A Framework for a Holistic Information System for Small-Medium Logistics Enterprises

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***Abstract*—Logistic or freight networks have gained considerable interest lately, calling for intelligent methods in order to deal with the increasing load requirements while maintaining sustainable costs. In this work, we focus on addressing the needs of small-medium freight companies so that they can cope with the emerging challenges in the post-COVID era. More specifically, we initially identify the requirements and the architecture of a candidate holistic information system that such a company would need to ensure optimal deliveries and efficiency of its operation. Then we focus on the scheduling-routing component of the proposed information system framework. We review the proposed solutions and propose a novel one based on the concept of backpressure joint scheduling-routing inspired from telecommunication networks. We believe that this approach can seamlessly and efficiently provide the means for small-scale companies, and larger ones as well, to optimize their operations and improve their offered quality of service.**

***Index Terms*—Logistics networks; Scheduling; Routing; Backpressure optimization; Information systems;**

I. INTRODUCTION

Companies active in the domain of logistics and freight transportation have faced a major challenge over the last two years in the COVID-19 and post-pandemic period. Skyrocketing demands for online shopping and home deliveries, financial complications and disrupted production rates, create a challenging environment, where logistics-related companies need to optimize their handling and delivery capacity, while at the same time maintain low operational cost and acceptable delivery times. This regards especially the small-medium enterprises, which most often have a more targeted focus in the transportation of goods, e.g., handling of dangerous/special loads, etc. In addition, such companies are characterized by a smaller network of intermediate collection points, they rely on collaborations with other freight companies, larger or not, and in general, their success is more dependent on providing quality of service (and sometimes quality of experience) to their end user, rather than bulky transfers.

Typically, large freight companies rely on integrated information systems that interconnect various dedicated components necessary for the overall operation of each such company. Examples of such components include CRMs, accounting, expert systems, etc. Significant research and development has been spent in the literature to develop such types of components separately, and in many cases, such components are state-of-the-art with respect to their functionality or the problem solution they provide. However, the overall information system may turn out inhomogeneous, in the sense that some components can be inferior to others. Yet, the overall operation ensures that such information systems still compensate the inferior components via the state-of-the-art performance of other components. The small-medium enterprises cannot afford this luxury in the typical case. Mostly, such companies rely on small-scale information systems, or in many cases in different systems not integrated under a common umbrella. Investing on an integrated information system, as the one described before, can be prohibitive for these companies, but at the same time the functionality offered by such systems, e.g., with respect to scheduling and handling of warehouses, freights, etc., can be crucial for the current and future operations of the company.

In this paper, we focus mainly on the case of small-medium enterprises, aiming towards addressing the aforementioned needs and providing a framework for developing efficient and effective information systems, which are both cost accessible and successful in addressing the daily needs of the companies. More specifically, we initially identify the requirements and architecture of a holistic information system addressing the exact needs of small-medium enterprises, with two goals. On one hand, ensure completely their daily functional operations, and on the other hand to allow for longer-term scalability of the companies by providing intelligent and advanced scheduling and routing functions that will ensure efficiency, cost reduction and quality of service provision in the long term. Then, in order to provide added-value that would give leverage to a small-scale company in a highly competitive market, we shift our focus on the scheduling-routing component of the proposed information system framework. We review the proposed solutions and suggest the use of a novel approach for making joint optimized scheduling-routing decisions for freight companies based on the concept of the backpressure

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scheduling-routing algorithm inspired by its use in telecommunication networks [1], [2].

We believe that the set of requirements defined and proposed architecture for the information system of a small-medium logistics enterprise, as well as the backpressure approach for performing optimal scheduling-routing constitute a sufficient framework for providing such companies the required impetus in their daily operation, sufficient economy of scales and reduced operational costs. This in turn, can contribute to a sustainable operation despite the unpredictable and "bursty" nature of emerging demand challenges, and potentially create the substrate for expanding their operation and increasing the volume of their market share. The purpose of this paper is to set the stage for this framework and provide reasoning for the envisioned design. A detailed design, evaluation and implementation of such framework will be the topic of our future work within the framework of VELOS project under the call RESEARCH-CREATE-INNOVATE of the Operational Program Competitiveness, Entrepreneurship and Innovation, which has been co-financed by the European Regional Development Fund of the European Union and Greek national funds.

The rest of this paper is organized as follows. In section II we present some relevant works and distinguish the contribution of this paper. Section III studies the requirements of the proposed information system and discusses a candidate solution architecture for a holistic information system, while Section IV presents the proposed solution for optimal scheduling-routing of loads. Finally, Section V concludes the paper and provides directions for future work.

II. RELATED WORK

The term logistics refers to the transferring and storage of products in a company and across companies or locations. Logistics management focuses on providing the right amount of resources at the right time, to ensure the transfer-carrying capacity of each company can meet the demand of assumed freight contracts. In addition, such allocation of resources may be required to meet specific quality of service requirements, e.g., special handling of the shipment, expedited/priority delivery time, etc. Efficient logistics management can help a company lower expenses and increase customer satisfaction. This is particularly true for last-mile supply chain management. In effect, various works have proposed solutions for meeting partially the previously mentioned goals particularly in the context of dynamic scheduling and routing of parcels based on location and quality criteria.

Cheng et al. [3] propose an algorithmic approach that facilitates couriers' pickup scheduling based on the nearest-neighbour dispatching policy. The authors posit that their approach provide benefits for courier companies in terms of reducing both waiting and total service time. Along this line, Lee et al. [4] present a decision-making framework for on-demand parcel delivery services that considers both temporal criteria (on-time delivery) and environmental criteria (such as fuel consumption and carbon emissions). The proposed algorithmic approach adapts Markov chains to serve parcel delivery requests. The authors argue based on experiments that applying the proposed approach could increase a courier company's revenue by up to 6.4% while reducing fuel and emissions costs by up to 2.5%.

Lin et al. [5] develop a hybrid neighboring search algorithm that supports a dynamic courier routing model taking into account new orders and order cancellations optimizing both offline and online routes. According to the authors, the proposed model enhances the overall service level without increasing transportation and laboring costs. Lopez-Santana et al. [6] propose an approach to solving the dynamic shipment scheduling problem in courier environments by considering factors such as capacity, multiple periods, time windows, due dates, and overall distance. The authors propose a scheduling model that determines the visit date for each customer by considering the release date, visit due dates, and travel times.

In this paper, we attempt to provide a meaningful architecture for an information system, specially targeted for a small-medium logistics enterprise, with emphasis and providing leverage at the most important component of the system, namely that of scheduling and routing of freights. Designing such a component with a differentiating factor, which ensures jointly optimal decision-making, cost reduction and quality of service for various and diverse performance indices can provide leverage, and a potential increase in the market share, leading eventually to the expansion of such SMEs. As will become evident, the proposed framework can set dynamically different quality of service goals, e.g., faster delivery times, bounded backlog at warehouses, priority routing, etc., and meet such goals in a scalable manner.

III. REQUIREMENTS AND ARCHITECTURE FOR THE INFORMATION SYSTEM

In order to cope with the pressing computation, freight companies and especially SMEs are using information technology at various capacities, hoping to cope with the emerging challenges. The design of a proper information system, particularly for an SME, requires analysis of both user and business perspectives. In the following, we provide a short overview of such analyses.

A. User Analysis

Users of the system can be divided in two categories: *internal* and *external*. The first regard all the employees using the system in order to provide services, while the latter includes customers that will b requesting services and expect their packets to be transferred by the business. Internally, the users may belong to different departments and have distinct roles, e.g., front-desk, manager, warehouse, owner. External users may also have different requirements, but in this case the essential offered service is the same, so that the same amount/set of information is generated. Of course, the interfacing of different types of customers may differ according to the volume of requesting service, e.g., an ordinary user may access the system through a simple account-based web interface, while a customer with significantly larger volume could access the system through a specially developed API.

B. Business Analysis

With respect to the business part of the envisaged system, the essential modules that will be required to ensure the operation of the SME are the service management subsystem, freight handling and storage sub-system, system status monitoring and management, data management and analytics sub-system, scheduling an decision-making sub-system, user interaction components and fleet management (if a fleet is maintained by the SME). The overall concept of the architecture is depicted in Fig. 1, where the whole system is perceived in layers covering the human interaction, system interface, system core (which includes all data handling, analytics and decision-making), and physical implementation of the transferring.

The specific workflow in a typical use case, at least for the case of an SME, involves the following stages:

- Generation of freight quote - insertion of freight data in the SME's system
- Receipt of package
- Storage of packet at one of the SMEs premises (warehouse)
- Packaging of freight (depending on type of service selected)
- Scheduling and routing of packet in the distribution network
- Last-mile delivery to customer and feedback report

Regarding the modeling of the associated processes, we have identified a set of necessary and sufficient ones that need be detailed in every case of developing such a system:

- Generation of a freight - the customer scenario.
- Packet distribution optimization - the customer's perspective.
- Generation of a freight - the system's perspective.
- Packet distribution optimization - the system's perspective.

The corresponding parts of the system will include different functionalities, e.g., the optimization of the distribution from the system's perspective includes the development of scheduling and routing algorithms for optimal assignment of resources, storage management and cost reduction. Packet distribution optimization from the customer's perspective, includes proper handling of a freight and timely delivery.

From the above a specific functionality regarding the daily operation is emerging for the end-system that will need to be developed:

- Order registration.
- Route scheduling (via the scheduling-routing component of the system).
- Contractor selection (as in most cases SMEs rely on subcontractors for the actual transfer of freight.
- Fleet management and cross-docking. The latter refers to direct swap of freight between transfer means (trucks, trains, etc.) without intermediate storage.
- Inventory and backlog management at the warehouses and leased storage locations.
- Charging and accounting.
- Order search and tracking.
- Reporting, statistics and analytics.

In the following, we will focus specifically on the most important component of such a system, namely the scheduling-routing component. The rest of the sub-systems discussed will be part of our on-going work.

IV. SCHEDULING AND ROUTING COMPONENT

The scheduling and routing components of a logistics information system are the most important functional modules, constituting the core feature, which alone can ensure cost reduction, optimality and flexibility, and economies of scale. Routing regards the function of determining the intermediate stops that a freight needs to take in order to get from its source to its final destination. This value can be from zero up to a bounded number of intermediate stops, as the freight can be directly transferred to its destination, if feasible, or required to be stored in intermediate warehouses, trucks, ship containers, etc. Scheduling on the other hand involves the function of determining when is the appropriate time to route a freight towards an intermediate stop or final destination. For instance, it may be more efficient to store a freight in an intermediate warehouse for a couple of days and send it over to its final destination together with another freight with the same final destination, to avoid the duplicate cost of transferring the two loads separately, provided that there are no delivery time constraints for the first freight.

Thus, the joint scheduling-routing problem in logistic systems, as depicted in Fig. 2, regards essentially making decisions on which freight needs to be transferred from one point to the other at each time. In such environment, there are various locations, e.g., collection points, warehouses, public and private transfer platforms (airports, train stations, ports, etc.) forming between them connections via a specific connection means so that the connection between the two points is defined in a univocal manner, i.e., the connection can be through one transport medium such as truck, airplane, ship, etc., and there is only one route between the two points. This allows us modeling the map of locations and their interconnections with a simple graph, not a multi-layer one.

A. Scheduling in Logistics Systems

Scheduling in logistics refers to problems in which decisions on job scheduling and transportation are integrated into a single framework [7]. The work in [7] presents a logistics scheduling approach for two processing centers located in different cities. Each processing center has its own customers. When the demand in one processing center exceeds its processing capacity, it is possible to use part of the capacity of the other processing center subject to a job transshipment delay. The problem is modeled as a parallel-machine scheduling problem with transshipment between the machines, including different objective functions and constraints.

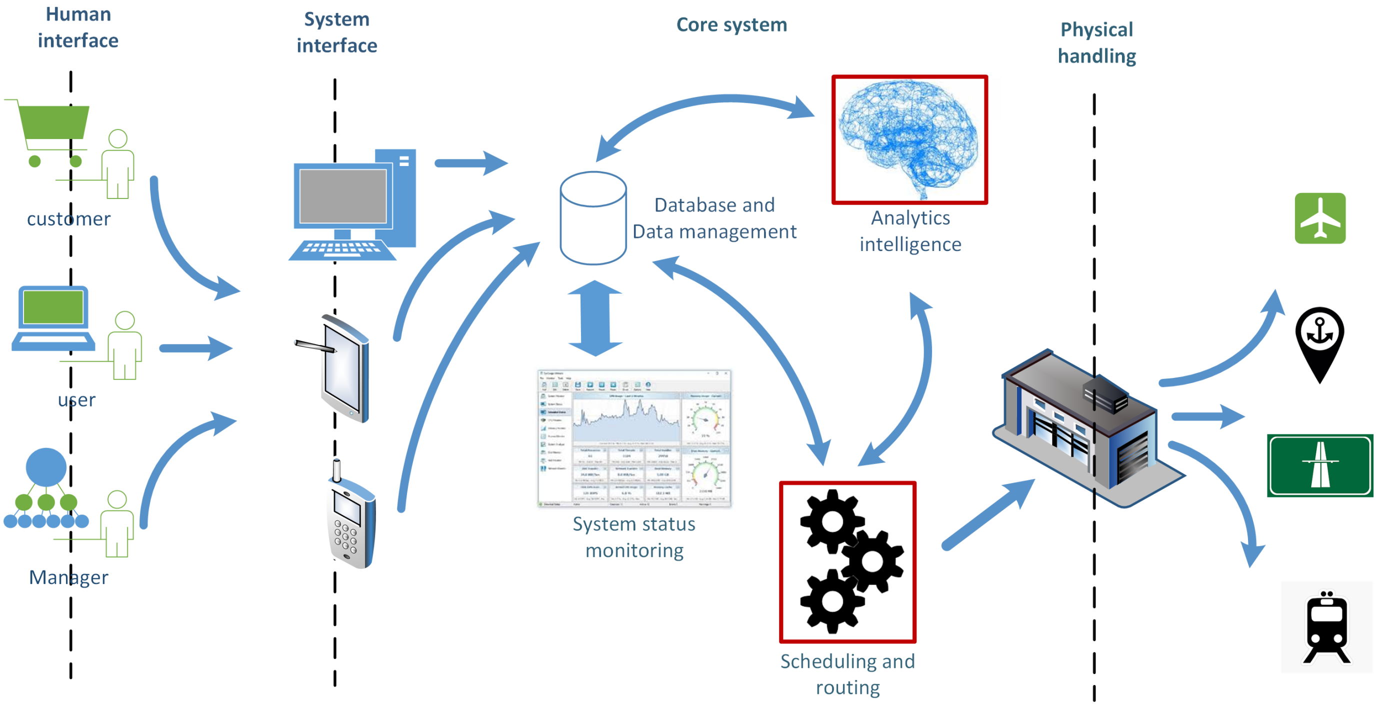

Fig. 1. Architecture of the proposed Information System.

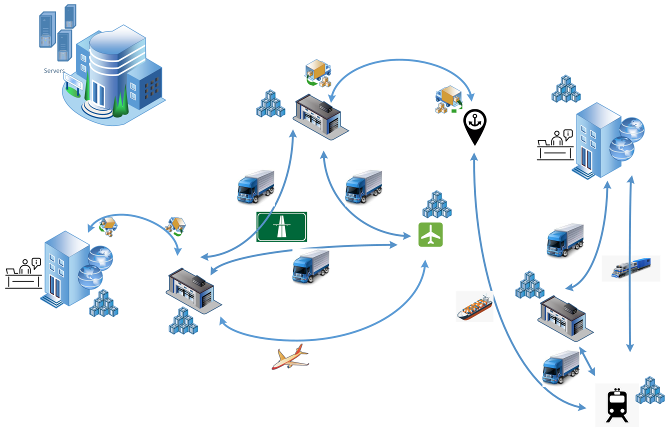

Fig. 2. The freight network as a simple graph.

Significant work has been done in the field of scheduling for supply chain management, namely the scheduling required for the transportation of shipments from their sources to their last-mile destinations. Reference [8] contains various such approaches, classified in different categories such as cooperative and non-cooperative scheduling, etc. As mentioned in [8], the field of supply chain scheduling is relatively new, approximately 20 years old, even though scheduling is a far older domain.

Scheduling in logistics have also considered another critical field of supply chain management, namely production planning. This joint consideration is meaningful in the case of large corporations producing various and diverse productions, e.g., vehicles, food products, etc. Production planning is a process to develop tactical plans based on setting the overall level of manufacturing output (production plan) and other activities to best satisfy the current planned levels of sales (sales plan or forecasts), while meeting general business objectives of profitability, productivity, competitive customer lead times, and so on, as expressed in the overall business plan. Application examples include the pharmaceutical and petroleum industries [9], [10], chemical processing [11], and computers [12].

In this work, we suggest a different approach for scheduling, based on the backpressure technique, proposed as an alternative in the field of logistics and supply chain management. This is the first attempt to apply the backpressure algorithm is this field, as it is described in the following.

B. Backpressure based Solution

In this subsection, we present the main concept underlying the backpressure joint scheduling-routing approach, which will be the core idea for our scheduling-routing component in the designed information system.

Consider a communications/data transfer network described by a directed graph $G = (N, L)$ with N the set of nodes (corresponding to the locations where freight is stored) and L the set of directed links (corresponding to the connections between locations). A link between nodes i and j is indexed by (i, j) and belongs in the set L. A flow represents an amount of freight (measured in a wuantity of interest, e.g., weight, volume, etc.) sent from a source node to a destination node and is indexed by f. There can be multiple flows between the same source-destination pair with different characteristics, e.g., priority level, type of packaging, and each one will have a unique index number f. Let F denote the set of all considered flows.

Let $r^f_{(i,j)}(t)$ be the amount of freight to be transferred over link (i,j) for flow f at time t with $\sum_{f\in F} r^f_{(i,j)}(t) \leq r_{\max}$. Each node i has a queue for every flow f, the length of which (e.g., number of shipments/amount of freight) at time t is denoted by $Q^f_i(t)$. If node i is the source for flow f, it generates traffic for f and let $a^f_i(t)$ stand for the amount of freight generated by i for flow f at time t. Let $a^f_i = \lim_{t\to\infty} \frac{\sum_t a^f_i(t)}{t}$ be the arrival rate of node i for flow f and $\mathbf{a}$ the arrival rate vector collecting the arrival rates for all flows.

Typically, each queue length evolves with time as:

$$Q^f_i(t+1) = \max\{Q^f_i(t) - \sum_{j\in N_i} r^f_{(i,j)}(t), 0\} + \sum_{j:i\in N_j} r^f_{(j,i)}(t) + a^f_i(t),$$

where N_i is the set of the one-hop neighbors of node i, i.e., for each $j \in N_i$, it holds that $(i,j) \in L$.

However, several works apply simplifications of the above queue evolution equation, which allow for obtaining theoretical guarantees for the corresponding backpressure schemes in more straightforward ways.

The conventional BP algorithm was first proposed by Tassiulas and Ephremides in [1] for a queuing network with interdependent servers (e.g., a multihop packet radio network). Before describing the BP algorithm, let us introduce the notions of network stability and of the capacity region, which are necessary in order to state the properties of the BP algorithm.

Queue and Network Stability. A queue is strongly stable if it holds $\lim_{t\to\infty} \frac{\sum_t E[Q^f_i(t)]}{t} \leq B$, with $B \geq 0$, a constant. A network is strongly stable if all its individual queues are strongly stable, [2].

Network Capacity Region C: The set of all arrival rate vectors $\mathbf{a}$ for which there exists a policy π, such that the system is strongly stable under π. A policy π is throughput optimal if it can ensure strong stability for all arrival rate vectors $\mathbf{a}$ in C.

The conventional BP algorithm performs a distributed per link routing decision and a centralized link scheduling decision over the whole network. In particular, first the routing decision is taken where each link chooses the flow that will be served if the link is selected for transmission. Then, BP takes the scheduling decision for which it solves centrally a maximum weight matching problem to select the set of links that will transmit the current time while accounting for transmission constraints (e.g., due to interference). In detail:

Routing step (distributed per links)

Each link (i,j) computes the backpressure for every queue, i.e., the quantity

$$\Delta Q^f_{(i,j)}(t) = Q^f_i(t) - Q^f_j(t) \tag{1}$$

Then, it chooses the maximum for all flows, i.e.,

$$\Delta Q^*_{(i,j)}(t) = \max_f\{\Delta Q^f_{(i,j)}(t)\} \tag{2}$$

Let f^* be the flow that achieves $\Delta Q^*_{(i,j)}(t)$ (ties break arbitrarily). If the link (i,j) is selected for transmission in the scheduling step of the BP algorithm, then node i will transmit from the queue $Q^{f^*}_i(t)$ to the queue $Q^{f^*}_j(t)$ at node j.

Scheduling step (centralized)

A maximum weight matching problem is centrally solved to select the links that will transmit, i.e.,

$$\max_{\forall I} \sum_{(i,j)\in I} r_{(i,j)} \Delta Q^*_{(i,j)}(t) \tag{3}$$

where I is a set of links that can transmit simultaneously. Let I^* be the set that achieves the maximum. Then, every link in I^* transmits packets of its selected flow in the routing step of the BP algorithm at time t.

Backpressure algorithm is a suitable approach for the purpose described in this work, due to its provable performance guarantees, robustness to stochastic network conditions, and, most importantly, its ability to achieve the desired performance without requiring any statistical knowledge of the underlying randomness in the network.

Limitations of the conventional BP algorithm: There exist some limitations of the conventional BP algorithm that, despite its simplicity and its inherent suitability to our problem, hinder its direct application as a solution approach and pose the need of adaptations. These are namely [13],

1) Slow start phenomena when in slightly loaded network conditions packets follow unnecessarily long routes.
2) Routing loops that may lead to high packet transfer delays.
3) Last packet problem, in absence of consistent backpressure toward the destination (for low rate flows or short-lived flows).
4) The fact that in a realistic setting, the queue size is finite and fixed, whereas in the conventional BP queues have infinite sizes.

Our design will also take into account various quality of service criteria, relevant specifically to logistics and freight shipping, e.g., bounded delivery end-to-end times, bounded backlogs at the node queues (warehouses), expedited shipments, etc., which can be naturally accommodated by the backpressure approach, by analogy to the quality of service guarantees provided in communication networks, e.g., [**?**], [13]. Our design will modify the original (conventional) backpressure algorithm, allowing for incorporating pricing mechanisms, which can be used for ensuring additional features, e.g., priority and expedited handling.

V. CONCLUSION

In this paper, we presented a holistic framework for developing an information system specially targeted for a small-medium logistics enterprise, aiming towards a fully functional and scalable operation, capable of reducing daily costs, while providing perspective for expansion of the carrying capacity of the company. We provided specific requirements that the targeted system should satisfy and then focused on identifying the most appropriate solution for the scheduling-routing module.

We believe that having available an efficient optimized routing-scheduling mechanism can provide leverage and scalability to such companies. We reviewed some of the most corresponding works, and we presented a framework for developing on backpressure based optimal algorithms for scheduling-routing freights.

As part of our ongoing work, we are developing a fully functional backpressure based module and we will demonstrate its operation in a realistic setting, while developing a prototype for the proposed holistic information system. Finally, we will extend the proposed backpressure scheduling-routing approach to scenarios where specific quality of service requirements are posed and the proposed algorithm can meet them in a flexible, dynamic manner, as e.g., applied in [13].

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