Towards a Framework for Smart Resilient Logistics

Doctoral Consortium paper

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***Abstract*— In order to remain competitive, logistics companies are forced to provide smart solutions within a network that is characterized by complexity and heterogeneity. The advancements of sensing and communication technologies stimulate logistics organizations to improve their business performances by using more advanced decision support tools. This research is devoted to improve logistics decision making by exploiting the enormous datasets originating from IoT networks in combination with Big Data Analytics. The main aim is to develop a resilient planning framework that stimulates logistics planners to combine both human experiences and pattern recognition mechanisms (e.g., machine learning, data mining, etc.). In this paper, four research deliverables are proposed to pursue this vision: (1) a state-of-the-art overview of modern decision support tools to enhance logistics resilience and efficiency; (2) the development of dynamic optimization algorithms using real-time data; (3) the construction of data-driven algorithms to identify, assess and resolve the presence of logistical disturbances and; (4) the formulation of resilient planning framework that enables real-life implementations of the algorithms developed. A brief overview of the required research activities is given as well, including a visualization of the activities' coherency. This paper concludes with a description of the preliminary results and some future research directions.**

Keywords — Internet of Things (IoT), Big Data Analytics, Operations Research, Logistics Management, Decision Support Systems, Research Planning

I. INTRODUCTION

Supply chain decision making heavily relies on the application of well-analyzed data, especially in the field of logistics planning and control. Logistics planning refers to all type of decisions that bring supply and demand together to meet the customers' requirements in terms of volume, timing and quality [1, 2]. A well-organized logistics network requires proper orchestration of various planning functions like process modeling, resource allocation and material coordination [3]. Since these interrelated decisions present themselves as choices between alternatives [4], it is the management's task to gather, analyze, compare and interpret multiple data sources to determine which alternative fits the stakeholders' interests best. Therefore, the knowledge acquisition enables true optimization of the logistics network by properly defining all relevant alternatives, objectives and constraints [5].

Over the years, multiple tools originating from different scientific disciplines enabled logistics managers to make better informed decisions and stimulated improvements in supply chain designs (e.g., Operations Research, Information Technologies, Business Intelligence, Statistical methods, etc.). However, it remains difficult to construct efficient and resilient designs for supply chain networks, mainly because of the highly dynamic and heterogeneous nature of these environments [6]. It seems almost impossible to predefine an optimal planning due to unpredictable and unprecedented events. Schedules are often affected by a wide variety of disruptions, suggesting that online modifications of the initial plan are required. Most decision support tools originating from management sciences are data intensive and irregularly applied, while disturbance detection should rely on data obtained from the actual business executions to stimulate proactive operations and predictive intelligence [7]. The planning complexity aggravates even further because collaboration between logistics companies is required more often in a market that is highly fragmentated and characterized by single-enterprise IT infrastructures [8, 9]. Therefore, the question arises how the real-time detection of disturbing events can be included into logistics planning and control.

One way to address the issues of detecting disturbances is to implement multiple tracking and monitoring devices at key logistical milestones (e.g., RFID tags, mechanical sensors, video cameras, etc.). These devices could be installed on objects that are physically operating within the supply chain, providing the opportunity to gather real-time data about the resource allocations and the corresponding performances. The stand-alone sensing objects would already provide useful insights into the daily activities, allowing managers to adjust their operational decisions in the short term. Even better understanding would be obtained by connecting all these sensing objects into one interconnected network of data gathering and actuator devices [10]. This way of digitalizing the supply chain enables the physical objects to communicate with each other in the so called 'Internet of Things' (IoT), while the analysis of large quantities heterogenous data sets is better known as 'Big Data Analytics' [11, 12, 13].

This research is devoted to make logistics decision making more resilient against disruptions by exploiting the enormous datasets generated by IoT networks. The empowerment of monitoring devices with pattern recognizing algorithms (e.g., machine learning, data mining, etc.) will enable logistics planners to be expeditiously informed of emerging patterns influencing their logistics' performances. The assessment of registered disturbances may also require modifications into the planning initially made, allowing the logistics planners to

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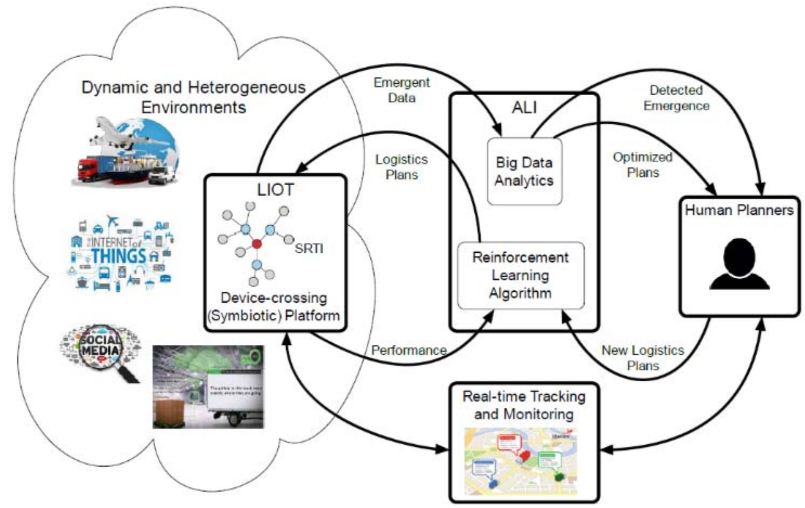

Figure 1: A visualization of the alternative research topics and its relationships within the DATAREL research project [6].

re-optimize their operations based on the network's conditions observed. Therefore, I hypothesize that the increased interconnectivity of data gathering and processing devices will enable logistics companies to move beyond track-and-trace services only, since the development of data-driven algorithms will allow logistics planners to anticipate adequately on future events in the medium- and long-term as well. The main aim is to develop a resilient planning framework that enables logistics companies to organize their physical movement of goods, services and information in a more effective, efficient and flexible way by combining both human experiences and machine learning mechanisms.

Research question: how to make effective use of the large and heterogenous data streams generated by IoT networks and other external data sources to support resilient logistics decision making?

The research question is valid for a wide variety of logistics activities throughout the supply chain (e.g., internal material handling, warehousing, returns management, etc.). In order to limit the scope of this research, I will mainly focus my research efforts within the domain of freight transportation. However, all research deliverables will include a generalized version to ensure external validity as well. The remainder of this paper is structured as follows. First, an overview of related academic publications is given in Section II, including a description of the overall research project. Next, the research methodology will be discussed in more detail in Section III. In Section IV, the research deliverables are defined, while Section V elaborates how to operationalize these deliverables exactly. Some early results are discussed in section VI, while Section VII will end this paper by highlighting the research activities in the near future.

II. BACKGROUND

A. IoT and Big Data in logistics

Both industry practitioners and scientists have high expectations for IoT and Big Data implementations into logistics decision making [10, 11, 13]. For example, the position of IoT platforms on Gartner's hype cycle for emerging technologies emphasizes the commercial viability and high expectations of these advancing monitoring technologies [14], even while the future's deliverables are highly uncertain due to lacking information of the actual benefits and limitations [15]. Logistics activities such as transportation, warehousing or maintenance are resource intensive, resulting into a wide variety of physical objects empowered by primitive or no intelligence at all [11]. Just a slight increase of the objects' intelligence would already provide new business insights that drive innovations. The inclusion of actuating, processing and storing capabilities would expand the business opportunities even further, revolutionizing the way how organizational decisions are made [10]. Businesses can use the enormous heterogenous datasets to develop and implement smart algorithms that could autonomously support human decision making [7].

B. DATAREL project

This research is part of the project 'Big Data: real time ICT for logistics' (DATAREL), which aims at advancing the extant logistics knowledge with novel Internet of Things (IoT) and Big Data solutions for detecting emergent behavior [6]. The increasing number of sensor implementations at multiple business operations provides the opportunity to monitor business performances constantly. Real-time analysis of large and heterogeneous data sets will be used to improve the quality control and (multimodal) transportation planning in terms of resilience, real time, efficiency and dynamics. Therefore, a strong connection can be observed between the IoT networks that will generate real-time logistical data and the autonomous algorithms using these datasets to predict, identify and manage supply chain disturbances (Figure 1). My personal vision is to develop a decision support tool empowered by Artificial Logistics Intelligence (ALI) to support human planners during operational, tactical and strategic decision making (focus on the right side of Figure 1). One of ALI's major data sources originates from real-life Logistics Internet of Things (LIoT) applications, but other data sources may be included to support the activity of resilient logistics planning as well.

III. METHODOLOGY

The Design Science Methodology from [16] is applied to develop the resilient logistics decision support tool in a systematically way. The methodology consists of six intertwined activities: (1) Identify problem & motivate; (2) Define objective of a solution; (3) Design & development; (4) Demonstration; (5) Evaluation and; (6) Communication. The methodology's problem- and object-centered ensures that the resulting algorithms and decision support tools will meet the requirements of multiple logistics stakeholders.

The development of a resilient planning framework requires advanced knowledge of both big data techniques and logistics planning methods. The IoT networks will provide new datasets that should be analyzed to detect logistical disturbances constantly. Machine learning algorithms and other pattern recognizing techniques are required to autonomously detect and assess the impact of real-life events, including a feedback loop that evaluates the tacit human experiences. The application of these data-driven optimization techniques should result into adequate workaround strategies. On the other hand, most logistics activities rely on multi-criteria objectives (e.g., speed, reliability, costs, etc.), which indicates the importance of using combinatorial optimization techniques as well.

IV. RESEARCH DELIVERABLES

Section III indicates that the development of a resilient planning framework is characterized by a multidisciplinary view consisting of both data- and model-driven optimization techniques. Four main deliverables are defined to enable the integration of these two approaches, including some relevant research questions as well:

Deliverable 1 – State-of-the-art logistics support:
- How do IoT networks support logistics decision making nowadays?
- How to ensure resilient logistics operations?

Deliverable 2 – Dynamic optimization using real-time data:
- How to apply real-time data obtained from IoT networks for logistics optimization?
- How to include dynamic optimization algorithms into decision support systems?

Deliverable 3 – Online disturbance resolver:
- How to identify, assess and manage logistics disturbances monitored by IoT networks?
- How to sustain acceptable logistics performances in the presence of both internal and external events?
- How to include online disturbance resolver capabilities into decision support systems?

Deliverable 4 – Resilient planning framework:
- How to obtain resilient logistics planning by using IoT networks and Big Data Analytics?
- How to integrate tacit human experiences and artificial decision making?
- What are the real-life results of the resilient logistics planning framework proposed?

The main vision is to develop a software agent empowered by ALI to support logistics planners during both operational, tactical and strategic decision making. Therefore, each deliverable should be fulfilled from two perspectives: (1) the scientific contribution and (2) the business interests. It is required to deliver at least one scientific paper for each research deliverable defined. The DATAREL business consortium also requires that the innovative IoT architectures, autonomous algorithms and business verified, validated and valorized in real-life.

V. RESEARCH ACTIVITIES & EXPECTED RESULTS

The following subsections will be used to elaborate on the operationalization of all four deliverables mentioned in Section IV. A more detailed description of the required activities and their interrelationships are visualized in Figure 2 (please note that the visualization is inspired by the Business Process Model and Notation [17]).

A. Deliverable 1: State-of-the-art logistics support

An increasing number of IoT applications are used by logistics companies to keep track of their products and movement equipment. However, the number of scientific publications demonstrating the feasibility of these techniques remains relatively limited. Therefore, the first deliverable is separated into three main activities to validate the usefulness of LIoT networks. First, I will read some review articles regarding IoT networks, Big Data Analytics and Logistics in order to gain better understanding of the DATAREL project. Second, a systematic literature review will be conducted to obtain a validated list of the (dis-) advantages enabled by the real-time monitoring of logistics activities. Third, another systematic literature review will be initiated to investigate how the concept of "resilience" is implemented in the field of Logistics Management currently. Two articles are made for both literature reviews, while the relationships between the two will be discussed in more detail into the PhD manuscript. The theoretical results will be used to create an initial framework for resilient logistics planning (e.g., Enterprise Architecture).

B. Deliverable 2: Real-time & dynamic optimization

The second deliverable aims for using the big data gathered by IoT networks to optimize the planning of logistics activities dynamically. Different activities include alternative objectives, parameters, decision variables and constraints. Therefore, a wide variety of OR techniques and data sources are required to improve the planning for each logistics activity separately. As a consequence, a modular IoT configuration is designed first to solve the wide variety of optimization problems. Some pattern recognizing algorithms may be required as well in order to analyze the real-time data gathered by the IoT devices. Currently, I would like to include within this research (please note that other alternatives may be derived soon as well):

- *Option A "Virtual queueing":* most of a vehicle's travel time is predetermined by the distance between its origin and destination. However, some additional time may result from congestion at the logistics hubs on the way (e.g., airports, seaports, cross-docks, etc.). A real-time congestion prediction can be made by evaluating the tracking data of all vehicles moving towards (or within) a logistics hub. The combination of IoT devices and queueing theory provides useful insights for logistics companies, since they can adjust their routes based on the real-time port congestion figures observed;

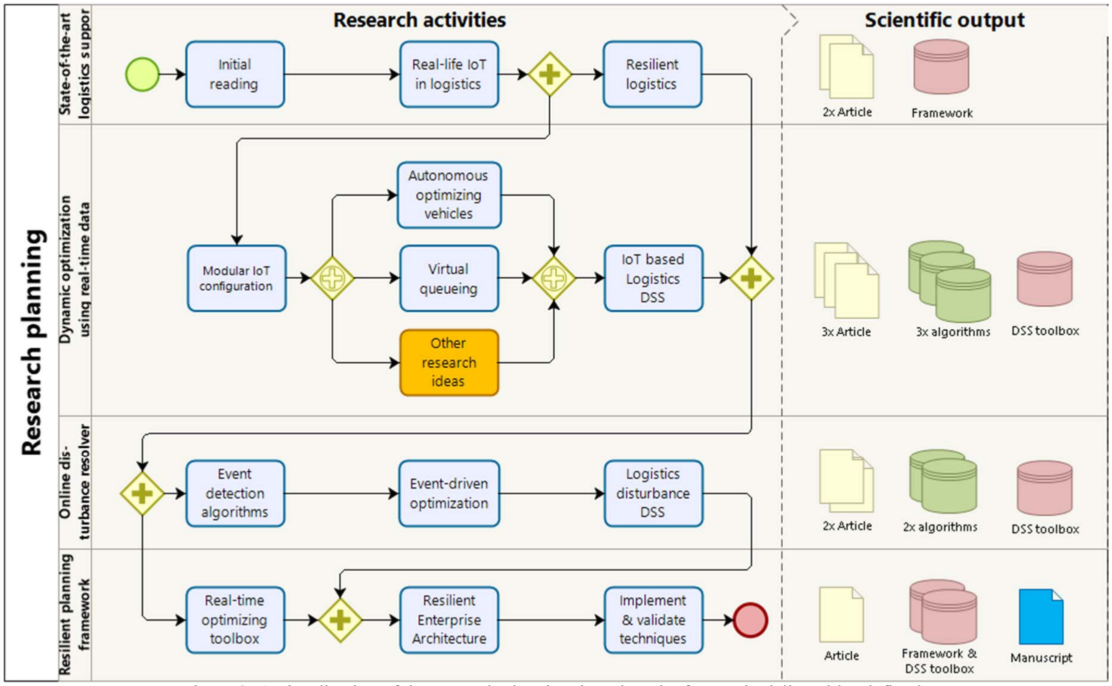

Figure 2: A visualization of the research planning, based on the four main deliverables defined.

- *Option B "Autonomous vehicle optimization":* the complex and heterogeneous nature of logistics networks makes it hard for scientists to derive the optimal system configuration. One way of addressing these types of logistics networks is to combine the concepts of Multi-Agent Systems (MAS) and autonomous vehicles to enable decentralized routing guidance. Since these vehicles are continuously registering their interaction with the environment, it may be interesting to investigate how the classical Vehicle Routing Problem can be improved by including the event logs generated. Empowering autonomous vehicles with MAS technology may be interesting for a wide variety of logistics operations like inter-terminal transportation and warehouse materials handling. The problem can be addressed by applying OR techniques (e.g., Linear programming or Approximate Dynamic Programming), but a more data-driven method can be applied as well (e.g., Reinforcement Learning or Process Mining).

For the second deliverable, one scientific article will be made for each optimization problem addressed. An agile development approach will be used to deliver the required algorithm functions in relatively short cycles (approximately two or three weeks). The performances of each algorithm will be verified by using historical datasets originating from the DATAREL business consortium. The algorithms' performances are validated by implementing an experimental setting or prototype in real-life. The derived knowledge will be used to develop an open-source decision support tool for using real-time data into logistics planning.

C. Deliverable 3: Online disturbance resolver

The third deliverable aims for the development of autonomous algorithms to predict, identify and manage disruptions real-time, allowing business planners to adjust the (optimal) planning made earlier. First, I will focus on the development of data-driven algorithms useful for the identification of events that may affect the logistics performances. The datasets will mainly originate from the IoT network taken into consideration. Second, new algorithms will be constructed to ensure resilient operations during/after an interrupting event has emerged. The accurate prediction of disrupting events will enable human planners to dynamically improve their planning activities, resulting into a more event-driven optimization. Finally, the derived knowledge will be used to develop an open-source decision support tool for logistics planners. These online disturbance resolver algorithms should contain/combine multiple big data techniques (e.g. data mining, process mining, machine learning, etc.), the human input should be considered as well. I will try to make an analogy to the field of Maintenance Engineering, especially by investigating the new trends of Condition Based Maintenance. The algorithm development, verification and validation phases use the similar methods applied for deliverable 2 (see section V.B). The derived knowledge will be used to develop an open-source decision support tool for logistics planners.

D. Deliverable 4: Resilient planning framework

The fourth and last deliverable will be used to merge the alternative Operations Research and Data Science techniques developed. First, I will construct a logistics decision support tool by integrating both the dynamic optimization algorithms and the online disturbance resolver (deliverable 2 and 3 respectively). The system will include a user-friendly graphical user interface (GUI) to gain advantage of all the tacit experiences that human planners have. Second, a generalized framework will be developed to ensure reproducibility of all the scientific output developed in this research. Therefore, an updated version of the initialized framework resulting from deliverable 1 is created at the end of this research project. Finally, some experimental settings or real-life implementations will be initiated in cooperation with the DATAREL business consortium to assess the validity of the framework developed. Please note that the performances of the individual algorithms will be verified/validated separately in deliverable 2 and 3, while the final validation phase will determine if the generalized framework stimulates logistics decision making in terms of efficiency, effectivity and resilience by exploiting the datasets originating from IoT networks. The project will be completed by summarizing all results in the PhD manuscript.

VI. Preliminary results

At the moment of writing this article (the 8th of August 2019), some preliminary results are available already: (1) the research planning; (2) a systematic literature search and (3) a workshop paper. The initial literature review has resulted into the research planning described in this article, which aims to explain how the development of methods and tools supporting resilient logistics planning can be operationalized. The other two preliminary results will be discussed in the following subsections.

A. Systematic literature search

A systematic literature search is conducted to obtain a validated list of all (dis-) advantages enabled by the real-time monitoring of logistics activities. This systematic literature search is characterized by two innovative applications:

- The search is based on a multidisciplinary view that covers all essential knowledge management activities: (1) data gathering via IoT networks; (2) data processing via Big Data Analytics and; (3) data/information application by means of decision support into the supply chain;
- A systematic keyword analysis is developed to yield the most relevant keywords for the three academic disciplines taken into account. An initial search for relevant review articles only resulted into a set of keywords most frequently used. The natural grouping of these keywords is visualized in so-called bibliometric networks for each discipline. These clusters of keywords are used to motivate the keyword selection for the major search.

The combination of multidisciplinary keywords, inclusion- and exclusion criteria resulted into a total of academic 81 articles. The resulting literature search still needs to be reviewed and published [18], but a few main conclusions can be made in advance regarding the real-life implementations of LIoT networks (see Figure 2 and deliverable 1 in Section V.A.). Most IoT applications are limited to low level monitoring and detection activities. Just a few papers bring these types of technologies in relation to the higher-level applications concerning process performance management and tactical decision making. Therefore, the resulting state-of-the-art overview supports the construction of an initial framework for resilient logistics planning.

B. Workshop paper

An agent-based process mining architecture is proposed to derive optimal system configuration in complex and heterogeneous logistics networks. The architecture includes an integrated overview of hardware, software and equipment to support the development of smart manufacturing environments (the architecture is in compliance with the ArchiMate 3.0.1 guidelines provided by [19]). The main aim is to autonomously construct an optimal set of decision rules for software agents by continuously analyzing the agents' event logs. A discrete-event simulation model is used to validate the architecture's usefulness, including a case study of a job-shop scheduling environment with Automated Guided Vehicles (AGVs) for the internal transshipments.

The validation results revealed that the application of process mining tools provide useful insight into the system's emergent behavior by investigating the corresponding event logs only. Therefore, the combination of MAS and Process Mining forms an interesting approach towards autonomous logistics network design (see Figure 2 and deliverable 2 in section V.B.). The agent-based process mining architecture and the validation results are summarized in a workshop paper entitled as *"An agent-based process mining architecture for emergent behavior analysis"* and is submitted for the Strategic Modeling and Reasoning meets Process Mining Workshop [20]. This workshop is in conjunction with the 23rd IEEE international EDOC conference. Further research is required to include event logs and process mining into real-life optimization problems like the vehicle routing problem.

VII. Conclusion & Future research

Logistics companies are forced to provide smart solutions within a network that is characterized by complexity and heterogeneity. The advancements of sensing and communication technologies stimulate logistics organizations to improve their activities by using more advanced decision support tools. The main question in this research is how to make effective use of the large and heterogenous data streams generated by IoT networks and other external data sources to support resilient logistics decision making. The answer to this question would enable the development of a resilient planning framework that supports logistics planners to organize the physical movement of goods, services and information in a more effective, efficient and flexible way. The development of data-driven algorithms will allow logistics planners to anticipate adequately on future events in the medium- and long-term, including a combination of both tacit human experiences and machine learning mechanisms.

In this paper, I explained which research activities are required to obtain the resilient logistics support system envisioned. Four research deliverables are proposed: (1) a state-of-the-art overview of modern decision support tools to enhance logistics resilience and efficiency; (2) the development of dynamic optimization algorithms using real-time data; (3) the construction of data-driven algorithms to identify, assess and resolve the presence of logistical disturbances and; (4) the formulation of resilient planning framework that enables real-life implementations of the algorithms developed. The integration of two main academic disciplines is required to fulfill all four deliverables successfully: (1) mathematical modeling to support the optimization of logistics operations and; (2) Data Science for the management of potentially disturbing events. The combination of these two fields would allow logistics operators to schedule their operations more dynamically. The coherency of all research activities is ensured with a visualization inspired by the Business Process Model and Notation [17]. This research approach will help logistics companies to valorize the innovative IoT architectures, algorithms and business models proposed.

In addition to the literature study on the validated (dis-) advantages enabled by the real-time monitoring of logistics activities, I would also like to perform a literature study on the concept of resilient logistics. The main question of this search is how logistics operators take the emergence of alternative events into account nowadays. A clear overview of disturbance resolving strategies would help us to construct autonomous event detection algorithms (see Figure 2 and deliverable 3 in section V.C.). I would also like to continue the development of autonomous vehicles empowered with optimization capabilities (see deliverable 2 in section V.B.). The main focus is to experiment with the integration of process mining algorithms and vehicle routing problem formulations, other pattern recognition algorithms could be included as well. Hopefully, this integration will enable real-time and dynamic optimization of the logistics network taken into consideration. Finally, I would appreciate expert advice concerning interesting optimization problems that may fit within this research approach (see deliverable 2 in section V.B.).

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