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Specifying Self-organising Logistics System: openness, intelligence, and decentralised control

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Abstract. This paper contributes to the development of a novel paradigm in logistics, i.e. self-organising logistics system (SoLS). A SoLS can be considered as a logistics system that can function without significant intervention by human, and without central control by software. It is functioning based on contextual local interactions. By such definition, SoLS could be a powerful solution to manage nowadays logistics that is much larger and complex than ever before. The goal of this paper is to provide a comprehensive and in-depth discussion to specify expected advantages and functionalities of SoLS, supported by some recent emerging concepts and technologies. The paper also attempts to provide a theoretical framework for the future work.

Keywords: Logistics, Self-organisation, Openness, Intelligence, Decentralised control, Holonic and Multi-Agents System.

1 Introduction

Nowadays logistics system is much larger and complex than ever before, and, therefore, difficult to manage as a whole. One may have heard about many emerging technologies, concepts and paradigms that are proposed as solutions to cope with this difficulty, e.g. intelligent product or intelligent logistics [1], Holonic and Multi-Agents System [2], Cyber-physical System [3], or Physical Internet [4]. One may be interested in the following question: what could be the next era of logistics if all these solutions have a joint effort to develop the logistics? This paper discusses one of the possible eras, namely self-organising logistics system (SoLS hereinafter).

Self-organisation is a popular term in many research fields, for example in computer science, human society and behaviour, and biology [5-7]. However, in the field of logistics, it is still a developing paradigm. As suggested in [8], a SoLS is a logistics

system that “*can function without significant intervention by managers, engineers, or software control*”. The suggested definition implies some potential advantages of such systems to today’s large-scale and complex logistics. Based on these works, we attempt to provide a wider and deeper vision to specify SoLS, by defining its main desired functionalities and analysing its advantages in the context of logistics organisation. The advantages are discussed qualitatively from perspectives on logistics performance and on sustainability, to illustrate that SoLS could make logistics more autonomous, efficient and effective, i.e. a more sustainable system.

For the sake of providing an overview and insightful discussion of SoLS, this paper proposes to discuss several main functionalities of future SoLS: openness, intelligence, and decentralised control. Openness means that a SoLS should allow actors (e.g. shippers, service providers, or customers) or assets (e.g. trucks, containers, or warehouses) to easily join and leave the system, for the sake of fast reconfiguration. Intelligence emphasises the object-based capability of local real-time communication and activeness [9]. Decentralised control focuses on collaborative rules and communication protocols designing, i.e. environment, for SoLS. It should be noticed that decentralised control for SoLS aims to avoid unexpected or disastrous outcomes of the system, but not to optimally plan activities or control objects. Further, we will also discuss expected advantages and performance of SoLS with regard to current challenges in logistics.

2 Relevant Literature

2.1 Self-organisation in Logistics

There is limited literature investigating self-organisation in the field of logistics. References [10-12] propose to consider supply network as complex adaptive system where self-organisation is considered as an internal mechanism between agents. Differently, reference [8] considers self-organisation as a organisational paradigm to cope with complex assembly lines, by using “bucket brigade” assembly lines as illustration. Other studies from the same standpoint can be found in the field of manufacturing, e.g. [2, 13].

This paper is in line with [8] and extended to investigate SoLS functionalities for effectiveness and efficiency, which is particular important to cope with current and future challenges in logistics, see Table 1. From our point of view, a SoLS is *an open, intelligent and holonic logistics system that aims to harmonise and lead individuals within the system towards a system-wide common goal, without significant human intervention from outside*. An individual within SoLS can be an object (e.g. a truck), a manufacturer, a service provider (e.g. 3PL), a receiver (e.g. a customer), even a supply chain or a supply network as a whole. Assuming that individuals may have different constraints and objectives, e.g. service rate improvement or cost reduction, we argue that SoLS should have the ability to respect individual’s constraints and objectives, meanwhile leading them towards a common goal - the sustainability for exam-

ple. To this end, individuals should be coordinated by system-wide well-designed rules, i.e. the system environment [14].

2.2 Expected Advantages and Performance

Based on the suggested definition, some advantages of SoLS can be expected. We here discuss qualitatively expected advantages according to six main indicators of performance measurement, as described in Table 1:

Table 1. Advantages and expected performance of SoLS functions

	Description	SoLS expected advantages
Effectiveness	How well a goal is adequately met? [15]	Individuals should be able to make autonomous decision to meet a given goal
Efficiency	How well the resources expended are utilised? [15]	Individuals should intelligently use the on-hand resources
Agility	Ability of a system to rapidly reconfigure [16]	Individuals should have good connectivity to each other and to environment for rapid reconfiguration
Flexibility	Ability of a system to change status within an existing configuration [16]	Individuals should be able to connect and adapt to each other to provide flexible solution
Resilience	Ability of a system to return to its original state or move to a new, more desirable state after being disturbed [16]	SoLS should be able to dynamically self-reconfigure to adapt to unpredictable and disruptions
Sustainability	Ability of a system to protect, sustain and enhance the human and natural resources that will be needed in the future while meeting a desired goal [17]	SoLS should function on the basis of common goal of sustainability, by protecting human and natural resources

2.3 Related Concepts and Paradigms

Before illustrating the features and functions of SoLS, it is necessary to provide consensual definition to the emerging concepts and paradigms used in this paper. The related concepts and paradigms are classified here according to their objective: conceptual criteria, technical paradigm, technology and application. Table 2 gives a short description from the literature adapted for the purpose of this paper.

Table 2. Concepts and paradigms related to SoLS

Classes	Short description
Conceptual Criteria	Openness: system boundary is unset but variable and flexible [4].
	Adaptation: objects adapt to each other for coordination of activities and to leads to more efficient processes [18].
	Reconfiguration: add, remove and modify logistics activities and functions [19].
Technical Paradigm	Self-organisation: a system can function without significant intervention by managers, engineers, or software control [8].
	Cyber-Physical System: integrations of computation with physical processes [3].
	Intelligent and active products: a product able to self-identify its state, and able to send information once certain pre-conditions are met [20].

	<p>Multi-agents System: system to coordinate intelligent behaviour among a group of agents which are autonomous and flexible computational systems [21].</p> <p>Holonic System: a system composed of holons. Holons are autonomous, cooperating and potentially recursive decisional entities, which can simultaneously be part or sub-whole of the system. A holon is most of the time composed of a physical part along with a digital one [22].</p> <p>Complex Adaptive System: a system that emerges over time into a coherent form, and adapts and organises itself without any singular entity deliberately managing or controlling it [11].</p>
Technology	<p>IoT: Internet of Things is the network of physical objects that are connected via Internet and technologies providing unique addressing schemes, such as RFID tags, sensors etc. [23]</p> <p>ICT: Information and communications technology for the communication between objects or systems [24]</p> <p>Embedded systems: combination of computer hardware and software, and perhaps additional mechanical or other parts, designed to perform a dedicated function inside a single identified system [25].</p>
Application	<p>Intelligent logistics: a will to plan, manage or control logistics activities in a more intelligent way [1]. It may rely on intelligent products, data techniques etc.</p> <p>Physical Internet: the network of logistics networks using the internet analogy [4].</p>

After this short literature review, the next section introduces specifications of the SoLS.

3 Specifying Self-organising Logistics System

To construct an effective and efficient SoLS, and to avoid some unexpected or undesirable outcomes, we propose several functionalities for the system. This part discusses three that are identified as crucial factors: openness, intelligence and decentralised control.

3.1 Openness

Openness in SoLS means the boundary of the system is unset and open so that individual (actors, assets, supply chain, etc.) can easily join and leave the system. An illustrative example can refer to connecting a computer to the Internet from all over the world for different purpose, like searching information or communicating with others. Individuals join the SoLS to provide, procure or share logistics assets (truck, facilities etc.) and logistics service (delivering, planning etc.). By that, SoLS becomes fast extendable and reducible to answer highly flexible logistics requirements, as shown **Fig. 1**. Here we discuss several functions that are essential to this end.

Function 1.1 Connectivity: this function means that individual can easily connect with others or and the environment. For example in **Fig. 1**, individuals outside can easily connect to the system or other individuals within, if rules and standards are respected. System-wide modularisation and standardisation of physical assets (e.g. Physical Internet Container [20]), information systems (e.g. ICT) and organisation

models is crucial to enable good connectivity. Examples can refer to Physical Internet [4, 26]. Notions of interoperability must equally be considered to allow an adequate communication between the different actors.

Function 1.2 Reconfiguration: Once the system receives new logistics requests (transport, stocking etc.), it should be able to add or change some current functions inside to fulfil the requests. The reconfiguration function is particularly important to cope with disruptions, i.e. the system can rapidly self-reconfigure [27].

Function 1.3 Adaptation: individuals should adapt to each other and to environment, in order to rapidly build up effective and efficient coordination between them [11].

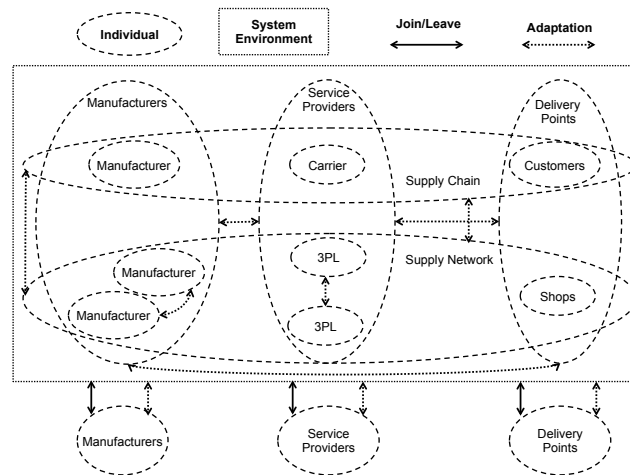


Fig. 1. Open logistics system

3.2 Intelligence

Intelligence in SoLS means that every individual within the system is able to make and execute autonomous decision, and to interact with other individuals and with the environment. For that, they should have the ability to collect, store and process information from other individuals (their state and decision) and from environment (rule modification). We propose that IoT technology is a fundamental support to such requirements. Further, two important functions are identified for such a functionality.

Function 2.1 Activeness: individuals should have to ability to collect information from other individuals (their state and decision) and from environment (rules and any modifications), then to store and process the information for autonomous decision-making. Further, they should also be able to send information to others, to advertise the changes of their state and to take decision. Each event can be seen as a change to the system, e.g. a warehouse is disrupted, a truck is full, or an order is cancelled. Activeness is therefore an important functionality for SoLS.

Function 2.2 Autonomous acting: once a decision has been made, systems should also be able to apply and execute the decision. This function could be relying on embedded systems of autonomous operating assets, autonomous supply chain or autonomous network, including sensors and actuators inside decisional loops.

Fig. 2 illustrates some existing and emerging examples of intelligence applied in logistics. It is obvious that some of the three functions are questionable under current organisation and technologies in logistics. However, emerging innovative technologies may help us to project the future of intelligence in SoLS, e.g. drone, autonomous operating truck, or Kiva.

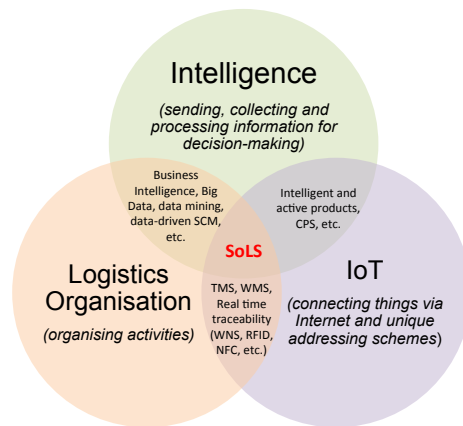


Fig. 2. Technologies and Techniques of intelligence applied in logistics

3.3 Decentralised Control

As stated in [11], “imposing too much control in a complex system detracts from innovation and flexibility; conversely, allowing too much emergence can undermine managerial predictability and work routines”. In this paper we propose to specify SoLS as rule-based decentralised control system, for the sake of effectiveness and efficiency [28]. More precisely, rule-based decentralised control in SoLS aims to help the autonomous decision-making of individuals within the system. It has a twofold objective: to avoid unpredictable and undesirable outcomes, and to lead individuals towards a system-wide common goal. We propose that decentralised control should rely on system-wide well-designed rules and individual-wide protocols, which should be respected when local autonomous decisions occur [28]. In such a context, we propose that the decentralised control in SoLS should be modelled as a holonic and multi-agent system [7, 21], with the following functions:

Function 3.1 Holonic multi-agent system: we propose to model SoLS as holonic multi-agents system (HMAS), since controlling in such a system should be at individual level, i.e. at holon level (whole, part, or sub-whole). Each holon is composed of a physical part mirrored by an agent in the model. Each agent is self-controlling so that no controlling agent is necessary in the HMAS.

Function 3.2 Rule- and protocol-based: rules here represent the common regulations of the system that every individual should respect; and protocols stand for communication protocols that allow individual communicate to each other, i.e. interoperability. Take digital internet as an example, in which rules are law and protocol is internet protocol like TCP/IP. In other words, rules are designed for meeting common goal; and protocols for effective and efficient communication.

Fig. 3 presents system architecture of rule- and protocol-based HMAS. We consider here a transport request as an example of logistics activities. *As per* current organisation, driver (P1) and transportation means (P2) are essential for it. In SoLS scenario, a HMAS model is employed to help P1 and P2 to make decisions. More precisely, each of P1 and P2 is mirrored by an agent in the MAS model. Rules of logistics organisation (e.g. speed limit, preconizing multi-modal transport, etc.) and protocols between objects (e.g. driving instruction, autonomous driving control etc.) are translated as the environment of the MAS model. By that, P1 (or V1) and P2 (or V2) should respect the environment when they make autonomous decisions. The MAS model here thus aims to coordinate and cooperate the agents – physical objects, but not to control.

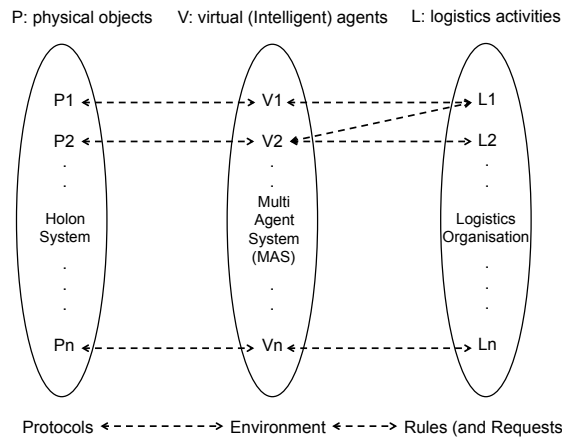


Fig. 3. Modelling SoLS as rule- and protocol-based holonic multi-agent system

4 Conclusion

This paper aims to contribute to specify advantages and functionalities of self-organising logistics system (SoLS), which is a novel paradigm in logistics. Openness, intelligence and decentralised control are the three main functionalities proposed and discussed in this paper as vital functionalities of SoLS to cope with the current and future challenges in logistics. Real world examples can refer to the recent DHL research project - Parcelcopter SkyPort¹. Basically, the idea is to conjointly use autonomous drones (Parcelcopter) and automated parcel stations (Packstations) to cope

¹ http://www.dpdhl.com/en/media_relations/specials/parcelcopter.html

with demanding logistics challenges such as “same day delivery”, especially in rural zones. Drones and Packstations together can be seen as a SoLS. Once a package to be delivered is arrived at Packstation with known constraints (volume, delivery location and time etc.), the system will autonomously plan and optimise the delivery. Only monitoring is necessary from outside. We may assume that, supported by the emerging technologies and techniques, more and more examples of SoLS would be found and realised.

The paper provides also an insightful overview and theoretical framework for the future work. For example, organisational and technical issues related to SoLS, such as protocol design, coordination or security issues, can be investigated through mechanism design theory for example. Quantitative researches through simulation and optimisation approaches are also necessary to investigate the performance and viability of SoLS in real-life cases.

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