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Centralized versus decentralized control—A solvable stylized model in transportation

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ABSTRACT

Today's supply networks consist of a certain amount of logistics objects that are enabled to interact with each other and to decide autonomously upon their next steps; in other words, they exhibit a certain degree of autonomous cooperation. Therefore, modern logistics research regards them as complex adaptive logistics systems. In order to analyze evolving dynamics and underlying implications for the respective systems' behavior as well as the potential outcomes resulting from the interaction between autonomous decision-making "smart parts", we propose in this contribution a fully solvable stylized model. We consider a population of homogeneous, autonomous interacting agents traveling on $\mathbb{R}$ with a given velocity that is itself corrupted by White Gaussian Noise. Based on real time observations of the positions of his neighbors, each agent is allowed to adapt his traveling velocity. These agent interactions are restricted to neighboring entities confined in finite spatial clusters (*i.e.* we have range-limited interactions). In the limit of a large population of neighboring agents, a mean-field dynamics can be derived and, for small interaction range, the resulting dynamics coincides with the exactly solvable Burgers' nonlinear field equation. Explicit Burgers' solution enables to explicitly appreciate the emergent structure due to the local and individual agent interactions. In particular, for strongly interactive regimes in the present model, the resulting spatial distribution of agents converges to a shock wave pattern. To compare performances of centralized versus decentralized organization, we assign cost functions incurred when velocity adaptations are triggered either by multi-agent interactions or by central control. The multi-agent cumulative costs are then compared with the costs that would be incurred by implementing an effective optimal central controller able, for a given time horizon, to reproduce an identical spatial probability distribution of agents. The resulting optimal control problem can be solved exactly and the corresponding costs can be expressed as the Kullback–Leibler relative entropy between the free and the controlled probability measures. This enables one to conclude that for time horizons shorter than a critical value, multi-agent interactions generate smaller cumulative costs than an optimal effective central controller.

1. Introduction—Smart parts transportation logistics

In the daily life, many of our decisions are taken with limited rationality. Indeed, the lack of complete information, the huge number of control parameters and criteria together with their nonlinear relationship and the ubiquitous presence of random fluctuations corrupting preplanned strategies force us to take actions with relative uncertainty. Highly complex,

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multicriteria decision issues in modern management raise basically similar difficulties, thus questioning the overall relevance of centralized organization processes.

Logistics is one field of application in which recent developments of information and communication technologies, such as RFID tags or sensor networks, enable logistics objects like products, containers or even ships to interact and autonomously decide on their upcoming actions. These so-called "smart parts" [1] triggered a discussion about the pros and cons of a decentralization of decision-making in logistics processes, *e.g.* Ref. [2]. The underlying idea is based on a shift from an important degree of external control to a higher degree of the organizational principle of autonomous cooperation [3]. Following this concept consistently, supply networks can then be regarded as complex adaptive logistics systems (CALS) [1,4–7]. Inspired by the exceptional performances obtained by populations of social insects able, via mutual interaction mechanisms, to self-organize and ultimately produce robust and highly efficient patterns (*e.g.* Ref. [8]), modern management aims to favor decentralized decision processes. Decentralization is implemented by introducing a collection of suitable agents able to process local information in real time. These agents are endowed with an autonomous decision capability and their choices are based on this local and incomplete information (*i.e.* only a part of the population is usually observed). The multiple interactions between neighboring agents are ultimately expected to generate an emergent global behavior that, due to self-organization, should ideally outperform a centralized decision process.

However, effects of a reduction of external control and an increase of the degree of autonomous cooperation in transportation logistics on performance indicators, such as delivery time or delivery costs, have not been shown yet in analytically solvable models. Inspired by this logistics field of application, the aim of the present paper is to propose a stylized, fully solvable transportation problem for which this paradigmatic view can be mathematically observed. Benefits of self-organization have notably been pointed out in the context of urban road networks. In Ref. [9], a fluid-dynamic model is proposed to unveil that self-control of traffic lights and vehicle flows might lead to efficient traffic processes. As intersecting flows of vehicular traffic are often managed by an external control that might lead to oscillatory behaviors, decentralized control strategies become thus interesting and fruitful alternatives, [10,11]. Also somehow related to the present study, a model of commuters having the choice between alternative roads and basing their routing decisions on their neighbors' most recent waiting experience and on their own complete waiting history (*i.e.* on their exponentially weighted average experimented waiting times for each road) is proposed in Ref. [12]. This contribution explicitly exhibits the striking feature that a self-organizing system based on local information and locally rational agents might outperform (*i.e.* the average travel time of commuters is reduced) the Nash equilibrium (that assumes full information).

The complex evolution of statistical mechanics models involving multi-agent features usually precludes any analytical approaches, with the exception of the case when large and intimately connected populations are considered. In this case, the law of large numbers enables one to collect the numerous mutual interactions due to neighboring agents into an effective external field. The resulting mean-field approximate dynamics is described by time-dependent nonlinear field equations for which some analytical information can be extracted. This is precisely the method that we will follow in this contribution and which will lead to explicit solutions.

Stylized models, as the one introduced in this work, handle the complexity by reducing drastically the number of considered parameters. The aim of such kinds of models is to remain analytically tractable but to allow nevertheless for a detailed understanding of the origin and nature of the emerging phenomena. Moreover, the desired simplicity of these models implies that changes and variants can be addressed in a simple way, in order to eventually incorporate additional features. The approach consisting in developing such types of stylized models has been recently adopted in economics [13,14]. In these contributions, a minimal agent-based model for financial markets is developed in order to understand the essence of several collective self-organized patterns that appear in price evolution. Closely related to the present methodology and without being exhaustive, let us also quote stylized multi-agent models in the field of investment behaviors in stock markets [15] and autonomous routing in queueing systems [16].

The paper proceeds as follows: Section 2.1 depicts the basic dynamics of the model under consideration and thus consists in a description of the regarded population of agents, their decision rules and interaction patterns as well as the noise sources affecting the agents' dispersion over time. Taking this as a basis for the analysis that follows, Section 2.2 provides under a mean-field approach (*i.e.* we consider homogeneous agents) an analytical solution to the considered dynamics, notably with regard to the resulting acceleration effects of the whole cluster of agents. Section 2.3 consists in a cost function analysis, the aim of which is to compare the cumulative costs that result from autonomous agents' interactions with those that would occur if an effective optimal central controller would lead the cluster of non-interacting agents to an equal dispersion. Section 3 is devoted to concluding remarks; the findings are summed up and future and further research requirements are pointed out.

2. Self-organized transportation based on an idealized smart parts paradigm

2.1. Basic dynamics

Consider a collection of agents $\mathcal{A}_k$, $k = 1, 2, \dots, N$, with evolution given by the stochastic dynamics:

$$\dot{X}_k(t) = v_k(t) + \gamma_k \underbrace{\mathbb{I}_k(\vec{X}(t))}_{\text{agent interactions}} + q_k(\vec{X}(t), v_k(t))\mathrm{d}B_{k,t}, \tag{1}$$