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Nature's Order? Questioning Causality in the Modelling of Transport Networks¹

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Abstract

Numerous social science studies found inspiration in the natural sciences to explain historical events and processes. Similarly, geography has a long history of scholarly work crossing boundaries between the natural and social sciences. A good example of such nature-society transfers is offered by the literature that models the spatial growth of infrastructure networks, ranging from the application of fractals, Newton's law of gravitation, and Shiatsu meridians, to laboratory experiments with slime mould in Petri dishes. This article focuses on how transfers between the social and natural sciences influence conceptualisations of causality, with the working hypothesis that economic thought has a key role in explaining the continued attraction. To reveal the particular ways in which researchers explain network development and try to uncover the underlying rationality and causality, two different approaches were applied to the same case, the development of Belgium's motorway network. The first approach is based on a quantitative topological gravity-style model, while the second offers a historical account. The confrontation of both approaches confirms that the risk of 'naturalising' history lies in the downplaying of the role of agency and political choices. But what makes this study especially relevant is that it shows how evolutions in economic thought shape the use of natural metaphors in novel ways, reinterpreting history using recent conceptualisations of demand, decentral planning, and the market/politics divide.

Keywords: transport networks, topology, causality, metaphors, history

¹ authors contributed equally to the writing of this paper

Introduction

In the past few years Andrew Adamatzky, Director of the *Unconventional Computing Centre* at the University of the West of England in Bristol,¹ with a number of co-authors, has published a series of academic papers on the rationality of motorway networks based on a surely unconventional research method (Adamatzky and Jones, 2010; Adamatzky et al., 2013). Rationality was traced by putting oat flakes in a Petri dish, mimicking the location of cities in a study area. Subsequently, slime mould (*Physarum polycephalum*) was added to the flakes representing the capital city. After the slime mould had grown and connected all cities with a network of protoplasmic tubes, the resulting network was compared with the actual motorway network. The topology of the motorway networks in Belgium, Canada and China was best represented by the protoplasmic networks, while the lowest values of 'bio-rationality' were found for the networks in the USA and Africa. This analysis of the growth and structure of infrastructure networks attracted media attention and has been applied by other research teams; a slime mould-based analysis of the Tokyo rail system even found its way to the pages of *Science* (Tero et al., 2010; see also Dupuy, 2013).

The intriguing slime mould research establishes a link between the social sciences –in particular the study of transport networks in relation to urbanisation– and the natural sciences. However, it does so in a fundamentally different way than research on nature-society relations in human geography that seeks "to 'bring nature back in' to their subject" (Castree, 2009: 942). In human geography, the past 25 years have witnessed a flurry of studies on the relation between nature and society. From scholarly work focused on the social construction of nature (e.g. Cronon, 1991; Heynen et al., 2006; Gandy, 2008), over careful explorations of human/non-human hybridity in the early 2000s (e.g. Whatmore, 2002; Hinchliffe, 2008; Braun and Whatmore, 2010), to recent post-human agendas (e.g. Latour, 2017; Haraway, 2016; Morton, 2013), nature as a given universal law has mostly been avoided, critiqued or deconstructed and reworked (Gandy, 2008, 2015; Swyngedouw and Ernstson, 2018). Indeed, authors such as Matthew Gandy (2008, 2015) are critical of tendencies towards 'philosophical naturalism' which involves the application of general, universal and natural principles as a way of understanding natural and social phenomena.

Yet, despite all criticisms, scholars keep publishing research that employs natural metaphors and analogies. A significant number of studies in such domains as geography and planning geared at understanding complexity, resilience, uncertainty and instability are currently generating new interdisciplinary alliances exploring nature-society interactions to trace underlying structures and systems. Analogies and metaphors from biology, physics and other natural sciences are instrumental in the search for a 'natural order' or rationality –an 'immanent justice of cause and effect' (Daston and Vidal, 2004: 14)– behind multifarious and incongruous phenomena. Natural science models are increasingly being deployed to search for causality and order in the social past (see Scheffer et al., 2017), and, even more so, are identified as 'general principle' or 'law' to extrapolate in the future (Hodgson, 2004; Gandy, 2015; Schwanen, 2017). The renewed popularity of organic metaphors is, arguably, nowhere more clearly to be observed as in literature on the historical evolution and development of the built environment, and transport networks more specifically (Batty, 2013; Gerber and Patterson, 2013; Reed and Lister, 2014; Luque and Jafari, 2017). The historical and spatial development of large-scale infrastructure has fascinated researchers from a variety of disciplinary backgrounds, with an increasing influence of physics and complexity sciences in the analysis and planning of network development (Timms, 2008). Transport networks are

conceptualised and explained using fractals (Kim et al., 2003; Benguigui and Daoud, 1991), Newton's law of gravitation (Koopmans et al., 2012), the vascular system, Shiatsu meridians (Ozeki, 2012), and in recent studies, as we illustrated earlier, even using slime mould in Petri dishes (Adamatzky et al., 2013; Tero et al., 2010).

According to Gabriel Dupuy (2013), studies of transport networks might benefit from slime mould studies and related forms of interdisciplinary research, in particular from the contributions of 'naïve' outsiders. Such outsiders include mathematicians, biologists and physicists who apply their toolbox and concepts, with an outsider's view, without much knowledge of transport studies and transport history. In fact, there exists a continuum of studies that apply naturalising models and metaphors to transport networks, ranging from 'naïve outsiders' who hardly make reference to traditions in transport studies (e.g. Benguigui, 1992), to work in the core of the discipline (e.g. Levinson and Karamalaputi 2003a, 2003b; Yamins et al., 2003).

This prompts the question of why models and metaphors derived from the natural world have continued to attract scholarly attention from different disciplines, and across different epistemic communities in time and space. This article focuses on nature-society transfers in research on transport network growth and on how these transfers influence conceptualisations of causality, with the working hypothesis that economic thought has a key role in explaining its continued attraction. First, we discuss the long history of nature-society transfers in thinking about networks and zoom in on post-war modelling and the influence of economic thought. While there is no shortage of studies that point to the increased impact of 'economics' and 'economic thought' on other disciplines and society, we offer a more in-depth study of recent economic reasoning on historical explanations of spatial structures. Doing this, we do not put slime mould-like approaches on a par with neoclassical network growth studies, but look for differences and similarities. The analysis builds on the history of economic thought (e.g. Backhouse, 2005; Backhouse and Medema, 2009; Mirowski, 1994, 2009; Zuidhof, 2012) to reveal the specific views and interpretations present in the network growth literature. In contrast to more standard –but nevertheless useful– deconstructions and analyses of natural science-inspired approaches (e.g. Gandy, 2015), generally pointing at a lack of attention for agency in these approaches, we present a deeper engagement with the specific literature driving the nature-society transfers. After the analysis of the economic rationales behind nature-inspired network modelling, and gravity-inspired approaches more concretely, we assess the merits and pitfalls of these transfers by mobilising the case-study of the Belgian motorway network. Therefore, the next part of the paper submerges the reader in two different approaches which explain the development of motorway networks, a (1) nature-inspired gravity network expansion model, and (2) a historical analysis focusing on intricate socio-economic processes, events and actors. The confrontation of both approaches puts their compatibility to the test.

While Dupuy argues that interdisciplinary studies can be a valuable source of inspiration, others question the compatibility of certain disciplines or approaches. The present paper engages with two approaches which largely correspond to the two distinct schools in the social sciences distinguished by Thierry Ramadier (2004: 435) in his paper on transdisciplinarity in urban studies. The first school is mainly influenced by the natural sciences, while the second strand is based on a cultural (critical, anti-positivist) vision. Regarding these schools, Ramadier states that 'interdisciplinary bridges have been built', but he also points to the existence of 'contradictory theoretical schools', and to the fact that

'few attempts have been made to confront their points of view'. Harding and Blokland (2014: 12-19) as well have recently stated how a 'positivist' stance within urban studies remains hard to reconcile with an 'hermeneutical stance'. They argue how especially the notion of prediction is a recurring tumble stone in interdisciplinary efforts. 'Hermeneutical' approaches believe people to be placed in 'open systems' –where change is constant and events are rarely repeated– contradicting fundamentally with the law-like thinking or 'closed systems' of particular interpretations of the natural sciences by social scientists. By diving into two different conceptual pools, we show how distinct schools in the social sciences approach the same problem differently. The Discussion Section confronts both approaches, and critically questions and examines natural models and metaphors within transport studies, which are mobilised to both explain and hypothesise on the historical and future development of transport networks. The conclusion reminds us that natural and other metaphors can be employed in many different ways, but that 'naturalising' historical explanations often result in reduced attention for political ideology and economic power within history. In particular, the case study illustrates how this reduction results in conceptualisations of infrastructure planning akin to Hayekian decentral planning, and how this is easily linked to ideas of consumer democracy.

Nature's order

Extracting norms from nature is not a new phenomenon. A well-documented case of a social science discipline of the 'philosophical naturalism' type is neoclassical economics, which is to a large extent inspired by nineteenth century physics (Mirowski, 1989) and is peppered with biological metaphors. We introduced the examination of transport networks using slime mould as an unconventional experiment, however, as Mirowski (1994) reminds us, in the 1970s, 1980s and 1990s, leading economic journals published the results of experiments with laboratory rats and pigeons in which animals stood for consumers with demand curves; for workers; and for players in different kinds of markets. These examples illustrate that the use of biological experiments and metaphors in our present day is not unique, but taps into a long-running tradition of extracting models and norms from nature, through the intermediary of an organic metaphor or, as in the case of Adamatzky, literal analogies with a bio-physical system.

Historians of science, like Lorraine Daston, have described this tradition extensively. During the last quarter of the 19th-century, when modern social sciences came into being, it assimilated many of its causal reasoning from systems and models from the natural sciences. From a study and discipline which was hitherto deeply stamped by religious practice and beliefs, it might have been expected that 'God' as prime mover would be replaced by the moral authority of 'Nature' (Daston and Vidal, 2004). The momentous publication of Charles Darwin's *Origin of Species* in 1859 has been pointed out as the single most important watershed in changing such Western viewpoints on the past, transposing nature's systems on societal development (Tollebeek et al., 2003: 3; Castree, 2009). But in fact, many other evolutionary conceptions, with Lamarckian thinking looming large among them (Livingstone, 1985), were reshaping the myriad ways of perceiving and interpreting the past and future around 1900 (De Bont, 2008).

When plunging even further into time and turning back to the case of infrastructure, the very idea of transport *networks* can be traced back to the rise of organic metaphors in the Enlightenment. Antoine Picon (1992) stresses how even before the ascendance and

towering influence of Darwin, late eighteenth-century and early nineteenth-century scholars and practitioners were avidly trying to reconcile the 'natural' and 'artificial' (see also Picon, 2018). In fact, the term 'réseau' (network) appears in engineering literature at the same time as it emerged in the medical sciences to refer to artery and nerve systems or tissue structures (Picon, 2002). In the course of the nineteenth century, these organic notions moved from medicine, biology and engineering studies to the social sciences and philosophy, in which principles of the natural sciences were transposed to society as a whole (Wils, 2005; Gandy, 2008; Castree, 2009).

Gandy warns for the difference in ontological and epistemological precepts and questions whether research is best served by fusing the natural sciences with the social sciences and humanities (Gandy, 2008, 2015). We might be searching for an all-encompassing causality which in reality does not exist (Gandy, 2008), or more troubling, end up with a renewed naturalism that moves from the 'safe' confines of academic analysis to large scale infrastructure planning predicated on bio-rationality rather than explicit political choice (De Block, 2016). In the quest to understand complex phenomena like cities and infrastructure networks, natural science rationalisations might help to point to causal factors (Zitouni, 2013), but it potentially downplays the role of agency and restricts the interpretation of causality (Gandy, 2008; Zitouni, 2013). The slime mould approach described above suggests that it reveals the underlying logic of the growth of infrastructure networks –a complex process that spans decades and involves many actors. In other words, the image of protoplasmic roads that grow between oat flake cities is an example of how complexity is seen as following an autonomous law of self-organisation.

Natural science concepts and models are now being increasingly deployed to plan and thus shape future realities, going from analysing an existing reality to planning a future scenario (Burger and Meijers, 2012). Critics of the 'natural science' approach point to the notions of description and prescription as a problematic issue. The critical distance between analysis and project seems to be losing ground when applying these 'natural' models (De Block, 2016). Moreover, historical development seems to be approached phenomenologically as an identifiable 'natural' pattern (Gandy, 2008), with an emphasis on morphological growth that tends to conceal socio-political and economic dimensions of decision-making. Besides blurring description and prescription, (morphological) form and (socio-political) norm are generally conflated in these approaches. Studies that turn to a literal employment of natural sciences tend to focus on association or visual similarity, and discuss causality at a general level referring to evolutionary mechanisms without detailing the underlying processes. For example, slime mould studies understand causality in terms of principles of association and correlation between topological maps and the structures build by living organisms. With this, the historical development of infrastructure networks is seen as an evolutionary process in which network connections are expanded in case of large flows, and abandoned in case of low flow rates (Tero et al., 2010). Yet, there are natural science based approaches that explain causality in a more balanced manner, attempting to bring in societal factors. Neoclassical transport economists, for instance, emphasise gravity-like laws as main causal mechanisms, but leave the door open for additional causes. A common way in neoclassical economics to represent causality is to make a distinction between 'natural' forces and residual noise, referring to market forces and politics (or 'historical accidents', David 1985) respectively.

Modelling the growth of infrastructure networks

As outlined in the introduction, the renewed popularity of organic metaphors can clearly be observed in the literature on the historical development of infrastructures, illustrated with a reference to experiments by the Unconventional Computing Centre where slime mould was used to mimic motorway growth. Somewhat less experimental than this method, and more in line with mainstream transport studies, are attempts to find 'natural' order in the growth of transport networks by transport geographers, engineers and economists (Black, 1971; Cervero and Hansen, 2002; Yamins et al., 2003). Indeed, a good deal of transport geography and economics studies have been published that explain, predict and simulate the growth of transport networks. The standard approach is a topological one, in which the nodes in the network commonly represent cities or junctions, and the edges represent transport infrastructures (Levinson, 2008; Levinson and Karamalaputi, 2003a). Several of these models are based on the physical 'law of gravity', assuming that networks start growing from and in between large population centres while more peripheral parts of the network are built later. Once congestion becomes an issue, investments are again concentrated in core areas (Levinson and Karamalaputi, 2003a, b). Adamatzky's model is also based on these gravity-principles: the oat represents population centres, slime mould showcases 'smart' and 'rational' connections based on productive, efficient and feasible growth.

Whether a 'transport segment' connecting two cities is added to a transport network depends on many factors (Kolars and Malin, 1970; Rietveld and Van Nierop, 1995). It can be based upon: the motivations driving the transport connection (political-military, agricultural, mining, or other purposes, etc.); construction costs (which are related to the complexity of the physical landscape); budgetary constraints; the structure of the existing network and shape of the cities (compact or extended); but, above all, transport demand, which is commonly measured by population data (Levinson and Karamalaputi, 2003b). Although income or economic output may be a better proxy for demand, data availability makes population size an often-used indicator. Demand is considered by far the most important causal factor, and becomes commonly estimated similarly to a standard transport model, i.e. demand is a function of both the size of and the distance between the cities: the larger the distance and the smaller the size of the cities, the lower the demand for transport between these cities. Rietveld and Van Nierop reformulate this in terms of the *rate of return on capital*: investment in an additional segment depends on transport demand, which determines the receipts, which are in turn a function of passenger kilometres travelled (or in the case of freight, ton-kilometres). The number of kilometres travelled also determines the variable costs, while the length of the network is a proxy for the investment costs (Rietveld and Van Nierop, 1995; Koopmans et al., 2012).

The discussion above illustrates that transport economists and geographers generally employ a richer set of explanatory factors than slime mould-like studies. While they may – just as 'naïve outsiders' – refer to Darwin and evolutionary concepts (e.g. Levinson, 2005), they also point to structural factors such as demand and costs. In addition, causality is generally not restricted to market factors. The transport economics literature on network growth is permeated with the idea that there is on the one hand, 'politics', and on the other hand, 'natural' (market) processes. For example, the study of Levinson on the co-development of London's rail network and land use contains a 'background' section referring to a considerable number of historical actors and particular decisions. However, the core discussion of the model lacks references to these 'politics' or 'history' (Levinson, 2008). The

following quotes illustrate the distinction that is made between underlying factors and 'politics' by transport economists:

'The development of network evolution models at the macroscopic and microscopic perspectives offers new insights into processes that previously were thought to result from the visible hand of planners, engineers, and politicians. While there is of course a residual to the analysis that can be explained as the product of conscientious decision-makers, there is a large part of network growth that is driven by the underlying geography, economy, and technology.' (Levinson, 2005: 187)

'a number of measurable properties drive network expansion. While it is obvious that politics factors into network expansion decisions, this model is based on empirically measurable attributes.' (Levinson and Karamalaputi, 2003a: 316)

As has been illustrated in the first two sections, such a 'positivist' stance differs from the approaches of the 'hermeneutical' camp. The latter emphasise historical contingency which implies that analysis of the growth of an infrastructure network can never be separated from particular political decisions, changes in the wider policy environment and the specific social, political, economic and cultural context, which is considered unique to each place and period. A variety of causal factors –both particular decisions as well as general evolutions– are then combined in a narrative that explains why for example motorways were built in a particular period and region.

Case study: The growth of the Belgian motorway network

To obtain a better understanding of the different approaches, we present two analyses of the same case: a 'positivist' and an 'historical' approach. The paper focuses on the Belgian motorway network, a network of which evaluations in the literature, paradoxically, diverge from being one of the most 'rational' in the world (Adamatzky et al., 2013) to being the most 'chaotic', or, indeed, 'irrational' (Ryckewaert, 2012; De Block and De Meulder, 2011). The question then becomes: rational or irrational according to which explanatory models, and according to which perspective? Is the Belgium network considered rational because it miraculously follows natural-science modelling, as was, indeed, suggested in a recent study (Adamatzky et al., 2013). And is a system then irrational or chaotic if it does not? And what if a 'rational' order is rather an historical reflection of a man-made and politically loaded decision-making process, that becomes objectified with nature as perfect 'disguise'? Based on two analyses of the Belgian motorway network –a quantitative topological approach predicated on natural sciences rationales and a planning history lens respectively– the present article critically assesses and discusses the views and values held by actors of the past, present and future on the development of transport networks. It ultimately reflects on the scientific and societal implications of using natural science causations in explaining historical processes.

In what follows, the Belgian motorway network after WWII is conceptualised as a topological network with cities as nodes and motorways as edges. This transformation of an infrastructure network in a graph necessarily involves choices and simplifications (see Dupuy

and Stransky, 1996). The criteria used to select cities (nodes) and motorways (edges) are given below, and while other criteria could be applied, the resulting graph (Figure 1) seems a reasonable approximation of the actual network.² Our example of topological analysis can, indeed, be transposed to all kind of transport networks at a variety of scales (Xie and Levinson, 2009). Intra-urban models investigate the development of street networks (e.g. Levinson and Karamalaputi, 2003a) or railway expansion (e.g. Levinson, 2008) within a particular city, while inter-urban models focus on the connections between cities (e.g. Rietveld and Van Nierop, 1995). Differences in scale exist within these models as well, for example the local streets in a small city and the major arteries in a large metropolis are both intra-urban, and the motorway network in a relatively small country (the case used in this study) and the major connections between urban agglomerations in Europe (Dupuy and Stransky, 1996) are both examples of an inter-urban focus. Scale and delineation matter since the type and purpose of traffic, and the decision making process differ between scales. At a more abstract level, it has been argued that spatial networks are not scale-free since the distance between nodes and the relative position of nodes in space matters (Barthélemy, 2003; Dupuy, 2013; Thomas et al., 2018). In the illustration discussed below, we have chosen a particular scale, namely the case of interurban links in one country. Nevertheless, our argument can be transferred to other scales in the sense that the particular use of natural science rationalisations in network expansion models can be found in analyses that investigate infrastructure networks at a variety of scales.

A threshold value of 50,000 residents was used to select cities. The population data was provided by the LOKSTAT project.³ Data were aggregated at the municipality level (merged municipalities, since 1983, $n=589$). To this end, the population of all municipalities within a range of 5km was taken into account. Two cities which were located at a distance of less than 10km were considered as one urban area (this was the case for Mons-La Louvière and Hasselt-Genk), and the centroid of the central municipality (whose name is used for the entire city region) was used for further calculations. On the basis of this method, there were 16 cities in 1931 and 19 in 1971.

The unit of the representation interlinking these cities was the 'transport segment', a finished motorway link between two of the nineteen selected cities. The period under consideration was subdivided into three intervals: 1954-1965, 1966-1975 and 1976-2001.⁴ The maximum number of edges in a network of 19 cities is 171 (note that cities in neighbouring countries are ignored, like in the work of Adamatzky).⁵ In our analysis, only transport segments with a length of less than 75km were taken into account, which comes down to a total number of possible transport segments that equals 79; note that the longest road built in Belgium is the Antwerp-Hasselt connection, having a distance of 74km.

Figure 1: Actual historical network development of the Belgian motorway network

Figure 2: Actual versus Simulated Motorway Network

Figure 1 depicts the actual, historical network growth of the Belgian motorway network after WWII, while Figure 2 compares this development with a simulation based on the popular 'gravity model'. Note that we employed a simple model in order to illustrate the general approach, but we believe that this example sufficiently represents the perspective of network growth models. What happened in reality? On the eve of the Second World War, the Belgian government had started building a section of the motorway between Ghent and Bruges. However, it was not until the first half of the 1950s that the first transport segment connecting two cities was completed. From a topological perspective, Belgium was an edgeless graph at the start of this period (1954-1965), only seven transport segments were completed during this phase, and investments were mainly directed towards peripheral parts of the network. This evolution needs an explanation, since our 'natural-science'-simulation based on some basic assumptions (further elaborated below), suggests a different evolution.

After the eventual completion of seven transport segments in the first period of study, there were still 72 possible transport segments that could possibly have been built. In the second period, between 1965-1975, thirteen segments were actually added to the motorway network, mainly between cities at a moderate distance from each other. The third period (1975-2001) witnessed the completion of six additional motorway segments. The structure of the existing network seemed to be the main determining factor for new investments since new links were built in some empty meshes of the network.

How does this real-life evolution compare with a simulation based on the popular 'gravity model'? In this exercise, segments were added to the network one by one in decreasing order of transport demand, which was defined as follows:

$$\text{Demand} = \text{Population}_{\text{cityA}} \times \text{Population}_{\text{cityB}} / \text{distance}^2$$

With following constraints and criteria:

- budget constraint: network length must be as close as possible to the actual length.
- angular constraint: the angle between two links should at least be 30°. This constraint accounts for the fact that parallel links or alternative routes can reduce the need for a new road segment.
- distances were measured as the crow flies between the centroids of the municipalities (making use of Lambert 1972 coordinates).
- population size of a city is the sum of the population of all municipalities within a range of 5km (on the basis of the centroids). The census years 1951, 1961 and 1971 are used for population figures in the periods 1954-1965, 1966-1975 and 1976-2001 respectively.

The graphic outcome of this natural science exercise shows that there are notable differences between the simulated (Figure 2) and the actual network (Figure 1). Table 1 gives some figures which indicate that the simulation does not perform too bad when the entire

period is taken into account, but that the actual development or 'growth' is less well described. In other words, a teleological perspective that only takes into account the end-result might positively value the simulation (from hindsight), while an historical perspective that focuses on the genealogy of the network might be concerned about the fact that the number of correctly predicted new links is never higher than the number of incorrectly predicted new links.

Table 1: Comparison between the actual and the simulated networks

variable	period 1	period 2	period 3
number of motorway links at the end of the period	7	20	26
new links	7	13	6
number of correctly predicted links	3	16	22
number of correctly predicted new links	3	6	2
number of incorrectly predicted links	6	8	6
number of incorrectly predicted new links	6	9	2

The case of the Belgian motorway network illustrates that, despite, according to Adamatzky et al. (2013), a 'rational' outcome, investments were not made according to a 'rational' plan that can be summarised in one or two variables.⁶ The comparison of the actual and the simulated development reported in the previous paragraph indicates that this supposed rationality is seldom followed and seemingly 'irrational' parameters literally deviate its growth. More specifically, for the early period, an explanation needs to be given why the motorway segments connecting Ostend-Bruges-Ghent-Aalst(-Brussels) were built first (1954, 1956), while the motorway between Brussels and Antwerp (via Mechelen) was not completed until 1981. Therefore, the quantitative, simulation-based part is complemented by an historical source analysis which focuses more on the role, and, indeed, 'rationality' –or better: intentionality– of historical actors and the wider institutional context.

History's intricacy: sociospatial development of the motorway network

In contrast to the early enthusiasm for motorways in countries like Germany, Italy and the United States, in Belgium this new type of limited access road for cars was perceived as 'snobbish' and even anti-democratic by many politicians as well as prominent engineers. Although the idea of special purpose roads was already known in 1900, it took decades to make the concept acceptable in Belgium (Weber, 2010). In addition to the loss of public street life, these roads –or *routes fermées* as engineer-in-chief Armand Devallée called them (1938)– were considered as potential barriers in the densely urbanised landscape of Belgium. Instead of being a means to rebuild the nation after World War I, the motorway would damage the 'typically' fine-grained Belgian landscape even more (De Block and De Meulder, 2011). Influential automobile clubs, often with a strong focus on recreational driving, also preferred more exciting sceneries and capricious routes over functional and standardised infrastructure (Peleman and Uyttenhove, 2012). Consequently, the Road Fund, set up in 1928 to reconstruct the post-WWI-damaged road network as well as to respond to the growing popularity of the car, was not used for the conception of modern motorways. In this first wave of public works during the interwar period, engineers focused on adapting the

road surface and profiles to multimodal road types. For example, considerable investments were made in the existing Brussels-Antwerp connection, with some financial input from the legacy of King Leopold II. Accessible for cars, trams, bicycles and pedestrians in separate lanes, it was more than an ordinary road, but definitely not a motorway (Weber, 2010). The availability of an, albeit somewhat less efficient, early alternative might have reduced the need for an entirely new motorway between Brussels and Antwerp during motorway construction, thus explaining why this section was not prioritised despite its high gravitational pull.

Although the new type of multimodal road did not allow for high speed car traffic, it did incorporate the sociospatial intentions of the Road Fund aspiring reconstruction and modernisation. Infrastructure was designed by the policymakers not merely as a connector, but primarily as a collector of traffic and consequently attractor of urbanisation and industrialisation (De Block and De Meulder, 2011). Translated to the slime mould method: not only the cities, also the connections between cities were designed to become attractors. In other words, the mould had to transform into oat flakes: this is a fairly improbable evolution in natural science, but a logic causal, and indeed intentional development in history.

On the level of the network design, engineers chose not to superimpose an entirely new road network, but to select existing roads requiring modernisation, like the Brussels-Antwerp connection. Similarly, to extend the road network new components were grafted on existing roads. Although based on flux analyses, the selection of new roads was primarily defined by a political agenda to connect productive cities and regions for industry, leisure and agriculture. This socio-political logic resulted in a plan by Devallée in 1938 (Figure 3). Most of the new roads in the plan are located in areas which are 'white' in the flux diagram; roads that fill gaps in the territory rather than following demand curves, as demand-based models assume. The historical actors did not conflate analysis and project, description and prescription.

In the materialisation of the plan, the road between Brussels, Ghent and Ostend was defined as one of the four sections to be built first (Figure 4) as it not only connected Brussels to the coast, but was also part of the international London-Istanbul connection. Here the potential high flux did influence prioritisation, yet international motives and the King's fondness of the coast were as prominent in the decision. Thus, the fact that this section was built first can be partly explained by flux, but needs to be complemented by, on the one hand, the socio-political agenda of international motives, exceeding the geographical lens of the model, and on the other, by different network rationalities focusing on missing links within the existing road network, which also conveniently served the King's wish to efficiently connect the capital with his favourite place at the coast –Ostend. Besides the logic of missing links, also regional preferences within the department of Public Works might have played a role in both the geographical pattern and speed of realisation of the motorway network. In particular, *Ponts et Chaussées* engineers Claeys and De Wulf in Bruges –a city positioned on the connection between Brussels and Ostend– did believe in the potential of motorways (De Block and De Meulder, 2011).

Figure 3: Flux diagram and plan with missing links as determined by policy-makers (Source: Devallée, 1938; De Brabandere, 1930)

Figure 4: The Belgian trace presented at the Budapest conference on the London-Istanbul connection (Source: Claeys, 1936)

Although in the course of the 1930s and 1940s, several proposals for motorways were made, there did not exist a comprehensive motorway policy in pre-war Belgium. It is not until the 1950s that the integration of the variety of proposals lead to a national plan worthy of the name (Ryckewaert, 2012). At the sixth Belgian road conference in 1950, engineer Henri Hondermarcq presented his program for 930kms of motorway defined by the twin goal of facilitating national socio-economic processes and surfing the wave of imminent European integration. Hondermarcq presented Belgium, and more specifically Brussels and Antwerp, as the strategic crossroad of the new European politico-economic configuration, resulting in numerous connections linking Brussels and the port of Antwerp with its national and international hinterland. The following Road Fund positioned the Antwerp-Brussels region as an economic and urban core in both Belgium and Europe (Hondermarcq, 1950, 1964; De Block, 2011.), explaining why motorways around Brussels and to the neighbouring countries were prioritised over connections between the large population centres in Belgium. In addition, post-war network design focused on underdeveloped, often peripheral regions, thus conceiving motorways as modes of an economic development policy. These explicit choices about international geopolitics and national political economy targeting specific population centres and regions responds to a ‘supply-side’ politics. This approach does not align with the logic of the gravitational model with demand as most influential variable.

Discussion

The previous sections presented, on the one hand, a ‘positivist’ model and, on the other, a historical analysis of the growth of the Belgian network model. The comparison of these approaches will be used to discuss the issues of (1) causality and (2) planning. Regarding causality, studies that employ natural science rationalisations rather literally –by using slime mould for instance– provide a superficial account of causality suggesting that there is some kind of evolutionary process at work. Neoclassical transport economists offer a richer explanation of the process and conceptualise it as a market process with demand as driving force, and construction costs as another relevant variable. Furthermore, economists leave

room for causal factors outside the domain of market rationality, factors which are described as 'historical accidents' or 'politics', and which may be more prominent in some contexts compared to others. Hence, they build an interdisciplinary bridge between positivist economics and those who focus their research efforts on contingent historical facts. However, regarding the history of the development of transport networks, Levinson (2005: 176) states that:

'the idea that planning, engineering, and the intentions of decision makers drives the topology of networks is a top-down creationist viewpoint, in contrast with a model which suggests that networks evolve, with successful facilities being expanded, and less successful transport sections allowed to wither.'

Such downplaying of the role of historical actors and intentions may be one of the reasons why authors in the 'historical contingency' camp do not accept the division between 'natural' processes of decentral planning, and 'politics', since this is effectively 'black-boxing' (Callon and Latour, 1981) questions about the role of agency and contingency in the historical development of transport networks. In the literature on network growth models, political actors are responding, albeit not perfectly, to the logic of the market and demand pressures. In other words, natural market forces operate through, and are mediated by, people and their politics, which results in the infrastructure networks that can be observed empirically. This view ontologically assumes that economic demand is almost always a prime driving force throughout history, also in non-market contexts. This assumption might be too extreme for academics who highlight that the application of demand and supply metaphors as universal causal factors is a phenomenon of the last decades (see e.g. Zuidhof, 2012). For them, a high level of correlation between empirical networks and a demand variable might not be a convincing argument to stage demand as main causal factor that explains history.

Besides causality, the introductory section referred to a number of authors that problematise the normative message of natural science-inspired approaches. We can now raise the question: what type of planning is being implied by the slime mould experiments? The word 'polycephalum' is the Latin name of the slime mould organism meaning 'multi-headed' and indicates that the mould is a single cell with multiple nuclei. In other words, the development of a transport network is compared with an organic process carried out by a decentral organism resulting in a rational, orderly outcome. Decentral planning seems to be the viewpoint used in both the transport economics perspective and the bio-rationality approach. Planning concepts as well, like polycentricism in relation to the currently popular notion of 'bottom-up' policymaking (Davoudi, 2003), tie in with the notion of decentral development (see also Graham and Marvin, 2001). This might not only be problematic from an analytical perspective, but also from a normative one. It is only a small step to Friedrich Hayek's position against central planning and his preference for 'spontaneous order' (Hodgson, 1994). In Hayek's view (1945), no central planner can gather and process all available information to plan the most optimal outcome, instead, he proposes decentralised planning based on market mechanisms since the market can process information better. The market is thus the ultimate information processor, on top of being an efficient allocator of resources (Mirowski, 2009, 2013). Paradoxically, Hayek was not convinced that economics should imitate the natural sciences, and it was an opponent of the Chicago School of

economics, William Vickrey, who is credited for introducing the idea in transport economics that markets should guide investments in transport infrastructure since the 'willingness-to-pay' of road users is 'decentrally' revealed in their willingness to pay tolls (Vickrey, 1969; see Vanoutrive, 2017).

In (transport) economics it is common that the supply and demand metaphor used to explain reality is also used to indicate what should be done, in other words, in a prescriptive way (see e.g. Yang and Bell, 1998; Verhoef and Mohring, 2009). In the case of infrastructure development, the analytical network expansion models are conceptually related to network design models or cost-benefit analysis (CBA)-type of tools that tell us which infrastructures should be built where. The major difference may lie in the inclusion of external costs in prescriptive models. An historical analysis of infrastructure growth which highlights that there has existed a natural, rational order, might too easily be used to state that this 'natural, rational' order should be followed in future infrastructure policy. Hence, the stress that is put on self-organisation and nature can be problematic. We do not claim that central planning is the way to go, but we problematise the naturalisation of history, foregrounding the normative message present in network expansion modelling as well as the 'black-boxing' of human decision making.

To illustrate how this process of 'black-boxing' (Callon and Latour, 1981), of abstraction and exclusion of agency through the application of natural science models and metaphors works, we confronted a topological approach of the Belgian motorway network predicated on natural sciences 'rationales' with a planning history lens focusing on intricate socio-political and technical factors influencing network design and growth. The comparison of an historical analysis of the Belgian network development with an analysis based on classic gravity models, has shown that natural explanations or models are only indicative on a descriptive level, but generally fail to analyse and, critically, explain what is driving historical change. Thus, the supposed 'natural rationality' of the Belgian motorway network was refuted as 'natural process', whether such order is justified on the basis of biology by Adamatzky et al. (2013), or by gravitational physics cum market metaphor as in our example. Instead, we emphasised meticulous, source-based historical analysis in which political and socio-economic context and motivations of actors take centre stage, instead of being treated, separated or isolated as residual 'noise'.

What seems essential in tackling these questions, is the realisation that natural science rationalisations and causality models are not only used to explain the historical growth of transport networks, they are also employed to indicate which future transport segments would make the network more 'rational'. However, causality and rationality is often defined in terms of productivity, efficiency and demand, disguised in sweeping concepts referring to 'natural' development.⁷ Important to note is that basing investments on 'rational' economic principles such as demand, productivity and efficiency, is distinctly different from an economic development policy rationale. Models based on principles such as demand and productivity identify projects that make the best use of resources, and this economic 'rationality' tends to favour the core regions, as is often argued in the regional policy literature (Armstrong and Taylor, 2000). In contrast, the economic development policy rationale of the post-war planning consensus aimed to develop the entire territory, positioning it within an international geopolitical constellation as well as focusing on the growth of underdeveloped regions. Motorway construction in Belgium was mainly based on

an economic development agenda (Ryckewaert, 2012), fitting with a Keynesian state which emphasised planning and large public works (Witte et al, 2005; Saey, 2013).

The distinction between economic development and market-based rationality can be seen in light of changing views about markets, the economy and economics. The modern view of the market, which was popular in the first decades after World War II, is built on the distinction between, on the one hand, a government sphere, and on the other hand, a market sphere, the economy (Foucault, 2004; Zuidhof, 2012; 2014).⁸ Both spheres are supposed to follow their own logic. Applying this to the case of motorway planning, we have an engineering/planning logic aiming at national or regional economic development in the government sphere, and a market logic of firms which are supposed to locate themselves in new industrial estates near motorways. However, the modern government/market dichotomy has been blurred and has often been replaced by a political rationality which boils down to the application of market norms, metaphors and logics to all social phenomena. The rise of market thinking is thus, despite all anti-state rhetoric, better described as a new way of thinking about what the state should do and how the state must be evaluated than as an attack on the state itself. Motorway construction is then no longer a tool of the Keynesian state, but the outcome of market-like processes. In the latter case, the consumption behaviour of individual motorists, preferably measured by their willingness to pay road user charges, indicates where new road capacity is needed (Roth, 1966; Vickrey, 1969). This is nothing more than applying the principles of consumer democracy to motorway development, rendering public debate about road construction obsolete (Dardot and Laval, 2013). Although metaphors can be interpreted in many different ways, the slime mould approach seems, indeed, to correspond to the type of decentral market-like planning described above. Likewise, advanced versions of the demand-based gravity-style model can be used to replace democratic debate by a specific kind of technocratic decision-making.

Nevertheless, these models have the potential to generate useful descriptive information for network planning. Dupuy (2013) refers to the use of graph theory in Geographical Information Systems (GIS) as an example of a fruitful collaboration between geographers and other scientists. He also refers to the work of Laporte et al. (2011) who employ operation research methods to measure network characteristics and to suggest new designs for transport networks. Laporte et al. stress the flexibility of the heuristics which can be adapted to meet a variety of objectives. In other words, the metaphors (which are abundant in the field of operations research),⁹ and conceptualisations are less binding and constraining. The discussion of the slime mould approach in the work of Adamatzky et al., (2013) refers to several network indicators and sees the Randic index –borrowed from chemistry– as a measure of transport inaccessibility. Whether these kind of indicators are useful for transport scholars and policy makers remains an open question, and this openness is a requirement for the use of models in network design if democratic dialogue is to be taken seriously, and if external actors are allowed to bring in their own rationalities.

Despite its potential advantages, the topological approach has its limitations. The role and function of nodes may change over time and it is not certain whether a topological analysis will fully grasp changes such as the development of the Paris metro system from a relatively autonomous network serving the local population to one of the building blocks of a much larger integrated transport system (Dupuy, 1993). Returning to the case of the Belgian motorway network, the topological analysis presented here ignores the lively debate that ensued over the integration of motorways in the urban fabric, democratic access, and the

number and position of motorway entries and exits (Ryckewaert, 2012; Weber, 2010). While it is possible to see each entry as a node in the motorway graph, this would add much noise to the analysis, and the approach would lose its appeal of rationality.

Conclusion

This paper compared a 'natural science' approach to transport network development with a 'historical' view, and we particularly focused on the supposed and desired 'rationality' of transport networks. We conclude that while an *a priori* rejection of input from the natural sciences is not warranted, a historical approach is a necessary complement to explain the political agenda and process behind network growth. In addition, on a meta-level, a (historical) social science perspective uncovers the underlying principles and rationalities of the scientific models and concepts used. For example, the slime mould model used to mimic transport networks lends itself easily to describe it in terms of decentral market-like planning. Likewise, the economic concept of demand is regularly present in gravity-inspired models. The same metaphor can be used in many different ways, but what these examples illustrate is that it evicts the process of political-economics out of the equation. By 'naturalising' human sciences and historical explanations, the importance of political ideology and economic power within history is downplayed in favour of a positivist, technocratic reading of the human world and its past.

Material provided by the case study supplies fuel for discussion about broader issues, in particular the underlying ideological and political-economic claims associated with a particular methodological approach. This is especially relevant given the fact that models and concepts used to predict past transport investments are also employed to evaluate future investments in infrastructure. Quantitative approaches generally attribute a central role to the concept of demand, and thus degrees of 'rationality' are in fact linked to ideas of consumer democracy where individual demand guides investment decisions. In contrast, interpretations of a less demand-driven nature emphasise the degrees of freedom of political actors and choice. Since the metaphors and models used are not value-neutral, we conclude that the views held by actors of the past, present and future of transport networks are relevant for democratic debates on transport policy.

Although we recognise the merits of interdisciplinary, or even transdisciplinary research – and recognise that valuable inspiration can be found in other, seemingly unrelated, disciplines – we are critical of using natural science rationalisations and models to historically explain, let alone to predict and plan future human interventions. Natural models seem to signal a return of overtly reductionist ways of approaching the human world, considering natural law as main source of causality (Zitouni, 2013). Moreover, they evict 'exogenous' factors about societal change (Timms, 2008), or leave, indeed, the process of political-economics unaddressed, i.e. the consequential human conflict related to the fundamental process of societal decision making. A stronger and more explicit focus on the historical and socio-spatial context of transport networks, might lead to stronger democratic policy practices for the future.

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¹ <http://uncomp.uwe.ac.uk/adamatzky/> (last access date 7/6/2015).

² Note that the original slime mould study is static and that the selection of nodes by Adamatzky et al. (2013) seems to be based on a map of the motorway network at the end of the study period. Hence, a potential node (city) that falls below our population threshold may be selected because it is connected by a motorway. We tried to avoid this kind of endogenous selection by defining objective criteria and historical population figures.

³ Population data were obtained from 'Historische Databank van Lokale Statistieken –LOKSTAT', Universiteit Gent, Vakgroep Geschiedenis o.l.v. Eric Vanhaute en S. Vrielinck. For a descriptive analysis based on different data, see van Nederkassel (2015).

⁴ Data regarding the growth of the Belgian motorway network stem from <http://wegen-routes.be/> (access date 09/03/2016). This website takes 1965 and 1973 as cut-off points, here we take the year 1975 instead of 1973 to include the Tournai-Mons segment, which was finished in 1974, in the second period. No segments were added to the topological network in the periods 1965-1969 and 1975-1976, which makes these periods suitable candidates to act as breaks

⁵ Cities outside Belgium, however, were relevant as well, e.g. Lille, Luxemburg, Bergen-op-Zoom, Roosendaal, Aachen, Valenciennes, Dunkirk, Maastricht, Eindhoven, Breda, Paris, Rotterdam and Amsterdam.

⁶ Note that regression models for each period with three independent variables (demand, investment cost (distance) and angle) perform reasonably well with adjusted ρ^2 values of 0.86, 0.40 and 0.62 respectively (Vanoutrive et al., 2016). However, given that our focus is on causality and explanation, and not on forecasting, and taking into account that some estimates in the models did not have the expected sign, we do not pay further attention to these models.

⁷ Perhaps the most sustained critique comes from Karel Martens who points to the fact that demand-based cost-benefit analysis places a disproportionately large weight on transport projects beneficial for highly mobile groups. Accordingly, he proposes to replace the concept of demand by the concept of need (Martens, 2006). Gabriel Dupuy, to whom we referred earlier, is aware that some logics, in particular the preferential attachment principle, might result in networks providing unequal access to destinations (Dupuy, 2013).

⁸ Note that civil society might be considered as a separate sphere, besides the state and the market.

⁹ Sørensen remarks that 'the behavior of bats, birds, ants, bees, flies, and virtually every other species of insects – it seems that there is not a single natural or man-made process that cannot be used as a metaphor for yet another "novel" optimization method' (Sorensen, 2015, p.4).