Multimodal Transportation Network Design Using Physarum Polycephalum-Inspired Multi-agent Computation Methods

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Abstract. In this paper, a new approach towards P. Polycephalum inspired computational efforts is proposed, with specific application to the problem of Multimodal transportation network design for planned cities of the future. Working with a multi-agent model of the Physarum Polycephalum, parallels are drawn between agent properties and mode characteristics, and agents are allowed to dynamically change from one mode to another. A mechanism to compare the performance of resultant multimodal networks against single mode networks involving the same component modes is demonstrated. The observations point to the potential applicability of the new approach in city planning and design.

Keywords: Physarum Polycephalum · Multimodal transportation Network design · City planning

1 Introduction

The need to design efficient and resilient transportation networks has over the years led to the development of a large number of novel possibilities with regards to solutions that create near-optimal networks. To that end a variety of natural phenomena, such as ant colony behaviour [1,2] and human blood flow patterns [3] have been studied to see if insights can be gained from the way networks are created, sustained, and reorganised in these natural systems. More recently, the True Slime Mould, Physarum Polycephalum, has been at the centre of multi-disciplinary scientific research that seeks to move towards more unconventional forms of computing that hope to utilise the simplicity of natural frameworks to model emergent systems in a better way, and achieve more efficient computation on the whole. The behaviour of P. Polycephalum is of special interest to the field of Transportation Network planning, as the foraging behaviour it displays during and after its growth phase results in the formation of routes and networks that satisfy both the aims of efficiency and resilience. This behaviour has inspired research into creating computational models based on P. Polycephalum, using

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a number of approaches, some of which are Cellular Automata-based modelling and Multi-agent Modelling.

The main thrust of this paper involves the application of one of these approaches - Multi-agent Physarum modelling - to solve the problem of multimodal networks. This is inspired by two main causes for concern with respect to transportation network design -

1. The nature of most big cities in today's world is a consequence of their urbanisation taking place in multiple well-defined stages. This has led to the creation of extremely heterogeneous transportation systems. Coupled with the increasing population and number of vehicles across the globe, we are currently in a position where a large majority of people are forced to utilise multiple modes of transport to commute on a daily basis, and where these multimodal networks are plagued by a variety of problems ranging from poor quality and overcrowding to excessively large transfer times between nodes.
2. Looking to the future while keeping current trajectories of population growth in mind, finding solutions to these problems of multimodal transport is of crucial importance. Such a network would influence the creation of the city as a whole, and once implemented, allow for a sustainable transportation system that would increase the welfare of the masses living in the city. The idea of creating Planned Cities has been in existence since the late 19^{th} century, and has had mixed results in terms of success and impact thus far. However, with space becoming more and more valuable, and with the ever-increasing pressure that a growing population places on each square kilometer of land, the need for planning cities well into the future cannot be understated.

This is especially relevant when applied to countries developing at a rapid pace, like India [4,5]. As a country it has seen a great number of such planned cities flourish over the last few decades, the prime example of which is the city of Navi Mumbai, known today to be one of the largest planned cities in India and the world. Many plans to build cities are currently underway, in order to cater to the country's growing population as well as a significant portion of the current rural population that is making a shift towards cities in search for modern amenities. Perhaps the biggest and most recent of such endeavours is the creation of the city of Amaravati, the proposed capital of the Indian state of Andhra Pradesh.

As we build cities for the future and rework the cities of today to make them better places to live in, ensuring that the transportation network is efficient and robust is of paramount importance. Through this paper, the authors propose a new approach to solving such network problems using Physarum based multi-agent modelling, demonstrate possible ways by which the solutions obtained could be evaluated, and discuss the potential for further research and refinement of the model moving forward. The rest of the paper is divided as follows. Section 2 provides a brief review of literature and research work related to Physarum computing and modelling. The formulation of the proposed extension to the model, its results, and potential mechanisms for validation are detailed in

Sects. 3 and 4. In conclusion, the shortcomings of this work are discussed, along with future research directions in the area of computational network design.

2 Previous Work

As a natural system, the Physarum Polycephalum has demonstrated a remarkable ability to perform computational feats. This is especially significant given the mould's lack of a nervous system, or any overarching complex structure. Over the last few years, significant research efforts have been directed towards the applications of Physarum based computing [6–9] - its formulation [10,11], demonstrations of its ability to solve complex mathematical problems [12] and studies on its evolution and emergent behaviour [13,14]. Applications to areas such as the Traffic Network Equilibrium Assignment Problem [15], approximating real-world road networks and recolonisation problems [16,17], and Shape Representation in response to environmental stimuli [18] have been explored to a large extent. A multi-agent model of the Physarum Polycephalum is presented in [19]. The multimodal transportation problem is one that has been discussed a great deal over the years, and some research efforts regarding the same include [20–22].

One aspect that does not seem to have been touched upon in the Physarum based research reviewed for the purpose of this paper, however, is the nature of the agents in the model, and the possibilities afforded by allowing these agents to change dynamically in response to certain cues, either geometric or environmental. This is the primary direction that we go on to look into in the sections that follow.

3 Research Methodology

3.1 Model Background

The Physarum model implemented in this paper is based on the multi-agent simulation approach in [19]. Here, a number of simple agents follow a set of rules that outline motive, growth, and movement on a representation of a real substrate that is modelled using a diffusion-based matrix. Each agent has a limited ability to sense its environment (by means of the sensors FL, F, and FR), and interacts with surrounding agents by means of depositing quantities of chemoattractant that diffuse over the substrate. For the model used, the parameters that define the agent's field of perception are the Sensor Angle and Sensor Offset, while those that characterise its physical response to stimuli are its Speed and Rotation Angle. Figure 1 presents a simplistic version of such an agent, indicating the relative positioning of the sensors with respect to the agent center.

Once initialized at random locations within a given geometry and with random values for initial parameters, these agents begin their operations, eventually leading to complex forms of emergent behaviour. At every iteration, the agents

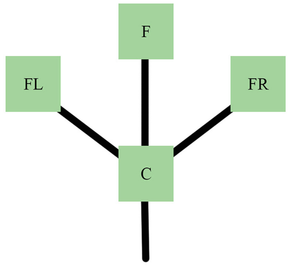

Fig. 1. Simple agent schematic (based on [19])

sense their surroundings, turn by an amount defined by the characteristic rotation angle towards the direction with the strongest chemical trail concentration, and attempt to move in said direction. The success or failure of this attempt is what determines the amount of chemoattractant deposited in turn by the agents themselves. Further, the substrate itself diffuses the trail values that it contains, hence imparting temporal variability independent of the motion of the agents, much like the manner observed during similar real-world experiments. Over multiple iterations on a given geometry with specific locations of nodes that constantly deposit the chemoattractant, distinct paths are developed that resemble those obtained through established mathematical network design and assignment solutions.

The parameters mentioned earlier, namely sensor angle, sensor offset, rotation angle and agent speed, can vary between certain limits to ensure that the desired emergent behaviour is produced by the simulation. These Physarum based models have been used to create efficient and resilient transportation network designs in the past.

Fig. 2 presents the progression of a simulation at specified cycle times for a nodal network based on the train stations in the city of Tokyo. Below these snapshots are illustrations of the actual train network, the Minimum Spanning Tree based on the network nodes, and a sample modified minimum spanning tree network with more links to improve resilience [15]. As can be seen, the Physarum network at various points shows characteristics and links that are quite similar to the established networks, an indication of how as a framework, the model seems to be sound.

3.2 The Multimodal Physarum Model

The Authors propose an alternative approach to the use of such models (as in [19]) when applied to problems in Transportation Network Design, and more specifically, to the Multi-Modal Network design problem. Each agent within the model has a common set of characteristics, and communicates with agents via chemical trails, eventually finding routes that can be used as solutions to problems on network design. Building upon this, parallels are drawn between the four parameters stated above - Sensor Angle, Sensor Offset, Rotation Angle,

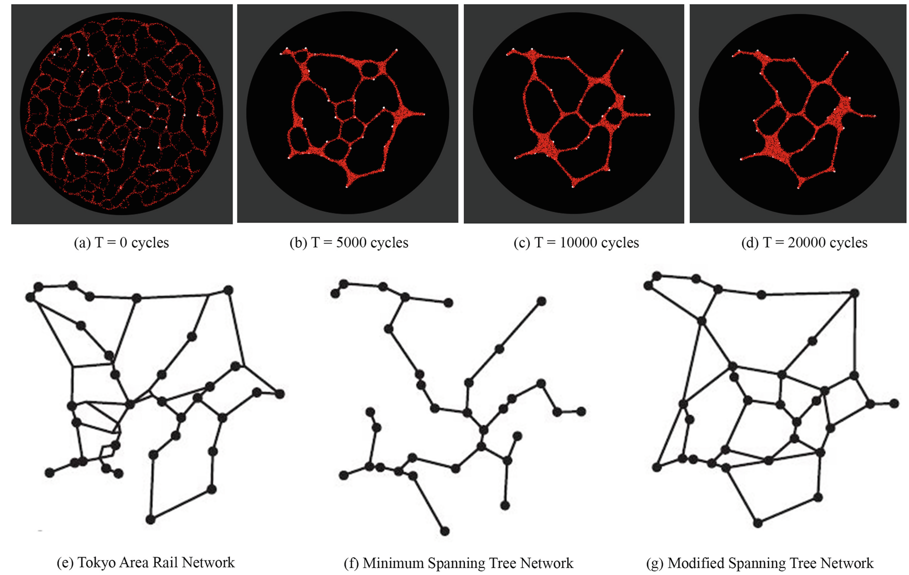

Fig. 2. Processing model comparison (from [15])

and Speed - and the real world characteristics of various modes of transport. For a given mode, a certain set of parameters would define its properties to the best extent, and by allowing an agent to morph between one mode type to another within a given topography, a continuous, multi-modal network can be obtained.

In this paper, the authors have chosen to focus on two modes of public transportation - Bus Rapid Transit Systems (BRTS) and Monorail networks. Assigning a standard set of values for the four agent parameters to the BRTS mode, hypothetical values for the same parameters are then associated with Monorail mode. This association is informed by the physical relationships between vehicle and agent as mentioned earlier. Here, the authors draw parallels between the speed of the agent and the speed of the mode, the sensor offset of the agent and the awareness along path of the mode, sensor angle and the angular window of focus, and between the rotation angle of the agent and how constrained a vehicle would be to the path of that mode. Comparing the two modes qualitatively, it can be seen that Monorail systems have higher average vehicular speeds than buses, are usually more constrained to their path over a longer distance, and have lower maneuverability. As opposed to buses, Monorail systems need to be aware of objects farther away along their current trajectory due to an increased stopping time, and usually do not need to factor in stimuli that are much outside a small angular window centred around their tracks. The parameters assigned to the BRTS mode are scaled in accordance with these guiding principles to determine and generate a sample set of Monorail agent parameters.

Further, a predefined nodal arrangement was used as an environment to test the two agent types and their mutual interactions. This arrangement consists of six sources, two intermediate stations, and four destinations. The models were made to run within the environment, and three main test cases were observed based on the nature of the network population - Only BRTS agents throughout, only Monorail agents throughout, and BRTS agents till the intermediate stations with Monorail agents for the remaining route area till the destination. The simulations were halted when a steady state network pattern had been formed by the agents in all three cases. The test geometry and resultant networks after simulation are presented in Fig. 3. A clear variation in the networks formed in the three cases can be seen, indicating that agent characteristics play an important role in determining the nature of the route mapped out by the simulation. Further, these networks are non-trivial ones, in the sense that on repeated trials using the same initial conditions, the steady state pattern remains the same for each case. A thorough study on the relationship between the agent parameters and real transport mode behaviour would be needed before commenting on how close these networks approximate their real-world counterparts. However, for the purposes of this paper, the three model geometries obtained were considered and further studied.

4 Model Evaluation

The network diagrams obtained for the three cases are implemented and analysed using Anylogic agent based simulation software. The model is created in Anylogic 8.1.0, with [23] being an example of its use in transportation-based research. A simple demonstration of the logic used to generate idealistic traffic flows for the BRTS network is presented in Fig. 4. Two main test scenarios are considered. In both cases the networks obtained from the previous model are used to create further simulations in a road network setting. First, the average travel time for vehicles and the network performance at nodes is qualitatively analysed, after which the network is placed in a real world context and its behaviour is gauged using certain ideal conditions of flow. These approaches are intended as indications towards possible future research into the analysis of similarly obtained networks.

4.1 Basic Network Performance Analysis

In this step, all three networks were recreated within Anylogic, and agents native to the software were modified to represent BRTS and Monorail agents. These agents were then deployed in the network and studied, by creating intersection speed/density maps and recording the times spent by the vehicles within the network. Samples of the resultant data representations obtained are shown in Figs. 5 and 6. The nodal analysis (Fig. 5) depicted is for all three scenarios; however, the plot of Transit Time in network versus Cycle time is for the specific case of the BRTS agent network (Fig. 6).

For the nodal analysis (Fig. 5), the colours of red and green are assigned to specific values of low and high speeds respectively, and intermediate speeds are

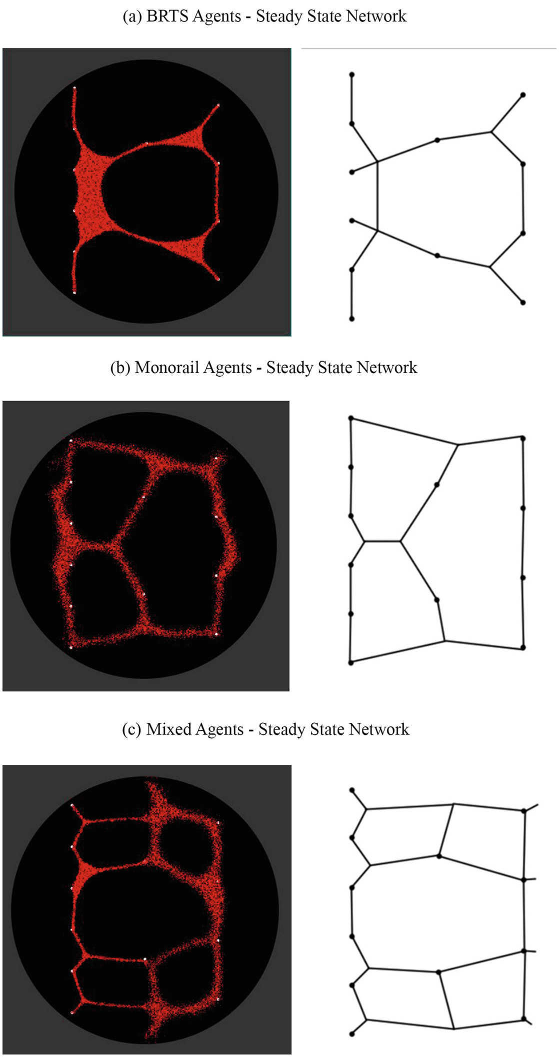

Fig. 3. Model results

represented by shades between the colours. From this initial level analysis of the results obtained, it was observed that the mixed network allowed the junctions to function with more ease in terms of traffic density at the node, and that jam conditions were more prominently seen in the single-mode networks. The vehicular input volumes were generated by idealised sources with a constant rate of arrival.

In the Transit time graph for the BRTS network (Fig. 6), the horizontal axis represents time in model time units, and the vertical axis represents the Transit Time per agent as a fraction of the model time. The discretization of

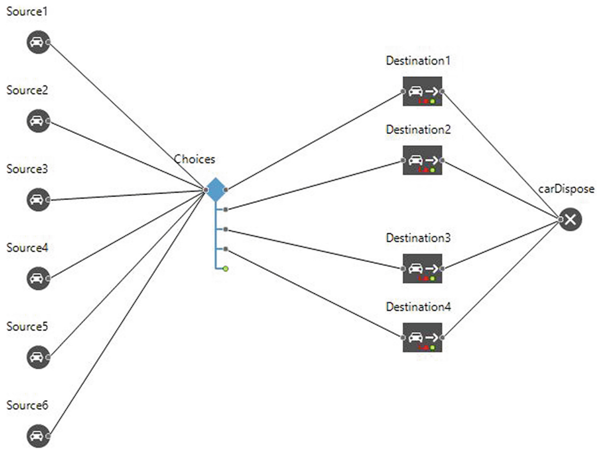

Fig. 4. BRTS model flow diagram

the Transit Time graph is a consequence of the ideal nature of the vehicular volumes generated - there are only a finite number of possibilities as no element of randomness or continuity has been introduced to a significant effect. This points towards further work involving the refinement of these test cases and deployment in more realistic scenarios. However, on comparing the values of BRTS Transit Time with those obtained in the remaining two cases of Monorail and Mixed BRTS with Monorail, it was seen that the performance of the Mixed network was in fact better than the initial single-mode networks. While further work would involve going about these forms of analysis with more mathematical rigour and in a variety of contexts, these preliminary indications serve to highlight the applicability of the Physarum multi-agent model to transportation problems, with specific emphasis on the improvements obtained upon the introduction of agents that are allowed to change their characteristics in response to geometric and geographic cues.

4.2 Implementation in Real-World Context

To demonstrate a possible application of the networks generated via the Physarum Model, the characteristic network for the combined BRTS and Monorail case was considered and the routes were marked via a GIS interface onto the map of the proposed planned city of Amaravati in Andhra Pradesh, India. Given how the city is yet to be built in entirety, the transportation networks have a large degree of flexibility without pre-existing barriers to paths, and hence this provides a good basis to test new networks like the ones obtained from the Physarum models earlier. Fully developed versions of these models could even be used as design tools for Policy makers as they go about the planning and construction of cities.

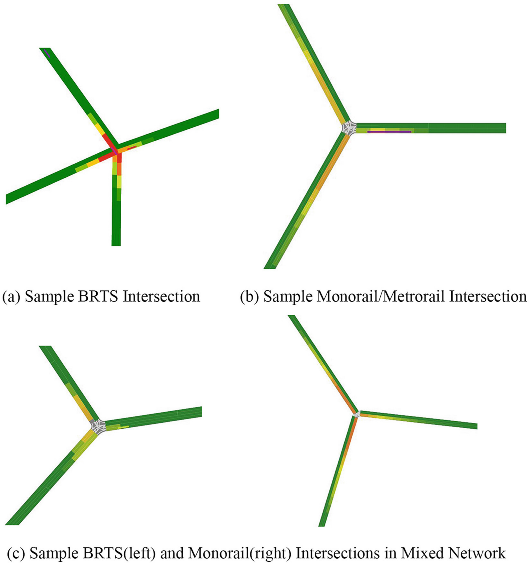

Fig. 5. Intersection speed maps (Color figure online)

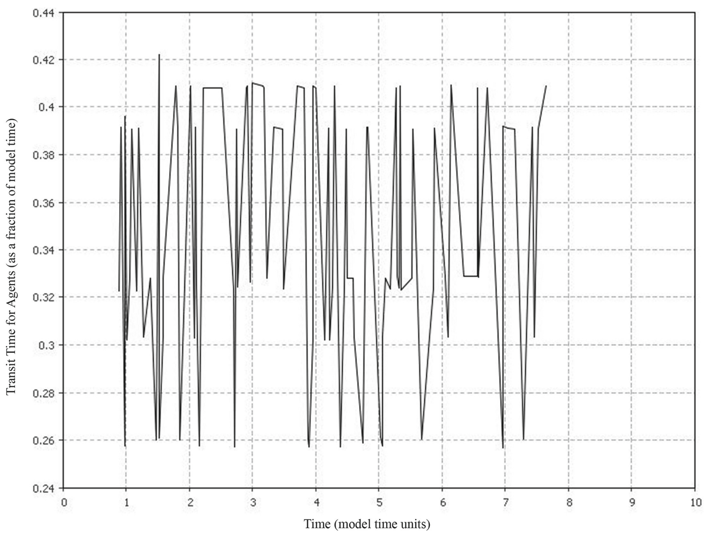

Fig. 6. Transit time graph for BRTS Network

The same nodal configuration as the previous examples of the BRTS and Monorail networks have been used. The network was defined using native tools that allowed the routes obtained via the Processing model to be replicated as roads within the simulation software. The roads were then assigned a certain

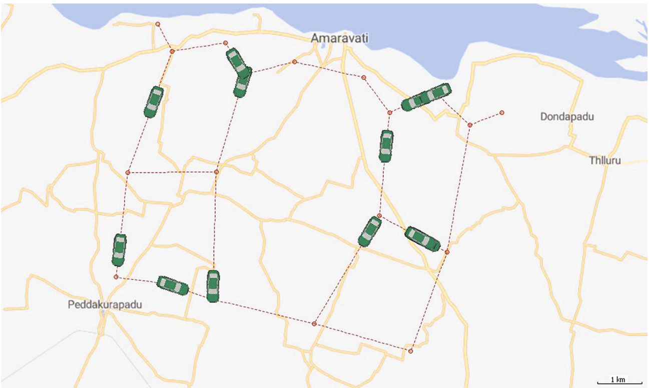

Fig. 7. Real-world network visualisation

sense of direction, and the number of lanes on which vehicles are allowed to travel was specified. The route choice logic was defined as a simple probabilistic model wherein at each junction the vehicle is equally likely to move along the possible paths that would take it towards the destination. These relatively ideal test conditions were established, and the simulation was allowed to run. Figure 7 presents the simulation at a certain instant of time. Here the vehicle modes are represented by generic car icons.

Such an analysis allows us to visualise the impact of these proposed networks in a more tangible manner, and also allows to take insights from the actual geography of the proposed area of implementation and factor those into the Physarum model. An example of this could be to use illumination parameters (a deterrent to the Physarum agents) to indicate water bodies, valleys and the like as demonstrated in [10,11,16]. Such simulation packages offer robust testing frameworks for the networks obtained through the Physarum model, with emphasis on the system's functioning amidst a number of constraints modelled on real life. At this stage, given the nature of the networks used and the work yet to be done with regards to the calibration of the agent characteristics with real-world transport mode behaviours, as well as the development of more rigorous testing and validation mechanisms, the immediate results obtained from these simulations serve more as an indication of the potential use of these networks, and demonstrate how a Multimodal Physarum model is different from its single mode counterparts.

5 Conclusions and Future Research

In this paper, an extension to existing Physarum based computational models was proposed, and implemented within the Processing Framework. Test cases for two different public transport modes were formulated, and networks relating to their individual and combined behaviours were generated via this Physarum model. Finally, the resultant network routes were visualised using the Anylogic software package, both in an ideal network context as well as a demonstration of one network placed in a real geographical region. From all of this, indicators of the potential validity and applicability of the proposed model were obtained, as well as directions for further research and the issues that will have to be addressed through the same. Firstly, the relationship between agent parameters in the model and real-world transport mode behaviour would need to be rigorously analysed for multiple test cases and networks to prove that a true correlation exists between the mode and the agent. Once these links are established, the agents would have to be deployed on a number of synthetic networks and the performance of the multimodal network will need to be gauged against those with a single mode of transport. After this step, the multimodal networks will have to be tested against networks obtained through other bio-inspired algorithms, conventional route assignment techniques, as well as real-world situations to finally understand the validity and usefulness of the approach as a potential design tool for planning transportation networks for cities of the future. Further research will be directed with significant focus on two major aspects -

1. Working to establish a defined link between agent parameters within the model and the real-world behaviour of the various transportation modes
2. Creating an interface to allow for the Processing model to be used as a tool for network design.

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