Herman et Montroll. Cette méthodologie devra permettre d'identifier ensuite des similarités structurelles des processus de diffusion portant sur des technologies distinctes. Cette méthodologie de répresentation des processus dynamiques nous conduit enfin à proposer une nouvelle interpretation des similarités structurelles de la dynamique technologique, telles qu'elles sont reflètees par les paramètres temporels classiques de la diffusion.

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Introduction

In this paper we propose a first step towards developing a taxonomy of technological change. It is based on the dynamic transformations a technology undergoes in its systemic and technological characteristics as well as in its adoption environment during the diffusion process. The latter comprises not only diffusion (or technological substitution in case a new technology supplants existing ones) proper, but also the selection process in which standardization emerges and the basic structural and functional characteristics of a technology become stabilized.

Some of these basic characteristics are sketched out and illustrated in their relevance in the selection and subsequent diffusion phases of processes of technological change. The vector representing the dynamic transformations of these characteristics during the diffusion process is suggested as initial element of a taxonomy of technological change. Technologies are characterized and represented as "snowflake" diagrams with respect to a number of their systemic, technological and adoption environment characteristics. The resulting vector (between the gravity centers of two "snowflake" diagrams) of the transformation a technology undergoes during diffusion is suggested as measure to classify processes of technological change and to enable comparisons of their dynamics as reflected in traditional selection and diffusion parameters. It has to be emphasized, that the representation of a technology along the dimensions of a number of basic (structural) diffusion characteristics is seen to operate at a deeper fundamental level, establishing *ceteris paribus* conditions against which more traditional selection and diffusion mechanisms and variables can be discussed further in a comparative context.

Traditional Measures and Determinants of Diffusion Processes

A frequent point of critique of diffusion models has always been that the models tend to simplify (if not to ignore) the complex dynamics and transformations of both the market environment and the technological characteristics of innovations during the diffusion process. Both in terms of the measures of diffusion dynamics (i.e., of the diffusion rate)[1] and in its determinants, like the economic attributes (e.g., profitability, required investments, etc.) of an innovation and the characteristics of the adoption units (e.g., size of firms, communication channels, etc.), diffusion models hardly ever treat explicitly the dynamic transformations of the very object modeled. Moreover, the object of investigation, the technology in its embedding in both a technological and economic context, is introduced into the models in an exogenous fashion, without developing a theoretical framework to define what is actually diffusing.

Traditional measures of diffusion, and variables considered in most diffusion models therefore miss somewhat the fact that a technology ought to be defined first rigorously in order to capture its transformation during its diffusion throughout the economy, in which it acquires its industrial and economic properties, transforms itself, and widens the initial market in which it was first adopted.[2] Particularly when considering the diffusion of various technologies in a comparative context, the more fundamental properties and characteristics of technologies which are transformed during the diffusion process can no longer be ignored.

Here we argue not to replace traditional measures and variables considered in diffusion models, but rather to *complement* them in the direction of more fundamental dimensions of technologies in terms of their systemic, morphological and adoption characteristics usually excluded by the boundaries of the definitional systems drawn in a particular diffusion model or analysis. What we term in this context fundamental dimensions of a technology are precisely those measures which enable us to capture the fact that not only the object of diffusion but also the conditions and the characteristics of the diffusion process proper change during the process of diffusion.

A taxonomy of diffusion processes (i.e., of technological change)[3] therefore require in addition to criteria based on traditional variables of metric (e.g., a Δt) and driving forces (e.g., the [perceived] economic attributes of an innovation) of diffusion, criteria of (dis)similarity which are based on a synthetic measure of the transformations of the conditions for a diffusion process proper. Such a synthetic measure should consist of a vector capturing the transition from a particular configuration of parameters [a] representing the initial conditions, to a configuration of parameters [b], which represent the final conditions of a technology in the diffusion process.

Similarity between such vectors then constitutes a measure for a *structural identity* of two diffusion processes, albeit of distinctly different technologies. It is precisely such measure which we suggest as initial element of a taxonomy of technological change, as operating at a deeper (i.e., definitional) level of the changing characteristics of the object treated in diffusion models.

Before however, developing a method (a graphical representation) for constructing such a synthetic measure, let us discuss theoretically along which lines the diffusion conditions are transformed. In other words, what we consider as basic dimensions of the transformation of the characteristics of a technology in the course of its diffusion process, dimensions which are not (or only partly) taken into account in traditional measures of diffusion processes and their driving forces.

Characteristics of Diffusion and Dynamics of Transformation

Four dynamic principles can be highlighted which describe the way in which the very diffusion process of a technology may affect the diffusion characteristics of a particular technology, i.e., its technological and economic characteristics and its interaction within its industrial and adoption environment. These principles concern i) the transformation of the structural and functional characteristics of the technology; ii) the (changing) level of aggregation in which the diffusion process occurs; iii) the evolution of the criticality properties[4] of the interlinkages between adopters; and iv) changes in the level of the adopters' decisions (e.g., following Rogers, 1983, distinction between individual, collective and authoritative adoption decisions), i.e., how the unit of potential adopters is defined.

The first mechanism deals with the fact that the structural and functional characteristics of a technology itself may be changing during the diffusion process. Learning effects, network externalities, technological complementarity, varying economies of scale, etc. are phenomena which occur during the process of diffusion, influence the dynamics of selection between competing prototypes (see, e.g., the model developed by Arthur, 1983 and 1988, and the model overview in Foray, 1989), and lead to improvements in a technology performance (in terms of costs, quality, compatibility and substitutability for existing technologies, i.e., in the functional capabilities a technology is able to assume), which itself drive the diffusion process. This technological progress function affects the characteristics of diffusion, in terms that the rationale for adoption of a later adopter will be strongly influenced by the past diffusion trajectory of a technology. See e.g., Arthur, 1988, for a theoretical model and Grübler and Foray, 1990, for an empirical illustration of such adoption "path dependency".

The second principle concerns the level of aggregation at which the diffusion process operates. We define this level of aggregation to evolve hierarchically from subunits, units, to sub-systems and finally system. This four level hierarchy of aggregation may be considered departing from any particular level of aggregation, anywhere between the two extremes of basic chemical and physical processes and the whole technological system (see, e.g., the discussion of aggregation levels within process models, Gault *et al.*, 1985; Grübler *et al.*, 1982 and McInnis, 1981). The traditional System of Industrial Classification (SIC code) (UN, 1968) provides another illustrative example of the importance to differentiate between different hierarchial aggregation levels. We assume that the higher the aggregation level of the object of a diffusion process (i.e., the generally higher its level of [technological] complexity)[5], the higher (i.e., slower) the diffusion constant (speed) at which the diffusion process operates. Below we will give an illustrative example on the comparative diffusion dynamics of infrastructural development in the USA and the USSR to corroborate this hypothesis. Clearly the level of aggregation may be changing also during a diffusion process, in such case, both the characteristics of diffusion and the adoption rate will be significantly affected. In effect any technology can be conceptualized as a component belonging to a particular system on one hand, and as a system incorporating a number of components on the other. Thus an artifact can diffuse initially as a component, before it diffuses as a system (e.g., rockets firstly were adopted as an engine and developed later on into space vehicles). Or symmetrically, an artifact can diffuse initially as a system before it becomes incorporated as a component into a larger system (e.g., the evolution from robots and manipulators to whole FMS [flexible manufacturing systems]).

The third principle concerns the degree of interconnectedness between the members of the population of potential adopters. The network characteristics of a population of potential adopters, in terms of sub-criticality, criticality and supercriticality change radically the conditions of technological selection and diffusion. In a sub-critical systems (the number of interlinkages is below a certain critical value), diffusion operates within sub-sets (or sub-groups) of adopters, which are not connected to each other (much along the lines of physical communication barriers separating potential adopters in spatial diffusion models, see e.g., Hägerstrand, 1967). Global diffusion therefore requires the introduction of a technology into each subset (or group) of potential adopters. Sub-criticality may thus explain the diffusion of multiple standards (just consider the number of different electricity plugs in use worldwide), i.e., the selection process does not result in the "lock-in" of a single technological standard. Any particular standard does then not diffuse throughout the entire population of potential adopters, but instead only within subpopulations. On the contrary in a super-critical system (complete interconnectedness) diffusion is possible from a single/unique entry. It can be shown that also this diffusion characteristic may change during the diffusion process, moving as a rule from the sub-critical or critical level to super-critical forms of interconnectedness (e.g., the diffusion of EDI [electronic data interchange]).

The last principle deals with the unit(s) of the adopters involved in the diffusion process. Units of adopters can be either decentralized (an individual or a firm), operating at an intermediate level (e.g., an industry, or a regional administrative unit like a town) or be centralized (i.e., at the level of a country or an international organization). The particular adoption unit has a clear-cut influence on character and mechanisms of diffusion. Also the unit of adoption may be changing during a diffusion process, affecting thus the characteristics of the process greatly. The diffusion of EDI is a case in point: the initial adoption units were individual firms, then whole sectors and eventually will involve even the system of the United Nations

(Economic Commission for Europe, ECE).

After discussing above four basic characteristics of diffusion processes, we proceed to the next step of our approach, which consists in the graphical representation of the initial and final characteristics of technologies along the diffusion process and a representation of their dynamics within a five-dimensional space.

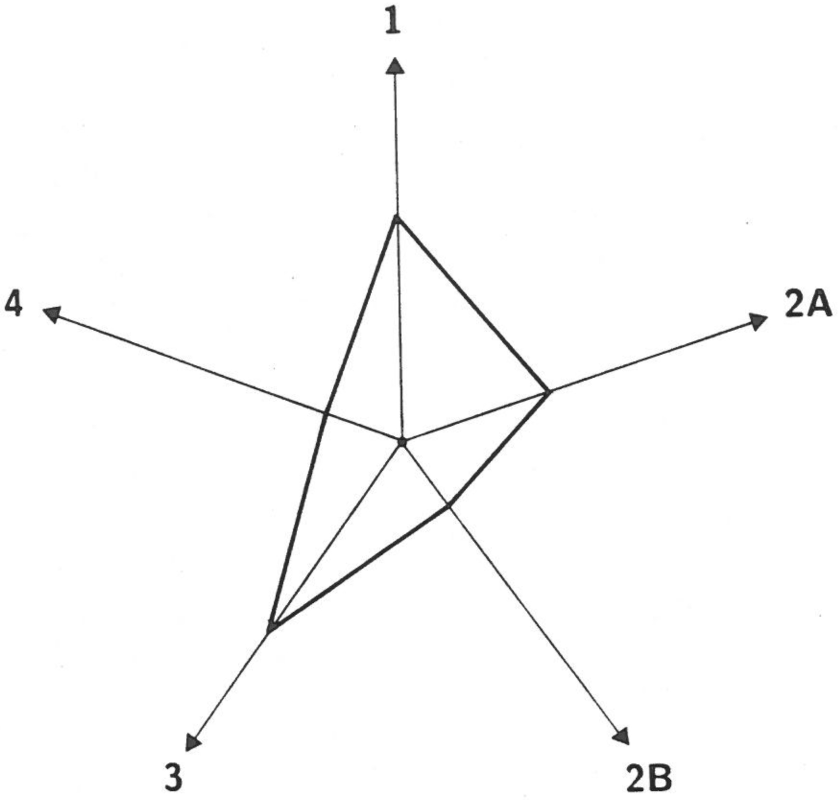
Describing Initial and Final Characteristics and their Dynamics

In a first step let us introduce a simple description of a n-dimensional representation of particular diffusion characteristics. In constructing n rays from the origin of a rectangular coordinate system (x,y), and letting successive rays form an angle of 2 π/n between them, one obtains a convenient graphical representation for the description of multi-dimensional diffusion characteristics. The length of each axis is either corresponding to a finite number of discrete intervals, or a renormalized continuum depending on a particular metric chosen. In connecting the end points of successive axes by lines, one obtains a "snowflake" diagram (Figure 1), a graphical summary representation of structural characteristics of socio-economic phenomena (see Herman and Montroll, 1972). By developing successive "snowflake" diagrams one can derive an aggregate representation of their transformations in time, e.g., be representing the changing gravity centers of such diagrams as vectors.

In our terminology, technologies with an identical or similar "snowflake" representation with respect to their diffusion characteristics dimensions, hold a common structural identity, independent from the fact that they may represent distinctly different technologies or artifacts. Their simplest abstraction is represented by a point defined by the center of mass of the "snowflake", i.e., where the x and y coordinates are respectively:

$$x = 1/n \sum dj \cos(2\pi j/n)$$
$$y = 1/n \sum dj \sin(2\pi j/n)$$

where $0 \leq$ dj ≤ 1 in case of a renormalized, continuous metric of the dimensions of the diffusion characteristics considered. In cases of similar/identical coordinates of the gravity centers of the graphical representation of technologies, we deal with a structural similarity of the characteristics of technologies with respect to the conditions of their diffusion. As an illustrative case we will consider below five[6] variables representing the diffusion characteristics of selected technologies and their dynamic transformations during the diffusion process proper (see Figures 1 and 2). As discussed above, we



1 Level of Aggregration (component – subsystem – system)

2 Functional & Structural Characteristics of Technology

2A Functional Distance to Existing Technologies (complementary – partial substitution – substitution)

2B Morphological Distance to Existing Technologies (neighborhood – distance – breakthrough)

3 Degree of Interconnectedness of Potential Adopters (subcritical – critical– supercritical)

4 Type of Adoption Decision (decentralized – centralized)

Figure 1. Snowflake representation of multi-dimensional technology diffusion characteristics.

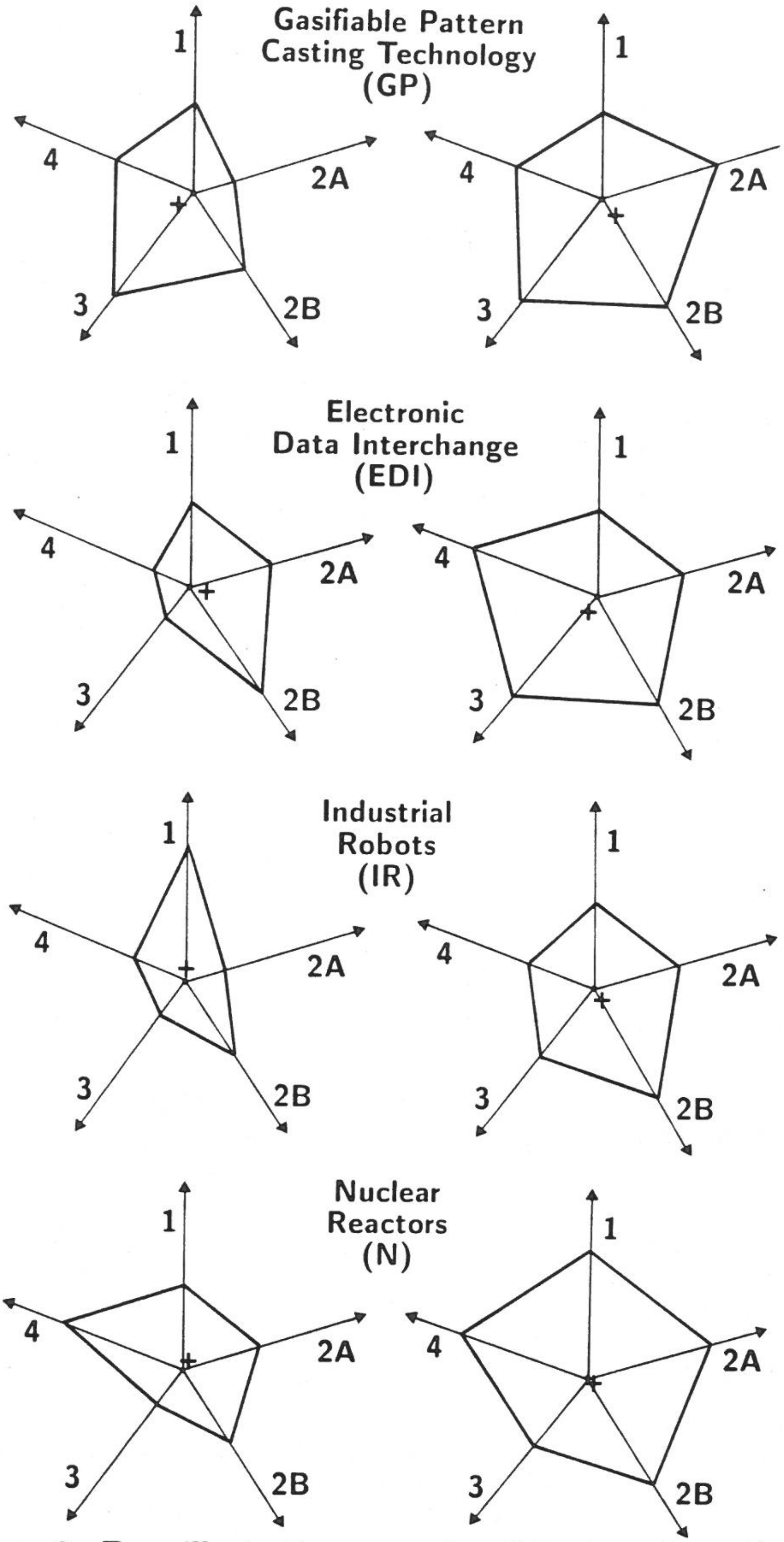


Figure 2. Four illustrative examples of the transformation of the structural characteristics of technologies during their diffusion process: *left*: initial state; *right*: final state. Note in particular the moving gravity centers (denoted by crosses) of the multi-dimensional "snowflake" representations.

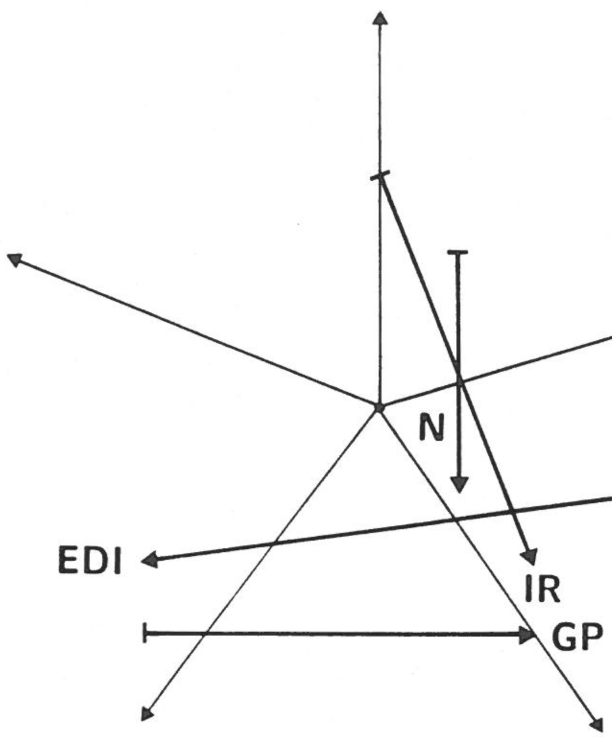


Figure 3. Elements of a taxonomy of technological change: vectors of changing gravity center points representing the transformations technologies undergo in their diffusion characteristics during the diffusion process.

consider the following dimensions[6]: *level of aggregation; functional and structural characteristics of a technology;* subdivided into functional distance (to represent functional complementarity versus substitutability between a technology and its rivals, as discussed e.g., by Saviotti, 1991) and morphological distance (to represent the technological distance to existing technological routes and artifacts, as e.g., reflected in the learning requirements for a transition between two points of a morphological "tree", as discussed in detail in Grübler and Foray, 1990); *degree of interconnectedness of potential adopters;* and the *units of adopters* (type of adoption decisions).

As *initial taxonomic unit* we then adopt the trajectory generated by the variation of the gravity center coordinates (x,y) of the five-dimensional representation in time, i.e., of the vector of the aggregate changes along the dimensions of diffusion characteristics between the beginning and the end point of diffusion (or any further intermediate dates in-between), as illustrated in Figure 3. Thus the initial element of the taxonomy proposed here is to classify technologies with respect to the dynamic transformation of their diffusion characteristics during the very process of diffusion. Their structural similarity/dissimilarity is revealed by similar vectors representing the changes in their diffusion characteristics. It is against these measures of similarity or dissimilarity that we suggest to proceed further in classifying group of technologies on the basis of more traditional diffusion variables and their dynamics.

An Illustration of Common Structural Diffusion Characteristics: The Level of Aggregation

As an illustration of the potential of above proposed classification scheme to understand better differences and similarities in patterns of diffusion we will consider below diffusion and technological change processes in the transport sector of two countries: the USA and the USSR. We consider that any similarity revealed in the dynamics of the process of technological change in countries with such a decisive difference in market clearing mechanism, relative cost and price structures and national innovation systems and policies may be traced back to a deeper, more fundamental mechanism, which resides precisely in their similarity with respect to their basic dimensions of the diffusion process, as exemplified by the aggregation level at which these processes operate. Therefore, we argue that the similar diffusion time constants in the two countries – after appropriate consideration of the different synthetic measures between different diffusion processes – is not coincidental, as driven by their commonality with respect to their basic structural diffusion characteristics.

The quantification of diffusion and substitution model parameters is based on estimating the respective parameters of univariate and multivariate logistic diffusion and substitution models from empirical data, based on earlier IIASA research (Marchetti and Nakićenović, 1979; Nakićenović, 1988; Grübler, 1990). Time variables of diffusion and substitution processes are the following (based on a logistic diffusion/substitution model): t_0 denotes the inflection point, i.e., the time of maximum growth (replacement) rate at the 50 percent diffusion (market share) level; and Δt the time period in years to grow (substitute) between the 10 and 90 percent diffusion (market share) level.

Our example focuses on the aggregation level, as one of the fundamental characteristics of diffusion processes. The diffusion/substitution processes considered for this illustrative case span three hierarchy levels of aggregation. At the highest (*systems*) level we consider the evolution (diffusion) of the length of the total transport infrastructure grid in the two countries. At the next (*subsystems*) level we consider as illustrative example the evolution of a particular kind of transport infrastructure, i.e., the growth (diffusion) of railway networks in the two countries. Finally, one level of aggregation further down (at the *units* level) we consider a process of technological change in the rolling stock using the railway infrastructure, in analyzing the replacement process of steam locomotives by diesel (USA) and/or diesel/electric locomotives (USSR). Finally to illustrate the difference between morphological neighborhood and morphological distance of technologies we consider an additional process of change which is represented by an upgrading *within* an already existing infrastructure grid, i.e., the replacement of wooden railway ties by treated ties in the USA and of track electrification in the USSR.

Table 1 illustrates a (temporal) hierarchy of diffusion processes as a function of their aggregation level in the transport sector of the USA and the USSR (Tzarist Russia prior to 1917).

Table 1. Hierarchy of diffusion processes in the transport sector of the USA and the USSR, measured by their temporal diffusion parameters (in years).

	USA		*USSR*	
	t_0	Δt	t_0	Δt
Total length of transport infrastructures	1950	80	1980	80
Growth of railway				
Network 1830–1930	1858	54	1890	37
Railways 1930–1987	decline	decline	1949	44
Treated ties (USA)	1923	26		
Track electrification (USSR)			1965	27
Replacement of steam locomotives	1950	12	1960	13

Table 1 shows –perhaps for some surprisingly– that while the diffusion processes are shifted in time, the diffusion time constants appear to be of similar order of magnitude between the two countries at similar levels of aggregation. Of course also decisive differences remain. For instance, the railway network in the USA has been decreasing ever since the beginning of the 1930s (reduction by some 40 percent of the 1930 network), whereas the USSR has experienced a "second pulse" of railway construction since that time period, doubling the length of its railway network. However, this "second wind" in railway construction appears close to saturation.

The similar duration in the diffusion of technologies and infrastructures between the two countries, with their distinct differences in history and market-clearing mechanism, enables us to develop a rough hierarchical classification of diffusion processes, as reflected by their diffusion constants (Δt). More noteworthy is however the systematic *acceleration* of the diffusion constants (roughly a factor of two) with each lower level of aggregation, i.e., when we move from the level of the whole transport system, to that of individual subsystems and finally to that of units.

Thus, we conclude that diffusion processes can indeed be characterized along a hierarchical structure of levels of aggregation, as reflected in the time constants (Δt) involved in diffusion. Thus, the identified similarity in the time constants of diffusion (although generally lagged in time in case of the USSR) must therefore reside in a deeper structural and functional common characteristic of these diffusion processes than can be captured by variables considered in conventional diffusion models. The validity of this conclusion is in our viewpoint primarily based on the fact of the entirely different market environments prevailing in the two countries. The explicative power of traditional diffusion models would in any case appear limited, if one ought to expect equilibrium configurations at work over the time horizon (several decades) spanned by the diffusion processes described above.

Finally we consider an intermediate case in the temporal pattern of diffusion identified in Table 1, i.e., the case of technological change or upgrading within an already existing infrastructure grid, i.e., the substitution of treated wooden railway cross-ties in the USA (a substitution occurring in a contracting market, as the railway network of the USA has been decreasing since the 1930s) and the electrification of railway tracks in the USSR (diffusion occurring in an expanding market as illustrated in Table 1). Although at the same level of aggregation (subsystem) as the diffusion of railway networks, diffusion time constants (Δt) of less than 3 decades are typical, i.e., significantly faster than in the case of new constructions of infrastructure grids. The reason for this is in our opinion primarily related to the notion of technological neighborhood and technological distance discussed above. In case of the upgrading of an already existing infrastructure, we are speaking of an incremental process of change, integrated within well established engineering and management practices, technical know-how and the like. Thus in our terminology only a change in artifacts is involved here. Contrary to this, the construction of new infrastructure grids, radically different in technology, financing, and organizational settings from existing ones (as the case of railways compared to inland water navigation), represent a case of technological breakthrough (morphological *distance*) and a corresponding change in the *knowledge* and *institutional base* involved. As a result the diffusion time constants are significantly longer (about a factor of two) than in the case of technological change occurring in the very same system but within a morphological neighborhood.

Conclusion

The general lines for developing ultimately a taxonomy of processes of technological change presented in this paper are still at the conceptual level. The approach outlined is based on taxonomic principles which do not describe *static technologies* but instead *dynamic processes* of technologies. These transformations resulting from the diffusion process encompass changes in the systemic and technological characteristics of technologies and the adoption environments in which they evolve. Secondly, the taxonomic elements (although they may not be exhaustive) take into account the most important dimensions of the transformations identified by the historiography of technological change. These dimensions constitute in our viewpoint a deeper level to identify similarities/dissimilarities of processes of technological change than pure phenomenological approaches (e.g., based on comparisons of diffusion rates) or constructions concentrating on comparisons of higher level attributes of diffusion processes, like their comparative economic performance.

A comparison of processes of technological change that does not take into account these deeper structural dimensions outlined here, will in our viewpoint necessarily be limited to remain at a somewhat "superficial" level. However, we also realize the formidable task ahead in developing the exact metric in terms of variables considered and their measures of the general dimensions outlined in this paper. Last but certainly not least, an empirical corroboration of the taxonomic elements suggested here, by an analysis of a large number of diffusion processes spanning a wide domain in their systemic, technological, and adoption environments characteristics will require more than in isolated effort of individual researchers, but active input from a larger community of researchers actively involved in diffusion studies.

But it is our contention that once indeed fully developed, a taxonomy of technological change would contribute to understand diffusion patterns in their diversity better, enable to generate new hypotheses and eventually to develop generalizations from the rich body of knowledge assembled by the empirical and theoretical research streams of diffusion research.

Notes

1. E.g., Δt, the time required to grow from 10 to 90 percent market share in case of a logistic diffusion or technological substitution model. For a review of such models see e.g., Posch, Grübler and Nakićenović, 1988, or Grübler, 1990.
2. For a detailed theoretical and empirical study of technological transformations in the casting industry, see Foray and Grübler, 1990.
3. We acknowledge earlier the work on taxonomic principles in the area of technological change, e.g., by Garrouste, 1991, or along the lines of a "natural taxonomy" proposed by Reeve and Metcalfe, 1989; on the classification of innovation trajectory characteristics developed by Pavitt, 1984.
4. This notion is adopted from the characteristics of the dynamics of self organized criticality (Bak and Chen, 1991) and refers to the network characteristics of the population of potential adopters, in terms of their economic interlinkages, communication channels and the like.
5. For an illustrative measure, e.g., number of parts or components, see Ayres, 1989.
6. This subdivisions into five variables of the basic diffusion characteristics is of course tentative and illustrative rather than definitive.

References

W.B. Arthur, *Competing Technologies and Lock-in by Historical Small Events: The Dynamics of Choice under Increasing Returns*, Center for Economic Policy Research Paper 43. Stanford University, 1983.

W.B. Arthur, Competing technologies: An overview, in: G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete (Eds.), *Technical Change and Economic Theory*, Pinter Publishers, London and New York, 1988.

R.U. Ayres, Complexity, reliability, and design: Manufacturing implications, *Manufacturing Review*, Vol. 1, No.1 (1988), 26–35.

P. Bak and K. Chen, Self-organized criticality, *Scientific American*, (1991), 26–33.

D. Foray, Les modèles de competition technologiques, *Revue de l'Economie Industriel*, No.49 (1989), 16–34.

D. Foray and A. Grübler, Morphological analysis, diffusion and lock-out of technologies: Ferrous casting in France and the FRG, *Research Policy*, Vol. 19 (1990), 535–550.

P. Garrouste, Eléments théoriques pour une approche stématique de la technologie, in: J. de Bandt and D. Foray (Eds.), *L'évolution économique de la recherche et du changement technique*, CNRS, Paris, 1991 (forthcoming).

F.D. Gault, R.B. Hoffmann and B.C. McInnis, The path to process data, *Futures* (1985), 509–527.

A. Grübler, *The Rise and Fall of Infrastructures, Dynamics of Evolution and Technological Change in Transport*, Physica Verlag, Heidelberg, 1990.

A. Grübler, R.B. Hoffman and B. McInnis, *Process Information Systems: A Synthesis of Two Independent Approaches*, CP-82-24, IIASA, Laxenburg, Austria, 1982.

T. Hägerstrand, *Innovation Diffusion as a Spatial Process*, University of Chicago Press, Chicago and London, 1967.

R. Herman and E.W. Montroll, A manner of characterizing the development of countries, *Proc. Nat. Acad. Sci. USA*, 69 (1972), 3019–3023.

C. Marchetti and N. Nakićenović, *The Dynamics of Energy Systems and the Logistic Substitution Model*, RR-79-13, IIASA, Laxenburg, Austria, 1979.

B. McInnis, (Ed.), The Process Encyclopedia Workshop, 26–27 March 1981, 81/08/25 Structural Analysis Division, Statistics Canada, Ottawa, 1981.

N. Nakićenović, Dynamics and replacement of U.S. transport infrastructures, in: J.H. Ausubel and R. Herman (Eds.), *Cities and their Vital Systems: Infrastructure Past, Present, and Future*, National Academy Press, Washington D.C., 1988.

K. Pavitt, Sectoral patterns of technical change: Towards a taxonomy and a theory, *Research Policy*, 13 (1984), 343–373.

M. Posch, A. Grübler, and N. Nakićenović, *Methods of Estimating S-Shaped Growth Functions: Algorithms and Computer Programs*, IIASA, Laxenburg, Austria, 1988.

N. Reeve and J.S. Metcalfe, *Technology Taxonomy*, PREST, Manchester, 1987.

E.M. Rogers, *Diffusion of Innovations* (3rd Ed.), The Free Press, New York, 1983.

P.P. Saviotti, *Technological Evolution, Product Characteristics, Competition and Variety*, Paper presented at the Conference: New Frontiers in Science and Engineering in a European Context, Paris, 27–29 May 1991.

United Nations (UN), *International Industrial Classification of all Economic Activities*, Statistical Papers, Series M, No.4, Rev.2, Department of Economic and Social Affairs, Statistical Office of the United Nations, New York, 1968.