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**SOME HYPOTHESIS ABOUT A GENERAL NETWORKS MORPHOGENESIS
PROCESS.**

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ABSTRACT

This paper synthesizes some reflections outlined in the French research group on Networks (GDR 903 "Réseaux" CNRS), in order to propose a generic model of development available for all technical networks.

The first section is a state-of-the-art on the history of networks. It shows that too simple models of networks' diffusion, considering that there is an intrinsic capacity to increase irresistibly in size, are not sufficient. The proposed model is detailed, with seven possible phases from birth to disappearance, and a possible "feedback loop" from decline to redeployment.

The second section shows an application to the railways networks in Western Europe. We see that this model is adapted to complex and long-lasting evolutions. Other application attempts are now in process, and more improvements would take place in the future.

1. Introduction

The first definition of the term "network" appeared 200 years ago in Europe. At the beginning, the network was considered to be a circulation machine as well as an instrument for the creation of new specific territories. The network appeared later as a territory-destroyer, knocking over spatio-temporal references and scrambling geographical scales with the appearance of high-speed transport means (highways, trains, planes) and the diffusion of telecommunications. Nowadays a network appears as a set of specific modalities of transactions between people or organizations¹.

In order to avoid an epistemologic reflection on the relevance of these different meanings of the same word "network", our object will be defined as "*the whole collective services materially organized as a network by a technical infrastructure*" (Offner, 1993b).

How do networks appear, develop and eventually, disappear ? This paper, which synthetizes the reflections outlined in the GDR "Reseaux" from 1993 to 1995, proposes a generic model of technical networks development, with a special interest in the domain of ground transportation in Europe. It's main aim is to introduce a discussion and to present some reflections, rather than draw final conclusions.

2. A critique of the endogeneous development thesis

The search of general laws for technical networks evolution, in an "internalist" way (networks generate their own development, without any external intervention), is a permanent feature of the scientific reflection.

A current idea is that there is a intrinsic capacity for the network to increase in size, in an irresistible way. The quantitative observations on the first networks' development periods, in which the growth rate is extremely high, support this opinion. For instance, the French rail network is 1931 km long in 1850, 4100 km long in 1860, 17400 km long in 1870 and 23600 km long in 1880 (Gökalp, 1983). The rail network is not a peculiarity : most of the networks observed have similar growth curves.

Fig. 1 - The growth of some urban technical systems (from Dupuy, 1991)

It would be tempting to propose simple models of networks diffusion : from single sections to a network (this is the case of the motorways), from a sum of lines to a network (this is the case of telecommunications), from connection to connectivity (public urban transport). W. Garrison (1990) proposed a similar model from the example of the Irish rail network : from a given state of the network, the first section to be built is the one which reaches the biggest town not yet served.

Some other researchers have recourse to the Fractals theory, directly stemming from Mathematics, in order to anticipate the future state of any network : for instance sewage systems (Thibault, 1991) or public transport networks (Frankhauser, 1991).

These two examples, among many others, demonstrate a certain faith in an autonomy of technique, without any connection with a general economic, political, social or cultural context. If we admit with Gabriel Dupuy (1985, 1991) that a network, which creates solidarity links,

¹ For more details on the difficult definition of networks, see Offner, 1996.

permits the functioning of a territorial system, there is no need to search laws of networks evolution. In the French context, this means calling into question the so-called "structuring effect" (i.e. a causal link between changes in the network's structure and territorial changes)(Offner, 1993a).

3. Taking into consideration long-lasting evolutions

An empirical observation is sufficient in order to demonstrate that technical-based networks function at the secular scale, with the same denomination : subway, rail network, roads, etc. A strong territorialization and a strong capital intensity make them long term-operated systems. But can we consider a hundred years later that they are the same as at the beginning of their operations ?

In fact, a network has several dimensions :

- a morphology (the layout of infrastructures).
- an infrastructure (also called "support-network"),
- functions (also called "services-network"). According to the services offered by the network, its uses will be different),
- a regulation mode (coordination between "support-network" and "services-network"),
- a territorial fixing (the topology of all places linked by the network).

Each one of these dimensions is susceptible to change while the others aren't modified. For instance, the morphology, the infrastructure or the use of the Parisian "metro" hasn't changed since its opening in 1900. On the other hand, it changed from the highest level to a simple subsystem of a transport network designed for a 11 million inhabitants urban region. The consequence is an impression of changing continuity : the network is the same ; it uses the same techniques, but its context has changed. Its main use is now the diffusion of day commuters coming from peripheral areas, and not, as in the past, a purely intra-urban transport mean. Therefore, the connection (or interconnection) with networks operating at a higher scale (regional, national, etc.) becomes fundamental. And the intermodal nodes become more important than the other ones.

This kind of evolution is a long-lasting one, with a succession of partial changes. Each development cannot be considered decisive on its own.

Moreover, we have to take into account the interactions between rival networks. New competitors appear for different reasons. For instance, a technological evolution provokes the emergence of a new network or of a new use of an existing one. They offer at least a similar level of service and similar prices, at the same scale. The challenged networks have to innovate, to improve their production facilities, to arbitrate between categories of services or market segments in order to survive : they enter a redeployment / transformation phase. If they fail this attempt, they enter a decline phase.

4. From monographs to a model

For several years, an interesting corpus of historical monographs concerning technical networks has been available. In the USA, we have to emphasize the vitality of the history of urban technologies (Tarr, Rose, Konvitz, 1991). In France, the original discipline called "histoire du

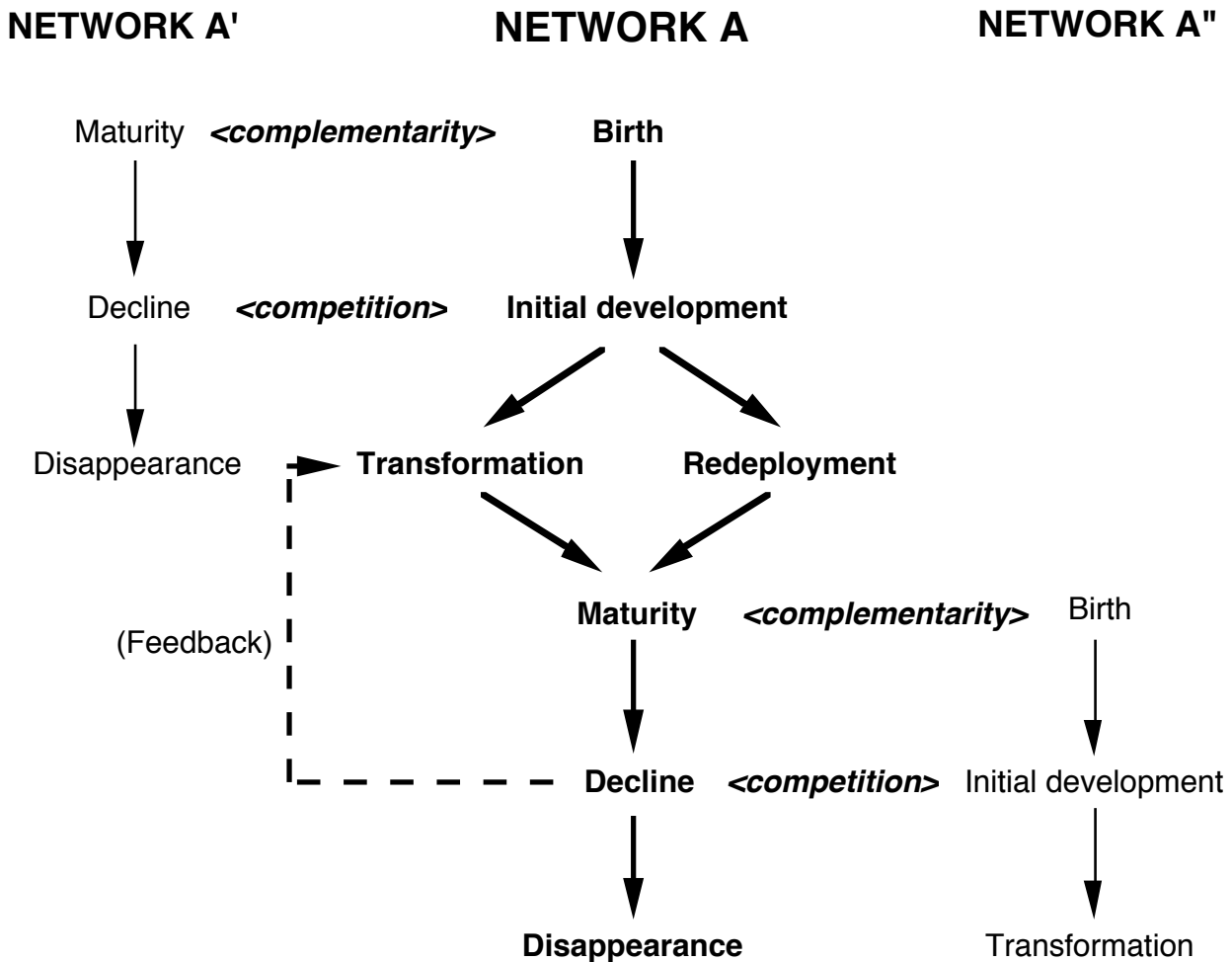
temps present" leans on techniques². Finally, the history of companies is aware of networks' operators, whose technical choices can be determinant when an alternative appears.

The large number of sites studied authorize and legitimate a reasoning by induction. From the various examples reviewed, a simple model of development emerges. It is formalized by fig. 2, with seven distinct stages. These ones have various time spans. The duration of each phase depends on the evolutions of the environment (technology, regulation, other networks) and on the reactivity of the network's management confronted to these evolutions.

We called it a "morphogenesis" model after Georges Amar (in Dupuy, 1988), who proposed a "conceptual model of a circulation network" quite different from this one, but based on a similar presupposition : the evolutions of networks can hardly be explained without any reference to their environment.

²See for instance the research works carried out by Alain Beltran, Pascal Griset, François Caron, Michèle Merger, etc.

Fig. 2 - Proposed model of technical systems development (Offner, 1993b)



These seven phases are as follows :

4.1 - The birth : innovations without an immediate eviction

A new network is generally generated by an existing one, whether it be material, immaterial³, support- or services-network. Firstly in complementarity with the oldest one, it becomes quickly a competitor : this is the case of public transport by coaches/ buses, which was firstly an auxiliary of railways networks before being a formidable competitor of regional branch lines, indeed even of some intercity services.

In a few other cases, there is no complementarity phase. This happened in the past between electricity and gas for energy supply networks (Beltran, 1989) and we witness nowadays a strong competition between Hertzian and cable-based television distribution networks.

In several cases, there is in fact a simultaneous double process of competition and complementarity : transoceanic cables and radio for international telecommunications (Griset, 1988), rail and air networks (it depends on the travel distance), etc.

Nethertheless, the emergence of a new network doesn't mean an immediate eviction of the existing ones every time. Instead, there is an adaptation, a transformation into new

³This includes any pattern of relationship.

configurations. For instance, the telephone doesn't substitute for transport and the fax doesn't substitute for regular mail.

4.2 - The initial development : towards a first equilibrium

Without any change of the creation conditions of the network, it expands in order to reach a first equilibrium between supply and demand :

- equilibrium from the point of view of economic profitability (most of the new networks are launched by private investors),
- equilibrium from the point of view of the number of users connected to the network (the economists call this a "club effect"),
- equilibrium as an optimal scale of management.

4.3 - The transformation phase : some modifications of the use of networks

Most of the current technical systems experience a second phase of development, faster than the first one, after a significant transformation of their use, which permits the increase of the number of users. Two examples illustrate this point :

-telephone networks were initially designed for purely professional uses. The idea of having a telephonic conversation, the use of telephone calls for private relationships, appears afterwards (Fischer, 1990). The technical innovation is progressively taken over by the social body, and the network's flexibility makes possible this real subversion of the use. Later on, other transformations took place, for instance, the use of the network for data transmission ;

-the use possibilities of cable networks made of optical fiber, initially designed for TV programs distribution, have been progressively extended to many new applications like home automation (starting up heating, lights or all kinds of electric appliances by remote control), or telephone routing (cable operators can now compete with local telephone companies).

4.4 - *Redeployment : how to secure the network's durability*

During this phase, the logics of use are not preponderant : the operator's logic prevails, with a concern to rationalize the management of the network, in order to make it more efficient and more attractive.

Two redeployment modes have been observed. We call them "intensive" and "extensive" modes :

-the "extensive" mode covers all kinds of topological connectivity processes between similar networks. Interconnectivity processes belong to this category. They can be found in the domains of transport (Zembri, 1997), water and power supply, etc.

-the "intensive" mode aims to homogenize and to group *a priori* different flows, in order to obtain better use and profitability of costly infrastructures. The organization principle in "hub and spokes" of some transport networks, or the digitizing of telephone networks (which permits routing in the same cable of voices, pictures, computer data, etc.) comply with this logic.

4.5 - *Maturity : the network depends upon its environment*

This is a stabilization phase of the network's growth, without any significant change of technologies or of use. Technical systems become very vulnerable, because they depend upon (i) a limited number of users, (ii) the level of consumption of the services, (iii) the solvency of the customers, etc. The irruption of new competitors may be dangerous, especially if they give better answers to a permanently changing demand linked to evolving ways of life.

In the domain of transport, the disappearance of urban tram networks in France from the 1930's to the 1960's couldn't be completely explained by the competition with buses or (more recently) with individual cars. The analysis must integrate financial or regulation aspects, and also residential transformations (urban populations are less dense, and move towards areas which are not served by public transport).

4.6 - *From decline to disappearance*

Pure and simple disappearances of networks are rare. They generally obtain a second or third chance by transforming or redeploying themselves. The linear progress from birth to disappearance is generally interrupted by successive feedbacks, which permit the network to survive.

If there is a real decline, it is very progressive, with a succession of micro-decisions, leading a posteriori to an acknowledgement of reduction of the territorial coverage. This is the case for instance of rail branch lines in rural areas : a few short sections, totalizing about a hundred kilometers, are closed every year (Zembri, 1993).

The decline phase is long and leads rarely to a complete closing down. Narrow gauge canals, not adapted to modern river transport, begin another life with tourism (renting houseboats). Telex didn't lose entirely its market with the rise of facsimile transmission, because of its value as a legal proof. In fact, each network finds its place in a given socio-economical and technical context.

5. An application to railways networks in Western Europe

European railways networks are at least 150 years-old. They are among the oldest networks still in operation. This gives us the opportunity to study them with hindsight.

A determination of the different periods has been made with regard to the following criteria :

- the policy leading to networks development, which may explain the speeding-up or the slowing down of certain processes ;
- the operators' status, which changes several times : the main evolution towards a relative coincidence between networks and territories (one territory, one operator), is now called into question with a nearly-generalized deregulation and dismemberment process ;
- the network's management logic : it results from the state of the market, the constraints imposed on the operator, and its own vision of the network ;
- the network's configuration, as a spatial translation of the confrontation between the different logics.

Five unequal periods have been determined. The turning points between them are average ones : from one country to another, the evolutions have not been the same.

5.1 - *The birth : an unusual sight playing a marginal role (1820-1850)*

The first links were built in order to transport mining products, from the mine to the nearest waterway. This is especially the case of France and Great Britain. These single sections were granted to industrial companies, using railways as a complement to existing networks (horse-powered road transport, waterways), not as an autonomous one. The transport of passengers was a by-product of freight transport at first (using the same carriages). The building of passenger-dedicated lines took place later (1837 in France with the Paris - St-Germain line).

There is no general plan for railways development : new lines appear in different places, responding to isolated needs. The States intervene more or less in the domain of security and tariff, in a liberal economic context.

Whatever the control means may be, the need of national networks increases at the end of this first period. The small initial companies merge together, and they become able to build long-distance lines. In France, the first main lines (Paris - Rouen, Paris - Orléans) were put into service in 1843, one year after the first national railways scheme called "*étoile de Legrand*".

5.2 - *The golden Age of railways (1850-1900)*

The beginning of this quite long period is characterized by a huge private and public joint investment, in order to develop national-scale networks, independent viz. other ground transportation networks : competition follows complementarity.

In order to reach ambitious development purposes⁴, financing must be important and operators must be strong. Small companies have no place in the new organization whose objective is to achieve numerous projects. A few large railways companies emerge. They operate homogeneous networks serving large parts of national territories. We note for instance Prussian and Badish

⁴As developed for instance in the French Plans "Freycinet I" (1878) and "Freycinet II" (1879).

railways in Germany, Great Western or London and North Eastern Railways in Great-Britain, Paris-Lyon-Méditerranée, Paris-Orléans or Midi in France. These "great networks" are able to develop and generalize a large number of innovations that put railways into a situation of monopoly in both passenger and freight transportation : improvement in steam power, electrification, traffic control and safety equipments. They put into practice tariff equalization between profitable main lines and branch lines in deficit. Their capacity to raise funds is considerable⁵.

The strategic interest of railways, an efficient and modern mode very useful for war operations, is not lost on by governments which, either multiply technical obstacles in order to avoid the possibility of the enemy using the national railways network⁶, or turn the network development to more connectivity and higher density in order to facilitate access to the most endangered border-lines by train. The notion of "strategic line", useless in normal conditions but maintained only for military use, comes in the 1870's.

However, interchanges between European countries are not discouraged at all. Interconnectivity and rolling stock exchanges are regulated after 1880 by international organizations, which define common technical rules. The first great international train, the *Orient Express*, runs for the first time from Paris to Istanbul in 1883.

5.3 - Crisis and nationalizations (1900-1950)

We enter a maturity phase. The expansion of the great companies becomes unhealthy : all the new links opened in order to increase the density of the networks are in deficit, and the rhythm of expansion is too fast. The result is a serious financial crisis. According to the reliability of the company, the crisis may be sudden or take more time to develop. The States have to intervene in different means. The (short or long term) end of the process is the nationalization of the companies.

The first country where railways are nationalized is Italy : The *Ferrovie dello Stato* (FS) are created in 1905. The German railways will follow in 1923, and the *British Railways* will be the last national company created in 1948⁷. France has a median position with a three-steps process : (i) purchase of the "Ouest" company, really in a poor condition, in 1909, (ii) the establishment of a financial solidarity between railways companies, and of a common status for railwaymen, (iii) complete nationalization of the "great companies" in 1937 and creation of SNCF.

The condition of railway companies is worsened by the spread of engine-powered road services (buses and coaches, haulage, private cars) in the 1920's and 1930's. During a first (short) period, railway companies and road carriers cooperate : the latter becomes a conduit for passengers and goods. Some companies create road transport auxiliary subsidiaries. In a second step, competition appears and the railways lose an increasing part of their market share, especially in rural areas.

Nationalization is an opportunity for the standardization of technical norms and operation regulations and processes at a national scale. At the end of the evolution, functional and institutional territories coincide.

⁵The interest of numerous bankers (like Pereire, Rothschild or Hottinguer in France) for railways is constant, despite several financial crises during the 19th century.

⁶That is the reason why different gauges are available in Europe.

⁷And the first to be dismembered in 1992.

5.4 - A generalized decline and redeployment (1930-1980)

Railways suffer from two parallel evolutions, making them lose significant market share : the population drain of rural areas and the increase of the private car. Massive shut down occur in all the low-density parts of Western Europe. Sometimes, important railway nodes totally disappear (Auphan, 1990) and long-distance flows are concentrated on a limited number of routes, where infrastructure is upgraded.

This period is also characterized by a lack of technological innovation in Europe, and by a lack of funding. Railways are no longer considered as means of transport of the future.

Finally, there is an important reorientation on main lines (17 000 km of 50 000 km are closed-down in France for instance between 1935 and 1980), and on urban areas, where suburban and express subnetworks (like *S-Bahn* in German main towns, *RER* in the Parisian Region, etc.) are developed.

5.5 - A limited revival and a change of scale (since 1985)

This last period (for the moment) begins in Europe with the opening of the first high-speed line between Paris and Lyon (1982-1984). Initially designed in order to relieve the most important transport corridor in France (a consequence of the former redeployment period detailed in 5.4), this new infrastructure will lead to new ways of using the railway network. The huge success of this first realization argues for additional ones. There is a change of scale, from an isolated high-speed line to a national high-speed network, and to a European high-speed network.

This evolution leads, in quantitative as well as qualitative terms, to a revival⁸ of the European railways system based on the new high-speed lines. Most of the pre-existing lines are reprocessed for concentration/diffusion routes connected to the high-speed core of the network. High speed is also an opportunity for some operators to question the specific technical characteristics of their network : for instance Spain builds its new lines with the European standard gauge (1,435 m) and the United-Kingdom will build in a few years a new line with continental characteristics (British trains are less wide than European ones, and the inter-track distance is smaller). More generally, all the European operators will progressively harmonize technical standards, but it's a very difficult task.

5.6 - Synthesis

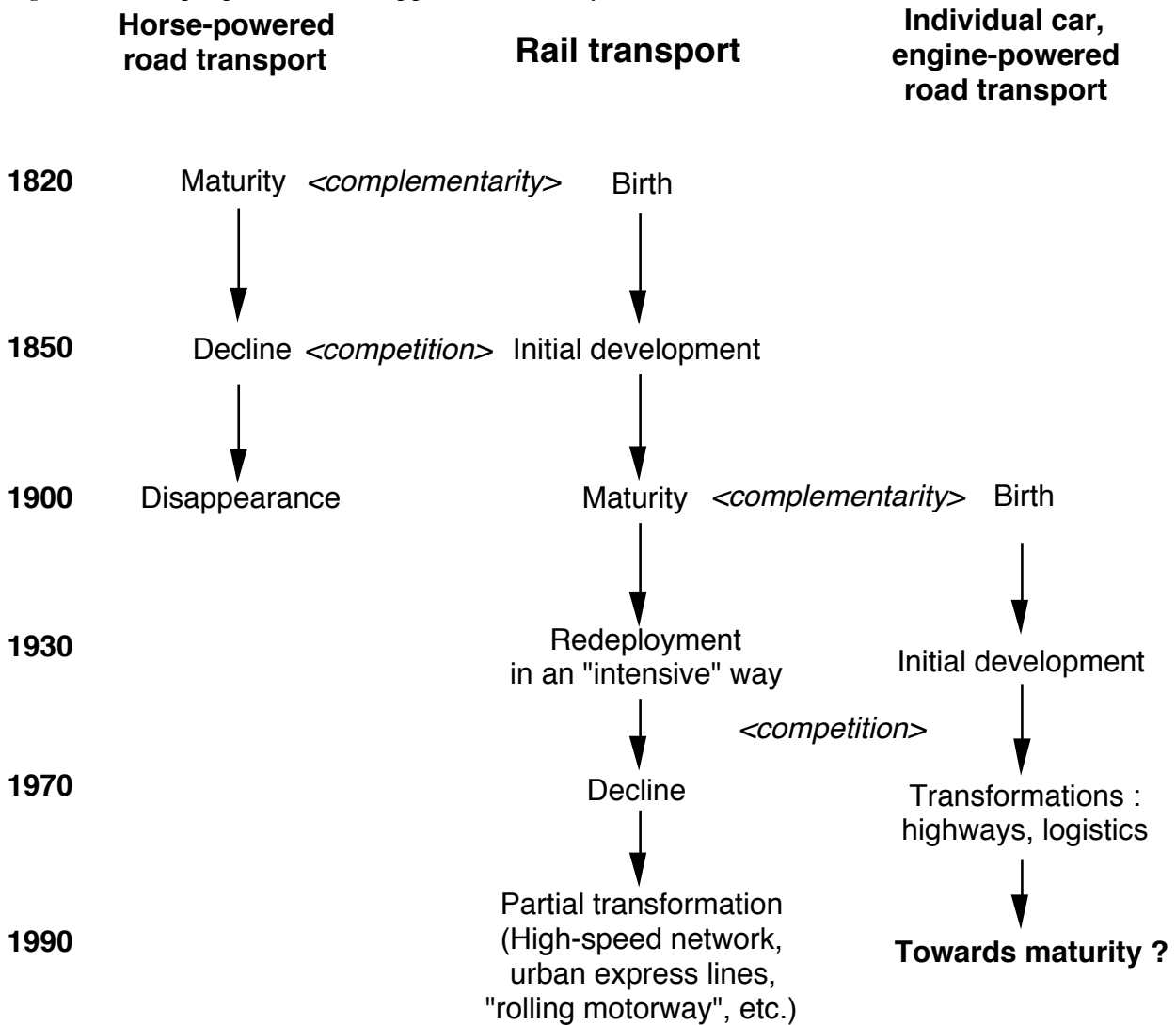
The history of European railways shows an increasing evolution of the scale of reference, from a local one (in complementarity with another mode) to a national, and nowadays to an international one, following a continuous increase of performance. The local scale is now inadequate, except in an urban context. Haulage and individual vehicles are more pertinent for short- and medium-distance journeys (under 200 km).

Railways supplanted and nearly ousted inland water transport, whose market-share is now very small in some countries (6% in France, 1% in Italy, etc.). Until the development of the automobile, they surpassed the road modes, acquiring de facto a monopolistic position for one century. When this position went into question, the rail companies were unable to react because

⁸That means that the process of decline is interrupted, and a feedback loop leads to another maturity phase after the present redeployment.

of financial reasons (see 5.4), and they went into decline. The present revival is limited to the most used routes. Could it be extended to the other ones ? Is the pertinence of the railways definitely limited to a few specific traffic categories ? Complementarity with other modes (especially road and air) means a new task sharing. European railways are now in transformation, with different options and different results. The study of these changes should be very instructive, but it's no longer a study limited to a single network...

Figure 3 - The proposed model applied to railways network : a schematic view



6. Conclusion

The main interest of the proposed model is to emphasize networks' self-adaptation to their environment. They modify some of their characteristics according to the demand, to regulation constraints or to the possible competition with other networks based on more recent technologies. Some of them disappear because they are no more compatible with their environment.

Another point of interest is that this model permits the reintroduction of a territorial dimension in the analysis of technical systems. Because they are always linked to spatial dynamics, which affect the network or which are transformed by it, relationships between networks and territories are double-sided.

However, this model doesn't take into account some transformation factors like demand induction by supply or the irreversibility of certain operation standards initially-chosen. These are endogeneous transformation factors.

Finally, networks seem to evolve according to a double-movement of reaction against external factors and of spontaneous tendency to more complexity.

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