Minimizing logistics risk through real-time vehicle routing and mobile technologies

Research to date and future trends

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Abstract *Vehicle routing (VR) is critical in successful logistics execution. The emergence of technologies and information systems allowing for seamless mobile and wireless connectivity between delivery vehicles and distribution facilities is paving the way for innovative approaches to real-time VR and distribution management. This paper investigates avenues for building upon recent trends in VR-related research towards an integrated approach to real-time distribution management. A review of the advances to-date in both fields, i.e. the relevant research in the VR problem and the advances in mobile technologies, forms the basis of this investigation. Further to setting requirements, we propose a system architecture for urban distribution and real-time event-driven vehicle management.*

1. Introduction

Supply chain management processes can be classified in two major categories: planning and execution. While supply chain planning (SCP) embraces the processes related to forecasting materials requirements, planning for production and distribution, and so on, supply chain execution (SCE) focuses on the actual implementation of the supply chain plan, comprising processes such as production and stock control, warehouse management, transportation, and delivery (Ballou, 1978; Lambert *et al.*, 1998).

SCP has attracted significant attention over the last two decade s, due to its critical impact on customer service, cost effectiveness, and, thus, competitiveness in increasingly demanding global markets. As an outgrowth of the research advances in this area, a number of technology-enabled systems have also emerged to assist in SCP operations – including materials resource planning (MRP), manufacturing resource planning II (MRP-II), and enterprise resource planning (ERP) applications, as well as integrated SCP information systems.

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SCE has, conversely, received less attention at least as far as real-time decision making and risk management are concerned. While processes such as stock control and warehouse management have been thoroughly investigated and supported by applications such as warehouse management systems (WMS), improvement opportunities still lie in the area of distribution management (Min *et al.*, 1998; Ghiani *et al.*, 2003; Ioannou *et al.*, 2003). In this area, most extant work has focused on optimally allocating vehicles to known delivery demand under a priori assumed conditions. Conversely, limited research has to date been devoted to the real-time management of vehicles during the actual execution of the distribution schedule in order to respond to unforeseen events that often occur and may deteriorate the effectiveness of the predefined and static routing decisions. Such events, that create a dynamically changing problem state, include traffic conditions, vehicle-related incidents (for example, breakdowns), market-triggered events (for example, changing customer orders or delivery times), and so on.

This latter area is the focus of this paper, which investigates how technological advances in the fields of mobile and wireless computing can be employed towards an integrated architecture for mobile-enabled real-time distribution management applications. The paper reviews selected bibliography in vehicle routing in light of recent technological developments and proposes a generic architecture for mobile real-time decision support systems (DSS) for urban distribution. The structure of the paper is as follows. Section 2 examines the characteristics of urban distribution, while Section 3 critically examines relevant research in the vehicle routing problem (VRP) and vehicle routing systems (VRS). Section 4 raises the need for real-time VRS incorporating mobile and wireless technologies and proposes a general system architecture. Section 5 concludes with a discussion on future research directions towards the development and implementation of the proposed architecture.

2. The urban distribution environment

Distribution is a key logistics activity and contributes, on average, the highest portion to the total logistics-related costs (Ballou, 1999). Distributors face complex problems of:

- determining the optimal number, capacity, and location of facilities serving more than one customers; and
- finding the optimal set of vehicle schedules and routes (Min *et al.*, 1998).

One may distinguish at least two ways for distributing goods in an urban distribution scenario: standard deliveries and ex-van sales. While both cases use a typical delivery network with N warehouses that deliver to M customers through a fleet of K vehicles, they differ in the way they handle demand. Standard deliveries are based on a known demand (usually driven by pre-placed customer orders), while ex-van sales operate in an unknown demand environment where orders are being placed during the truck's visit to the customer site. Table I summarizes the main attributes of the two modes of urban deliveries.

The performance of either urban distribution model may deteriorate significantly due to a number of factors (Min *et al.*, 1998). No matter how well the initial delivery plan has been designed, a number of unforeseen events inevitably occur during the distribution execution stage, thereby resulting in a need to make real-time adjustments, such as truck re-routing and delivery rescheduling (Brown *et al.*, 1987; Rego and

Rucairol, 1995; Savelsbergh and Sol, 1998) in order to adapt to the new conditions and achieve the objectives of the initial plan as closely as possible. In the case of standard deliveries, such events may include traffic congestion, ramp overload at points of delivery, truck breakdowns, unforeseen reverse logistics requests (for example, goods returns), and others (Ghiani *et al.*, 2003). This situation may become even more complex in the case of ex-van sales, where inefficiencies usually stem from the inherent demand/route uncertainty of the model, raising complex requirements for real-time decision-making. For instance, if a vehicle has disposed of its entire inventory in the first few points of sales due to unexpectedly high demand, it may be beneficial for another vehicle (carrying excess inventory) to be re-routed in order to accommodate the increased sales needs in the first vehicle's area. Other issues in ex-van sales involve requirements that arise for real-time connectivity with back-end company systems, in order to support processes such customer credit control, invoicing, and so on.

From the above, it becomes clear that, while an efficient initial routing plan is necessary, it is by no means sufficient to minimize risk in high performance distribution systems. Initial routing plans need to be complemented by the ability to make and implement sophisticated decisions in real-time in order to respond effectively to unforeseen events. We contend that this requirement may be facilitated by innovative technology-augmented approaches combining inter-vehicle wireless communication, back-end wireless connectivity with the distribution center, and real-time decision support.

The relevant research to date in the area of real-time distribution management is reviewed in the next section. This research is part of the extensive VRP literature and is classified and reviewed from the perspective of forming the basis for further work and/or the development of relevant real-time vehicle routing management systems.

3. Relevant literature on VRP and VRS

3.1. Parameters of the real-time VRP

Many problems in the area of goods transportation by vehicle fleets can be modeled, to a certain extend, within the VRP framework (Figure 1). The focus of the typical VRP is the design of routes for delivery vehicles that operate from a single depot and supply a set of customers at known locations, with known demand. Routes for the vehicles are usually designed to minimize the total distance traveled (or a related cost function). Bowers *et al.* (1996) present the formulation of the typical VRP.

Standard deliveries	Ex-van sales
Fixed geographical layout	
Fixed distribution center capacity	
Fixed truck capacity and fleet	
Known demand per sales point	Unknown demand per sales point
Fleet delivers based on orders	Orders are not known in advance (only sales area is)
Fixed schedules and delivery time windows	More relaxed schedules and delivery time windows
Truck routes determined a priori based on demand, network traffic, and other parameters in a near-optimal way	Distribution of work per truck is based on past area sales and business agreements with the drivers

Table I. Characteristics of standard deliveries vs ex-van sales in urban distribution

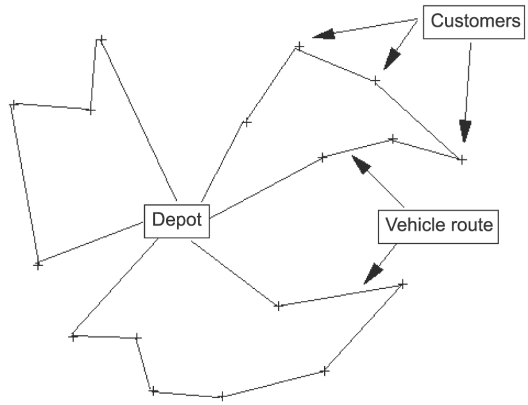

Figure 1.
Schematic representation of the typical vehicle routing problem

In an effort to model and address important practical issues, the fundamental VRP has been extended in a number of aspects. Indeed, one can distinguish no less than nine topics of critical practical importance that raise considerable challenges in VRP-related research and are all closely related to the real-time vehicle management problem:

(1) *Number of stages*: While the single-stage VRP (delivery only) is primarily concerned with the establishment of outbound delivery routes, the double-stage VRP considers both delivery and pickup, i.e. outbound and inbound distribution. The latter is a salient feature of real-time distribution, since reverse logistics may necessitate adjustments to the original schedule depending on the truckload and its capacity. For a treatment of the two-stage VRP see Savelsbergh (1995) and Yang *et al.* (2000).

(2) *Deterministic vs stochastic supply/demand*: The deterministic VRP assumes that demand/supply is known a priori, while the stochastic VRP encompasses uncertainty in demand and/or supply levels (Min *et al.*, 1998). As discussed above, demand uncertainty is a key characteristic of ex-van sales (see Section 2).

(3) *Fleet size*: We can differentiate between cases of single vehicle and multiple vehicles. As the number of vehicles in the delivery fleet is increased, the problem size, as well as the computational complexity, increases accordingly. It is clear, that the multiple vehicle case is appropriate in the real-time vehicle management problem, since many contingency measures involve the cooperation between vehicles through appropriate inter-vehicle communication infrastructure.

(4) *Vehicle capacity*: There exist formulations for both the capacitated VRP (CVRP) and the uncapacitated VRP depending on whether vehicle capacities are considered. The CVRP, as presented for example in Toth and Vigo (2002a), is perhaps among the most widely researched variations of the problem. Capacity considerations are important in the case examined here, especially in view of reverse logistics, in which the capability of the vehicle to respond to the customer need depends on its available capacity.

(5) *Planning horizon*. The static VRP takes into consideration a single planning period (for example, solving the distribution problem for next day's deliveries),

while the dynamic VRP considers optimal solutions in multiple periods. In this case the initial schedule can be adjusted, according to the current needs for distribution (Laporte, 1988).

(6) *Time windows*. A classical variation of the VRP refers to the consideration of time windows, outside which deliveries cannot be accepted. Time windows can either be "hard", when they cannot be violated, or "soft", in which case violations are accepted but penalized. A recent analysis of the VRP with soft time windows has been provided by Ioannou *et al.* (2003). Time windows present one of the most common causes for the need of real-time incident management.

(7) *Objectives*. There exist single-objective or multiple-objective formulations of the VRP. The most common VRP objective is to minimize the total cost of deliveries. However, additional objectives might be considered, such as minimizing number of depots or maximizing customer satisfaction (Renaud *et al.*, 2000; Fisher, 1994).

(8) *Source of data*: Proposed approaches for addressing the VRP are tested either through artificial data sets, constructed for this purpose, or through data collected via case studies. The latter are typically richer in terms of subtle issues that may affect either the approach or the quality of the solution.

(9) *Algorithmic approach*. The VRP is an NP-hard problem (Garey and Johnson, 1979; Lenstra and Rinnooy Kan, 1981; Dror and Trudeau, 1990) and, thus, cannot be solved to optimality within reasonable time (for problems of practical size). This fact has prompted the development of heuristics that started to emerge in the 1970s (Christofides and Eilon, 1969; Yellow, 1970; Wren and Holliday, 1972; Ashour *et al.*, 1972; Gillett and Miller, 1974), which still comprise a significant research area (Laporte, 1992; Breedam, 1995; Hachicha *et al.*, 2000; Laporte *et al.*, 2000). A recent example of a meta-heuristic tabu search method for the VRP has been presented by Ho and Haugland (2004). Exact solutions have also been developed, however they can only be applied to vehicle routing problems of limited complexity (Reimann *et al.*, 2003). In fact, exact algorithms are challenged by problems with more than 50-75 customers (Toth and Vigo, 2002b). An example of an exact, branch-and-bound approach is presented by Fisher (1994), where the solution approach uses the minimum k-tree approach.

The above topics have received different degrees of attention in the large body of VRP literature. Table II includes relevant papers and indicates that, while specific cases of the VRP have been rather extensively addressed in the literature, others do not seem to have attracted similar attention. For example, relatively limited attention has been paid in topics, such as the double-stage delivery and pickup case, stochastic demand/supply, time-windows, multiple objectives, and application-driven vehicle routing problems. At the same time, more than approximately two-thirds of the approaches employed use heuristics, while exact approaches can be found in about one-third of the cases. It is also pointed out that the problem of ex-van sales, which incorporates several complexities, such as uncertain demand, multiple planning horizons, time windows, and others, has yet to be fully addressed in the literature, despite being an important practical case with significant potential for improvement.

Table II.
VRP taxonomy and classification

	Number of stages A	B	Nature of demand/ supply C	D	Fleet size E	F	Vehicle capacity G	H	Planning horizon I	J	Time windows K	L	M	Objectives N	O	Source of data P	Q	Algorithmic approach R	S
Ashour *et al.* (1972)	✓		✓		✓		✓		✓		✓			✓		✓			✓
Gillett and Miller (1974)	✓		✓			✓		✓	✓		✓			✓		✓			✓
Robuste *et al.* (1990)	✓			✓		✓	✓		✓		✓			✓		✓			✓
Vliet *et al.* (1992)	✓		✓			✓		✓	✓				✓		✓		✓		✓
Fisher (1994)	✓		✓			✓		✓	✓		✓			✓			✓	✓	
Koksalan *et al.* (1995)	✓		✓			✓		✓	✓		✓			✓			✓	✓	
Savelsbergh (1995)		✓	✓			✓		✓		✓	✓			✓		✓		✓	
Bowers *et al.* (1996)	✓		✓			✓		✓	✓		✓			✓		✓			✓
Beasley and Christofides (1997)	✓		✓			✓	✓		✓		✓			✓		✓		✓	
Modesti and Sciomachen (1998)	✓			✓	✓		✓		✓		✓				✓		✓	✓	
Barbarosoglu and Ozgur (1999)	✓		✓			✓	✓		✓		✓			✓		✓	✓		✓
Van der Poort *et al.* (1999)	✓		✓		✓		✓		✓		✓			✓		✓		✓	
Coy *et al.* (1999)	✓		✓		✓		✓		✓		✓			✓		✓			✓
Larsen (1999)	✓		✓			✓	✓		✓				✓	✓		✓			✓
Secomandi (2000)	✓			✓	✓			✓		✓	✓			✓		✓		✓	
Renaud *et al.* (2000)	✓		✓		✓			✓	✓		✓			✓		✓			✓
Nanry and Barnes (2000)	✓		✓			✓		✓	✓				✓	✓		✓			✓
Yang *et al.* (2000)		✓		✓		✓		✓		✓		✓		✓		✓			✓
Rego (2001)	✓		✓			✓		✓	✓		✓			✓		✓			✓
Fagerholt (2001)	✓		✓			✓		✓	✓			✓		✓			✓		✓
Glover *et al.* (2001)	✓		✓		✓		✓		✓		✓			✓		✓			✓
Toth and Vigo (2002a)	✓		✓			✓	✓		✓		✓			✓		✓		✓	
Tarantilis and Kiranoudis (2002)	✓		✓			✓	✓		✓		✓			✓			✓		✓
Tarantilis *et al.* (2004))	✓		✓			✓		✓	✓		✓			✓		✓			✓
Ho and Haugland (2004)	✓		✓			✓		✓	✓				✓	✓		✓			✓
Ioannou *et al.* (2003)	✓		✓			✓		✓	✓					✓			✓		✓
Coverage (%)	92	8	77	23	27	73	42	58	88	12	73	12	15	92	8	73	31	31	69

Notes: A = single stage; B = double stage; C = deterministic; D = stocastic: E = single vehicle; F = multiple vehicles; G = uncapacitated; H = capacitated; I = single period (static); J = multiple periods (dynamic); K = no time windows; L = soft windows; M = hard windows; N = single objective; O = mutiple objectives; P = hypothetical; Q = real-world; R = exact; S = heuristic

3.2. Real-time vehicle routing and VRS

Another area with significant potential for research is dynamic planning, especially dynamic re-scheduling and re-routing of vehicles, the relevance of which, has increased due to the emergence of technologies enabling real-time, high-bandwidth information exchange between fleet vehicles and/or between a vehicle and its headquarters. Real-time vehicle management depends strongly on significant information exchange supported by appropriate information system infrastructure. Information systems related to the VRP and VRS are reviewed below.

A number of VRS have been developed by the logistics community since the 1980's. These systems were essentially DSS (Belardo *et al.*, 1985; Evans and Norback, 1985), and included typical DSS elements; i.e. a database, an algorithmic engine, and a user-interface. During the same period, the evolution of information technology provided the opportunity to combine vehicle routing DSS with geographical data, in an image form, in order to enhance user support.

Brown and Graves (1981) have developed a system for real-time dispatch of petroleum tank trucks, whereas Powell (1986) has presented a stochastic model of the dynamic vehicle allocation problem, as well as a system for real-time optimization for truckload motor carriers (Powell, 1990). Brown *et al.* (1987) have presented a real-time wide area dispatching system for Mobil tank trucks and Ritchie and Prosser (1990) have developed a real-time expert system approach to freeway incident management.

During the 1990s, the emergence of geographic information systems (GIS) permitted the display and manipulation of spatial information, and, thus, supported the realization of a more comprehensive model of the road network, thus, allowing more realistic modeling of path constraints (Keenan, 1997).

Tarantilis and Kiranoudis (2002), present a spatial DSS to coordinate and disseminate tasks and related information for solving the VRP using a metaheuristic method. Its architecture integrates a GIS system, a relational database management system (RDBMS), and special software tools. Zografos *et al.* (2002) developed a DSS to address incident response logistics (IRL). The system provides functionalities including districting, dispatching of response units, routing of response units, and on-scene management. Gayialis and Tatsiopoulos (2004) developed a DSS that combines a supply chain management application with a GIS system and an ERP system to support planning and management of oil delivery trucks. Tarantilis *et al.* (2004) discuss a DSS that employs a metaheuristic algorithm for solving the open vehicle routing problem (OVRP); i.e. finding a set of routes to be used by delivery vehicles that do not return to the distribution center. Matsatsinis (2003) presented the design of a DSS for the dynamic routing of a ready-mix fleet. Last, but not least, Bertsimas and Van Ryzin (1991) presented a stochastic and dynamic VRP in the Euclidean plane and Savelsbergh and Sol (1998) discuss a system for dynamic routing of independent vehicles.

These systems present different approaches for addressing specific instances of real-time vehicle routing. However, they lack an analysis of the technological infrastructure needed to support real-time inter-vehicle and vehicle/headquarters communication, which is necessary to enable real-time information exchange and decision making. Such an analysis yields important findings regarding the type of algorithmic approaches that can be realistically implemented in a cost-effective fashion to support real-time vehicle routing, as well as regarding the technologies that can support these algorithmic approaches. In the next section, we present the results of such an analysis, synthesized into a generic architecture for real-time VRS.

4. A generic architecture for real-time VRS

4.1. Real-time vehicle management framework

Most solution approaches to the VRP are in practice implemented in a centralized computer resource (normally at headquarters), producing a daily plan to be provided to the vehicles before the beginning of the distribution execution. Some of these approaches have been implemented in commercial systems that are successfully used by numerous transportation, logistics, and manufacturing companies over the last 20 years.

These systems have not, however, been designed to address the case in which the execution of delivery cannot follow the plan as prescribed, due to some unforeseen event. When there is need for real-time intervention, it may be necessary to re-compute the plan using new input data. If a typical VRP approach is used for re-planning (i.e. re-planning the whole schedule from scratch), many vehicle schedules may be affected, thus causing significant performance inefficiencies (high overhead, nervousness, errors, and high costs).

Thus, re-planning based on classical VRP solution methods may not be a realistic option. In the absence of algorithms capable of "isolating" the part of the VRP affected by the unexpected event in order to minimize the disturbance to the overall schedule, interventions are typically performed manually (for example, through voice communication between drivers and the logistics manager) and the quality of decisions taken is naturally affected.

The need for enhancing existing methods or developing novel approaches becomes clearer in view of recent advancements in mobile and positioning technologies. Using such technologies, information about unforeseen events may be transmitted when they occur directly from the affected truck(s) through a mobile network to headquarters and/or other parts of the fleet. Given an efficient re-planning algorithm, appropriate and implementable plan modifications may be transmitted back to the fleet in a timely fashion to respond effectively to the new system state.

The real-time VRP is depicted schematically in Figure 2, using control system formalism. The important issues regarding this problem can be classified in two groups: system issues and decision-making issues.

The system issues include the following:

- *Observation of the system's state*. This concerns the selection of the parameters to be monitored, such as truck position, truck speed, truck inventory, and so on. These parameters need to be regularly monitored, as they will trigger

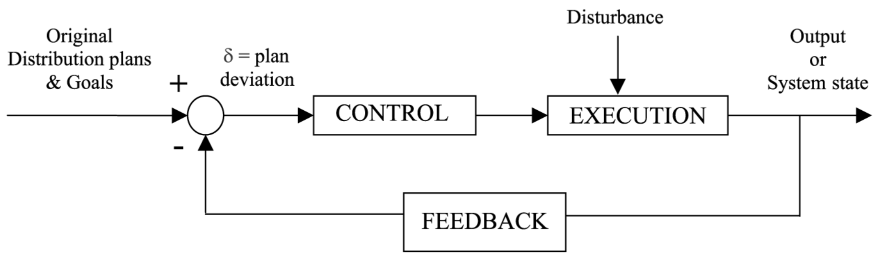

Figure 2.
Schematic representation of the real-time vehicle management problem

intervention if needed. It is noted that interventions may lead to system "nervousness"; thus, the cost of intervention should be balanced against expected benefits.

- *Type of interventions (local plan adjustments vs global re-planning)*. Global re-planning may lead to near optimal solutions, however, as discussed earlier, can also cause significant disturbances to the original routing schedule. Moreover, global re-planning imposes heavy communication overhead and additional costs to the system because all trucks need to report their current status (position, inventory, remaining part of the route) to the headquarters in order to provide new input data for the VRP. Finally, global re-planning also means heavy computing workload for the central system. Conversely, local plan adjustments may provide more cost-effective solutions without unnecessarily disturbing the overall initial plan. This benefit comes of course at the cost of needing to design more complex algorithms that decompose the VRP efficiently and solve only the affected part of the initial problem.
- *System objective.:* The selection of the problem objectives has significant effects on the intervention mechanisms employed. Objectives to be considered may include: minimize the deviation from the original plan, minimize the cost of non-conformance, minimize risk, and others.

Important decision-making issues include modeling of the real-time re-planning problem, and development of appropriate solution methods. In this case problem complexity and computational time play a significant role. The reduction of complexity appears to be a necessary condition in providing timely, implementable solutions. A classical way to reduce complexity is by using a hierarchical approach, whereby, a complex monolithic problem is decomposed, or disaggregated, to multiple, simpler problems that can be solved independently. The solutions of these lower-level problems are combined to yield the solution of the global, higher-level, problem. By doing so, one needs to consider the trade off between optimality and computational efficiency.

A critical issue in hierarchical approaches is the "goodness" of decomposition, or disaggregation, i.e. how to partition the problem in a way that favors near-optimal solutions. In the case of the VRP, decomposition should be based on the physical attributes of the problem. For example, spatial decomposition may be appropriate, since trucks in the geographical area within which an incident has occurred, may react easier to support the resolution of that incident.

An interesting, relevant approach for solving the VRP has been proposed by Reimann *et al.* (2003), who presented an algorithm that builds on the savings-based ant system. In addition to the way of decomposing the problem, an appropriate enhancement of this approach concerns the way the computation of the sub-problems proceeds. In the Reimann *et al.* (2003) work, the computations are performed sequentially fitting a classical model of developing an a priori delivery plan to be provided to the vehicles of the fleet at the beginning of the execution period. If a decomposition-based approach is to be used for re-planning in an almost real-time scenario, then the possibility of parallel computations that can be performed even by the truck on-board computer may be beneficial and should be examined.

4.2. System implementation issues

The model presented in Figure 2 can be realized through the use of mobile technologies, real-time decision-making algorithms (along the lines presented in the previous section), and back-office automated processing. In addition to providing the appropriate directions to the drivers of the fleet, the customer base may be kept informed, in regards to changes in the initial schedule, therefore improving service quality and customer relations of the company.

The proposed system architecture is shown in Figure 3. It comprises three major sub-systems. The back-end system consists of a decision-making module to facilitate automated decision making and ERP connectivity. The wireless communication sub-system allows a two-way communication between the back-end and the front-end systems. The front-end system enables:

- a robust user interface;
- local computations; and
- interaction between the software platform that is installed in the on-board truck computer and the company's back-end system.

Back-end sub-system. The back-end system is a DSS that incorporates algorithms needed for real-time routing, scheduling, and monitoring of the current state of the fleet, as well as a robust database containing both static (customers, geographical information of the road network, and so on), as well as dynamic (orders, quantities, time window information, and so on) data. The back-end system also provides ERP connectivity, which is especially useful in ex-van sales to provide information, such as customer sales history, customer credit, and other decision-critical data.

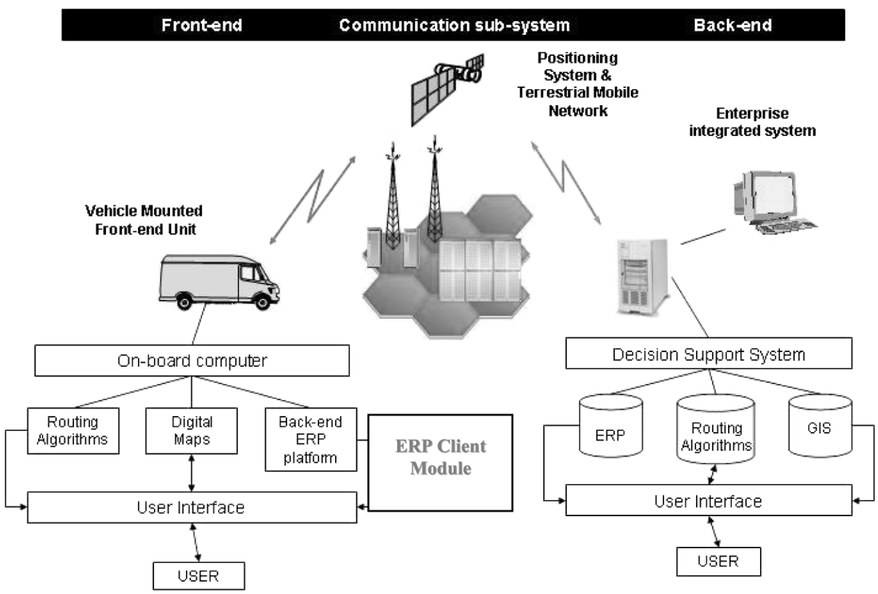

Figure 3.
Proposed system architecture for real-time vehicle management

Wireless communication sub-system. The wireless communication sub-system consists of two parts:

(1) the mobile access terrestrial network, which is responsible for the wireless interconnection of the back-end system with the front-end on-board devices, and

(2) the positioning system, which is responsible for vehicle tracking.

The mobile access terrestrial network can be based on any of a number of existing or emerging mobile technologies (illustrated in Table III). In examining the options available to support an integrated distribution system, bandwidth is perhaps the most important issue. The bandwidth requirements depend on the computational model chosen. If vehicle on-board devices support much of the computations, then the demand for bandwidth is different than in the case in which much of the computation is performed at headquarters. In either case, however, the demand for bandwidth is greater when compared to existing applications, such as fleet tracking, graphical representation of real-time information in digital maps, and voice communication.

GPRS, TETRA, and UMTS can provide always-on, packet-switched connectivity and high-speed data rates. GSM is a mature technology, however it cannot support high-data transmission effectively. GPRS combines high data rates, always-on connectivity, mature technology, and has also been used in fleet management systems. As far as TETRA is concerned, it is worth mentioning that it provides much better security than GPRS, as well as it supports point-to-multipoint voice broadcasting. UMTS is an emerging standard and its use cannot be assessed prior to thorough validation testing.

As far as the positioning system is concerned, positional accuracy of less than 100 m is deemed acceptable for urban distribution (accuracy requirements can of course be relaxed in non-urban settings). An analysis of the technologies that can be used for location identification goes beyond the scope of the paper (a complete taxonomy of such technologies is provided in Zeimpekis *et al.*, 2003), however Table IV illustrates the characteristics of some of the most widely-used technologies today. GPS appears to be the most preferable solution, since it is a globally available, free-of-charge system.

Type of mobile network	Availability	Maximum data rates	Data service provision
Global system for mobile communications (GSM)	Yes	9.6 Kbps	Circuit-switched
General packet radio service (GPRS)	Yes	144 Kbps	Packet-switched
Terrestrial trunked radio (TETRA)	Limited	36 Kbps	Packet-switched
Universal mobile telecommunications system (UMTS)	Limited	2 Mbits	Packet-switched

Table III. Mobile network access technologies

Network	Accuracy
Terrestrial beacon	Up to 50 m
Global positioning system (GPS)	100 m
Differential GPS	5-50 m
Low earth orbit (LEO) satellites	1 km

Table IV. Accuracy of positioning methods

Front-end system (access media). The front-end system generally consists of a mobile device, to which all necessary information is sent from headquarters or from other vehicles, and a tracking system that will be connected to the mobile device for the provision of routing information. The selection of the front-end device is important both from a user interface and from a computational performance perspective. The latter is required, since at least a part of the necessary computations will be performed on-board (e.g. route re-computation, or delivery re-scheduling), especially in those cases that a problem may be solved locally without affecting many other vehicles or routes.

Typical mobile devices that can be used on-board include mobile phones, personal digital assistants (PDAs), and tablet PCs. In their present state, mobile phones do not appear capable of coping with the requirements of the applications under consideration (e.g. digital maps, routing algorithms, back-end ERP connectivity). PDAs are already used for specific distribution applications such as back-end ERP connectivity. However, they have relatively small screens, and limited processing capabilities. On the other hand, tablet PCs seem to combine all features of mobile phones and PDAs and provide superior computational power. In addition, Tablet PCs include high-resolution displays, wireless networking capabilities, and integrated support for peripherals (such as bar-code readers).

5. Conclusions and research directions

Real-time vehicle management is important in supporting supply chain execution systems, and in minimizing the related logistics risks. It has been demonstrated that a good, near-optimal, distribution plan is necessary but not sufficient for high performance distribution. This needs to be complemented by the ability to make and implement sophisticated decisions in real-time in order to respond effectively to unforeseen events. The emergence of technologies and information systems allowing for seamless mobile and wireless connectivity between delivery vehicles and distribution facilities is paving the way for innovative approaches in addressing this requirement.

In order to develop robust, practical approaches to the real-time vehicle management problem, research efforts should focus on three fronts: systems design, decision support methods, and system implementation.

In the first area, significant issues to be tackled include: the definition of the system's objectives (minimize cost, risk and/or deviation from the original plan); the observability of the system's state; balance of intervention costs vs expected benefits; the extend of interventions (local vs global); and other parameters. System designs cannot be generalized beyond the extent achieved in this paper due to their heavy dependence on the characteristics of the problem addressed and the algorithmic approach chosen for intervention. Therefore, future research can assess alternative design specifications against real-life case studies of real-time vehicle routing problems.

In the second area, a review of the vast existing literature in the VRP has indicated that some research is relevant and can be used as the basis for the development of appropriate enhancements and/or novel decision support approaches in real-time vehicle re-planning. In this case, problem complexity and computational time play a significant role in system effectiveness. Hierarchical decomposition (or disaggregation) seems to be a promising direction, provided that the "goodness" of decomposition is appropriately addressed.

In the implementation area, it appears that there exist mature technologies to sufficiently address the requirements of the real-time vehicle management system. In terms of the communication subsystem, GPRS and TETRA are appropriate mobile access networks, while GPS technologies meet all the related positioning requirements. For the front-end system, tablet PCs have significant potential, since both their interface capability and the computational power support efficient user interaction, and the local computational system requirements, respectively.

All three fronts discussed above present interesting challenges with significant implications to both the VRP-related research and to the technology that will support effective logistics execution.

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