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Embracing the Topological Complexity of Transportation Networks

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ABSTRACT

Transportation networks have become a subject of scientific interest from the second half of the twentieth century. Studies related to growth of the transportation networks after resuming its activity after thirty years have changed focus from the topological complexity of transportation network to their structural properties. In other words, topological complexity has changed into structural complexity. In this paper, this lost scientific direction will be reminded to the present society. Firstly, early studies on the topological complexity will be summarized and compared to each other. Secondly, new studies will be summarized and analyzed in terms of topological complexity. Finally, in conclusion, a means of measuring the topological complexity will be discussed and gaps in current studies will be highlighted.

INTRODUCTION

The transportation systems in local, regional as well as global level commonly represented as a network consisting of multiplied routes and locations (origins & destinations). It can be argued that this representation originates from work of Hagget and Chorley[1]. Although there is no formal evidence such representation of transportation network looks similar to the Harry Beck topological map[2]. It can be assumed that Beck borrowed this idea from electrical networks[3] due to his specialty & resemblance of his network to the system of electronic circuits, but this link also still hasn't been confirmed.

Scientists usually define a topology of any network as a graph, which is consist from a set of arranged links and nodes connected with each other[4]. From this definition can be inferred that graph reflects a structure of a network[5]. Therefore, it is reasonable to pose a question about topological complexity of transportation network. Complexity of structure can only be accessed by its geometry and level of connectivity[5]. History of transportation always displayed a space/time convergence[5]. Land transport network evolution closely linked to technology (modernization of existing modes of transport & introduction of new modes on the market) and economy (cost of technology & transportation) under geographical constraints[5]. When a diffusion cycle of particular mode (technology) will reach maturity and will be eventually abandoned, or substituted with another mode (network of canals in 19th century)[5]. The automobile has reached the phase of its maturity by the end of 20th century[5]. However, this mode still hasn't been abandoned due to the lack of sustainable alternative. Even if alternative mode won't be discovered negative trends in demand will force car manufacturers to exit market[5]. At this point, abandonment or modernization of network's infrastructure will produce dynamic changes in the system and its skeleton. Particularly, changes in infrastructure underpinned by technology & new urban settings, spatial coverage, geometry (shape), connectivity and terminals as well as load and capacity make networks more complex to understand and classify. Transportation network by nature dynamic and its behavior like any other complex systems (for example Newtonian Systems in physics) is hard to predict[6,7,8]. Like any other complex system transportation network evolves under set of external constraints: geographic, historical (including urban context as well as urbanization waves), social, political, environmental, and economic as well as traffic configuration constraints[9]. Internal constraints usually represent infrastructure characteristics and limits (for undergrounds tunnels it can be the inclination of tunnels, relative depth, etc.)[9]. Transportation network isn't static, but rather dynamic. To study behavior (growth & evolution) of such complex system those constraints are essential because they have direct impact on change in network structure[9]. In other words, topological complexity is more than just structural properties of network. Which attributes (qualitative & quantitative) can describe topological complexity of transportation network? How to measure a topological complexity instead of structural complexity of network? In this review paper, those questions will be addressed in the narrative form.

2. Geography of transportation networks (1962-1969)

The geography of the transport networks is a branch of science that associated with the studies of formation and development of transport networks in terms of their topological complexity[1,3,5]. This branch developed during regional science movement in 1960s and 1970 and was represented by two strands of geographical studies: descriptive analysis of network growth in stages and model design for replication of network geometries (shapes) [10]. The most comprehensive outlines of those two strands have been found in the work of Haggett and Chorley (1969)[1]. Following this book, there weren't any developments in this field for a thirty six years[10].

First strand was introduced by work of Taaffe (1963)[10] in which four-step discrete model of road network growth in both time and space (expansion of network from the coastal baseline to the inland area of underdeveloped country)[10,11]. The topological complexity of such network is represented by geometry (pattern): incomplete linear-linear -rectangular (mesh)-incomplete radiated and chorded (random network)-network rarely contain highly connected nodes as well as average length of path in this network (average number of connections in this path) far from geographic barrier (sea), level of connectivity: minimum network (1-2 stage), intermediate network (3-4 stage), and hierarchy of nodes in the network: during 4 stage shows that some nodes are more important than other and have 3 connections while others have two or even one connection with the geographical barrier: ship as well as dynamics[11]. Historical and basic geographical constraints play an important role here: rural roads follow historic pattern and absolute barrier (sea) that can be only overcome by maritime services[5,10,11]. Aside from hose topological attributes is impossible to extract more information from this diagram[11]. This model was applied by Pred.(1966) to the Atlantic Seaboard of United States, and Rimmer (1967) applied it to the South Island in New Zealand[10]. Lachene (1965) proposed a four-staged model of network development on a hypothetical isotropic transportation network[10]. The topological complexity of this network is represented by geometry: from mesh to tree network (branches to better serve suburbia), level of connectivity: from complete network to minimum network, hierarchy of nodes became evident during the last stage when one node (urban center) became superior in relation to others (tree network) as well as dynamics (the same as Taaffe model)[11]. Unlike previous Taaffe, model is follow actual geographical route of roads and nodes (urban centers) placed in their exact spatial positions (in accordance with map)[11]. In other words, this network is rather concrete (clearly defined on the map) that abstract[5,10]. Historical constraints in this model very similar to the previous one (dirt trails, which are the links to urban centers evolve transform into the paved roads)[5,10]. Road network during the third step the system reach maturity and during the fourth step became abandoned[11]. At the same time railroad network introduced as a tree network that connects urban center with satellites in the hierarchical order[5,11]. From this data is possible to establish a basic topology of road network[5]. However, those attributes can really help us to understand why and how transportation networks evolve? Both Taaffe and Lachene model emphasize that change in the network result in shape (geometry) in which two feeder lines (railroad between the urban center and two satellites in Lachene model and roads between ports and some unknown centers of activity along the coastal area) produce a load surpasses capacity[11]. More remote nodes (satellites, centers of peripheral, or countryside, activity) with a route or branch carrying heavier traffic (maritime facilities, major urban center).

Second strand was introduced by work of Garrison and Marble (1962) in which attempts to design model for the replication of the changing topology of the Northern Ireland railroad network between 1830 and 1930 were described by using Monte Carlo simulation methods[10]. Unlike first strand, this research was focused on topological measures employing graph theory with the aim of measuring the structure of transportation networks[3,10]. This study not only introduced graph theory for abstraction of properties of the transportation networks structure but also incorporated behavioral (probabilistic) model in transport growth[11,12]. Later Morril (1965) employed the same approach in his study of the rail network in central Sweden, while Kansky (1963) developed a quantitative predictive model of network structure and applied it to the Sicilian railroad[3, 10]. Due to the difficulties in obtaining graphical data for this research is hard to objectively evaluate its work. \Model of network development was represented by the following function[12]:

$$T_s=f(c_i)=g\ (B,V,N),\ \text{where}$$

T_s-transportation network structure,

c_i-certain 'regional characteristics',

(V,N)-network size,

V-vertex (node),

N-length of link,

B-beta index (level of connectivity) = N/V- indicates the complexity of the network.

In other words, the structure of transportation system can be represented as a function network size and level of connectivity[5, 12]. The exact values of these indices were calculated for the documented Sicilian railroad network. Expected values were calculated by utilizing regression techniques (probabilistic model $T_s^i=f(c_i)=g\ (B^i,V^i,N^i)$). Then he selected 16 settlements of Sicily based on population size, absolute and relative incomes. In accordance with the values of a probabilistic model and location of selected settlements of map, the evolution of network structure was simulated[12]. From this point shape (geometry) can be defined 3 stages of network formation: linear- tree network (ero number of cycles) -radiated (1 cycle graph), radiated and circular network (2 cycle graph). Network geometry has auxiliary elements incorporated into it: circuit and fork[5,9,12,13]. To reduce the number of circuits V-shape connections were changed into Y-shaped[5,9,12]. In other words, it can be inferred that circuit evolved into pan- shaped loop to reduce a number of circuits in network due to difficulty in operation and lack of space for circulating puffin at night[9]. In addition, some links were shifted in accordance with relative barriers (topography)[5,12]. However, network structure became more complex to capture because of following strict geographical rules (exact location of nodes)[2,11,12]. Author is more focused on geography than on the network itself. In other words, complex system isn't simplified enough to capture it complexity[2,7,8]. Adjustment to the geographical setting makes this work more a map than a diagram[2]. By the time a model reached future state, complexity has remained on the intermediate level with average path length far from to the geographic barrier[5]. In such case in both existing and future state have the same level of connectivity[5,12]. Thus, qualitative indicators of system state became insufficient to measure complexity of network structure. Thus, Beta index was introduced to evaluate how the level of connectivity has improved in comparison with existing state[5,12].

This era of the growth of transportation network has reached a conclusion with the work of Haggett and Chorley (1969)[10,12] that provided review of these studies. Most of attention was paid to the level of connectivity and network size and types of flows by direction (centripetal or centrifugal) network were classified into branching(tree) and circuit networks that conduct flow, and barrier (cycle) networks that resist flow[14]. For determining network types mentioned above attributes were described[14].

According to the Haggett and Chorley (1969)[1] discussed above 'fragmentary' studies deal only with simple networks using heuristic and intuitive rules for modeling the network growth & development because of lack of elaborated concept on why and how transportation networks evolve[10]. However, Kansky never considered circuit as a network but rather an auxiliary ring within the network[5]. Indeed, due to operational difficulties and associated maintenance and time costs, health problems (mainly stress) it hard to view 'circuit' as a consistent network[9]. In addition to the above issues in the initial and terminal nodes of cycle load overcapacity would likely to occur in pick hours[9]. Length of circuit or cycle cannot be too long because of the need for commissioning with single starting complex and tracing of the line through the areas of the city with low population density for completion of circuit (or cycle)[9]. However, Kansky describes a network with one cycle as connected network[5]. He evaluates level of connectivity (complexity) of network by number of cycles [5,12]. As a network incorporates other elements (fork,etc.) existence one cycle line that form fully operated network comes into question[5,12]. Tree network considered as a simple network[15]. Network designed by Lachene on the fourth stage of development had a tree-like shape due to adoption of new technology and uneven regional development[5,9,12]. When road network became too complex and time consuming for the user and a huge financial burden for government new mode will open a road for simple high-speed networks, and a new evolution stage will began[12,16]. In addition, networks with low size doesn't always mean simple structure and topological complexity16. Beta index and classification of subway planning schemes applied to examples above can prove this point [5, 9]. Mechanism behind network formation and development is too complex to describe and measure, especially, in the review paper. Therefore, focus of this review paper is to provide insight on a set of attributes (qualitative & quantitative) that can help better understand the topological complexity of transportation network.

3. Renaissance in geography of transportation networks (2006-present day)

After 36 years of stagnation phase two works were sign of Renaissance in the domain of growth and change of transportation networks: book of Jean-Paul Rodrigue[5] with three editions published (2006-2013) and Camille Roth et al. (2012)[13]. Those studies doesn't contradict each other, and therefore, they are complementary ones[5,13]. First study is the qualitative and the second one is mainly quantitative. Those studies are mainly a continuation of two strands of geographical studies (1962-1969): descriptive analysis of network growth in stages and model design for replication of network geometries (shapes)[10]. Book of Jean -Paul Rodrigue[5] is the third work on descriptive analysis of the network growth in stages after Taaffe and Lachene pieces[5,10,11]. Precisely, the author has generalized topological attributes[5]. His generalized criteria, or comparison criteria, used to describe a transportation network in each stage of their development and to understand the main differences between the same types of transportation network in different countries[5]. The second work on the other side is an extension of a second strand of geographical studies: replication of network geometries[10,13]. Research paper of Camille Roth et al. (2012)[13] is the second work on network geometry from an empirical point of view (graph theory) after Kansky's probabilistic model[12]. Let's look into those two recent studies of network growth.

According to the Jean-Paul Rodrigue transportation network can be classified into categories based on following thirteen topological attributes[5]: level of abstraction, relative location (geographical settings), orientation and extent, number of edges and nodes, modes and terminals, types of road and level of control, type of traffic, volume and direction, load and capacity, type of correspondence (hierarchy of nodes), pattern (geometry), dynamics as well as mode of territorial occupation. Those attributes are generalized, and therefore, suitable for any existing transportation network (land, air and maritime networks). This set of topological attributes combined Taaffe and Lachene's qualitative measures: abstraction level, pattern, geographical settings, hierarchy of nodes with Kansky's quantitative network attributes: level of connectivity (Beta index), network size (number of edges and nodes), volume and direction and dynamics that represent the basics of Graph Theory [3,11,12]. Other topological attributes have been added to extend classification: orientation and extent (spatial coverage of network), modes and terminals (abstract networks that consist of edges, or abstraction of road, rail and maritime routes and nodes (ports, rail yards and airports), types of road (highway, road, street, etc.) and level of control (speed limits, vehicle restrictions, etc.), type of traffic (continuous or divided), load (existing volume/capacity) and capacity (level of congestion in quantitative terms) well as mode of territorial occupation (level of representation on the map and ownership coverage limits) [3,11,12]. Type of road and level of control as well as types of traffic clearly limits those two attributes to the road network. In this case generalization inapplicable. It clearly shows that other transportation modes underrepresented in this classification. Spatial integration of terminals for different modes its important to reduce travel time, especially, in the city where transfer time really matters (large portion of total travel time and excessive load in terminals)[17]. Therefore, based on the modes and terminal level of spatial integration in multimodal transportation network can be accessed. Network with a higher degree of topological complexity should have a higher level of spatial integration of terminals and least amount of land utilized for integration purposes. Load of links as well as hubs shows overall efficiency of planning structure[9]. The higher congested links & hubs in the network the less optimized it becomes[16]. When network evolves is becomes more optimized by introduction of new routes and hubs to relieve network. This process continues until further modification of network doesn't make the load more uniform. If the loads in each line & hub are known it is possible to judge how optimized the network is and identify a stage of the network growth[16]. The spatial coverage of network allows comprehending what percent of total market area (city, region or country) is serviced by the network[5]. In other words, network with the bigger coverage is more topologically complex. Mode of territorial occupation is a new attribute that introduces areas under infrastructure and ownership of that area. It relates the level of abstraction of network with a mode of transport and type of ownership[5]. By this criteria, it is possible to determine which network type is more complex[5]. However, to be used effectively in comparison between networks of same type other attributes (discussed above) are necessary. This classification forms a basic framework based on which general concept can be formed. However, inner structural properties (level of connectivity and network size) should be developed further through quantitative means (namely graph theory) before they could be adjusted to this framework[5,12,14].

The second study focuses on the geometry of the subway network[13] . Subway networks are the most affordable for users of the network that embedded in the structure of cities. The road network is very complex and uncontrollable in growth aspect. On the other hand, rapid transit can cover most of the urban area without significantly increasing overall complexity of network[11,13]. The study suggests that all networks in the world converging to the same shape (geometry) free from geographical and economic features of the particular city. Examples such as Chicago and New-York were left out because of the particular case in geography[13]. There exist absolute (river, lake, etc.) and relative barriers (topography, residential buildings, historical monuments, existing routes of other modes, etc.) in the inland transportation systems[5,9]. What about underground ones? Relative barriers for underground transport varies significantly from aboveground: inclination of the tunnels, laying depth, engineering &geological environment and hydrogeological environment[9]. Are those barriers have no influence on the network structure? That was a case in Kharkiv Metro (link between Akademika Pavlova-Akademika Barabashova stations on Saltivska Line) [18] and Paris Metro (stations of the loop on 7bis line)[19]. This means relative barriers can change location of stations and tunnels that influence the overall geometry of the system. Historical consideration indicates that a pattern of streets has an impact on the structure of the subway network[5,9]. Although there isn't any empirical evidence to prove or to oppose this argument, a pattern of most cities following this law (Kharkiv, Moscow, Paris, etc.)[9] Old pattern of streets, change in population and relocation of attraction centers (mainly for work purposes) make changes in the network geometry. Therefore, this claim seems to be unrealistic. In this study is very hard to find any new topological attributes of network[13]. Instead, as study is focused only on structural properties of network ratio between branch and core station makes an indicator to claim a relationship between shortest average path length and number of stations &clustering coefficient[13]. Other indicator is asses a nature of network structure between heterogeneous and highly reticulated structure of network[13]. In my opinion, although this coefficient can be used to define a pattern of network more precisely it doesn't reflect topological complexity of a real world network. However, it can be used as an addition to the beta index[5,12] to comprehend how far is possible to measure complexity of network after it became connected[5]. In addition, this coefficient indicates that measure a spatial extension of the branches (their topological complexity) was added[13]. Lastly, two indicators to comprehend complexity of core structure were proposed[13]. First one, the average degree of core structure to measure its density, and the second one to measure connectivity in the core[13].Unlike previous studies that focused on the structure of subway network in general this study have paid attention to the 'core' element that like the CBD in the city has its own limits and function in the network[13]. The peculiar point that this perfect shape of the network evolution is the clone radial and circular network of Moscow Metropolitan rail transit system composed of underground and light rail subsystems[9,13]. The generalized stages of evolution process from a simple entity to the complex structure doesn't shown[13]. Therefore, its hard to follow the mechanism that triggered an evolution of those networks. The structure of core and branches with forks represent a CBD (core) of the city and periphery (branches)[13]. High network density and connectivity in the core, and low level of both in the suburbs[13]. This study has wrongly assumed that a network converge in the similar shape despite of geographical and historical differences and ignored both internal and external factors which are causes of crucial to the dynamic changes in network geometry.

4. CONCLUSION

In this paper the most prominent studies related to the growth of transportation networks have been reviewed. Both qualitative and quantitative studies were accessed. However, it takes some effort to follow superficial links between those studies[11,12.] Scientists have forgotten that structural properties is tool for quantifying network geometry that is a one of topological attributes designed to define a topological complexity of transportation network[13]. Without full picture it is impossible to find gaps in the study and refine our understanding of topology of the dynamic complex system like transportation network.

Despite of that a set of topological attributes had been significantly enriched since 1962 only one of them (network size) had been contested empirically through graph theory[5,12]. For scientists is still remain as a challenge to measure twelve remaining topological attributes[5,13]. Some of internal attributes are statics network attributes: number of edges and nodes (network size), modes and terminals, pattern (geometry), type of correspondence (hierarchy of nodes) while others are dynamic: type of traffic, load and capacity, volume and direction. While attributes like types of road and level of control is pertinent to the road transport and cannot be used as generalized criteria for classification[5]. Subway network have location relative to the ground level that can be considered as similar attribute due to its indication of tunnel category[9]. However, its only pertinent to the rail transport and useless for other modes. Therefore, types of road and level of control should be excluded from a set of topological attributes. Further, three attributes indicate the space occupied by transportation networks[5]: level of abstraction, orientation and extent and mode of territorial occupation. Fundament of the building may be a good analogy for this space. A space that is outside of building and its fundament can be referred to as geography[5]. Finally, relative location (geographical settings) indicate geography, or an outer space[5]. The simplest case is to quantify the space occupied by transportation networks[5] and the hardest one is to measure its geography[13]. Transportation network like a ship in the ocean has internal and external constraints. During cruise trip the sea that can become stormy (internal constraints) and sky that can become rainy (external constraints). For transportation network geography can be measured by cumulative effects of internal & external constraints [2,9]. Taaffe and Camille Roth both disregarded geography by simplifying map to the level of schematic map (Taaffe)[11] and diagram (Camille Roth)[13]. Schematic map of Taaffe[11] is similar to Beck design of London Underground[2]. This means it is more like a simple user-oriented scheme than a complex research model[2]. Model of Taaffe has some spatial information embedded in it, but it doesn't reflect complexity of dynamic system under steed pressure[2,6,7]. Camile Roth disregarded geography completely by simplifying it to the level of diagram[2,13]. It is easier to study a simplified model of the complex system[6,7,8]. However, such models won't reflect a real change in the topology of transportation network. Without geography (including urban settings &dynamics) not only simulation of growth but also a true graphical representation of transportation network in each stage of development is out of question[5,9,11,12]. Lachene and Kansky incorporated geography in their model but haven't been tried to quantify it[11,12]. Kansky's level of connectivity and size of network[5,12] if integrated with Camile Roth's indicators of core and branches[13] is useful tool for refining the research on structural properties of network and for introducing the new challenges. However, Roth's research isn't related to the topological complexity of transportation network, but rather to the complexity of network structure[13]. Thus, the studies that challenge a full-fledged topological complexity of transportation networks is still yet to come.

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