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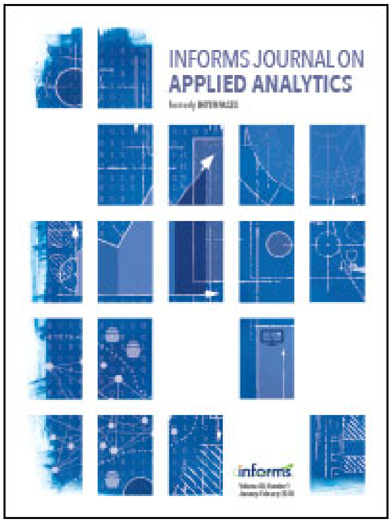

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State of the Practice: A Review of the Application of OR/MS in Freight Transportation

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Freight transportation is an important part of the global supply chain. As distances shipped grow and supply chains become more complex and fragile, operations research (OR) can play an important role in improving the efficiency and robustness of supply networks. This article describes the state of the practice in OR and freight transportation, highlighting recent successful and widely used analytical techniques in oceanic transportation and port operations, and barge, freight rail, intermodal, truckload, less than truckload, and air freight transportation, as well as the use of OR techniques in third-party logistics.

Keywords: freight transportation; oceanic; air; rail; truck freight.
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Freight transportation, an important part of global trade and supply chains, correlates strongly with economic growth. As suppliers, manufacturers, and markets become more global, freight transportation's importance is increasing. In the United States, for example, between 2000 and 2010, for-hire transportation grew 23 percent in real terms, from 2.9 to 3.1 percent of real gross domestic product (GDP), despite large gains in efficiency of operations (National Transportation Statistics 2012). This statistic is much more dramatic worldwide, because during approximately that same decade, international maritime shipping doubled, although none of the top 25 oceanic carriers reports the United States as its country of origin (National Transportation Statistics 2010).

Freight transportation is asset, labor, and fuel intensive. Managing variable and fixed costs in an inherently network operational structure creates vast and high-dollar complexities. Operations research (OR) has been used to help make informed decisions about managing these expenses and assets, and has had a large and growing role in the planning and execution of freight transportation services.

This article covers highlights of applied OR in oceanic freight, port operations, freight rail, truck-rail intermodal, truckload (TL) and less-than-truckload (LTL), and air freight and package delivery. Table 1 presents the structure we use in each section of the manuscript. Each section begins with a general introduction to the mode of freight transportation, discusses five topical areas, and concludes with a discussion of areas of opportunity for practical research. In some cases, a mode does not cover a topical area; thus, we skip it. Transportation network design and management planning and execution describe the OR models that consider the service and cost

General topic	Decision area (design or operational)	Oceanic freight	Rail intermodal	Truckload LTL	Air freight package
Network design and management	*Network design*	Line design; port selection			Hub location
	Network management	Vessel routing and scheduling	Load trip planning and train scheduling	Load planning	Aircraft routing-service design
Mobile asset planning and management	*Mobile asset planning*	Fleet size and mix	Locomotive planning		
	Mobile asset management	Empty containers	Rail cars and containers	Containers	
	Manpower management		Crew scheduling	Driver load matching	
Terminal management	*Terminal design*	Container terminal	Rail yard	Terminal layout	
	Terminal management	Container terminal operations		Door assignment	
Load management		Stowage planning	Train building		
Unique areas of research		Mode integration-hinterland operations planning	Line management-meet pass planning	Last mile of transport-flexible network infrastructure	Revenue management

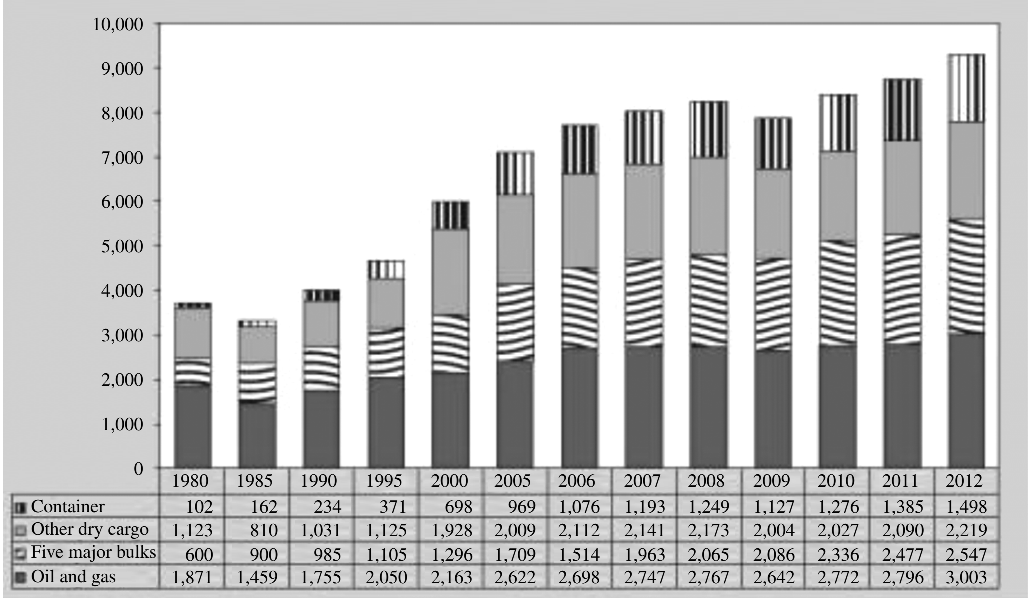
Table 1: We organized this paper by mode and topical area that tend to be common across modes. We cover each general topic area of freight transportation as it relates to each mode, but not all modes have successfully applied OR in all areas; those cells are blank. Accordingly, some sections do not cover all topics. Finally, despite their structural similarities, some areas of research are unique to all modes because of their idiosyncratic nature.

considerations in the transportation service networks, such as ocean freighter routing and scheduling, train makeup and scheduling, and load consolidation in LTL delivery. Mobile asset planning, allocation, and management describe the OR modeling used in the management of the mobile assets, such as locomotives, railcars, barges, tractors, trailers, and aircraft, required to create such transportation networks. Terminal or hub management describes OR applications used at the endpoints and consolidation points in a transportation network, such as ports, airports, rail yards, intermodal hubs, and LTL mixing centers. Load management problems describe OR methods used to assist in transportation decisions that govern the collection of customers on a single physical shipment, such as train building, plane balancing, stowage in oceanic shipping, and load planning in LTL transportation. Finally, some modes include unique topics of research, such as planning train meets and passes on congested rail lines or revenue management in air freight.

Our intention is to bring to light the critical recent role of OR in improving efficiency in freight transportation, with a primary focus on the past decade. We highlight successful applications, describe the most frequently implemented and successful methods, and suggest the best opportunities for further enhancing the role of OR in freight transportation. By presenting freight transportation research from different modes, we are able to compare and contrast the areas of focus in each mode.

Oceanic Freight Transportation

Oceanic transportation is the main driver of international freight transportation. More than 90 percent of all cargo is now transported across oceans and through man-made waterways (Henwood and Tan 2006). According to United Nations Conference on Trade and Development (UNCTAD) (2012), seaborne trade, divided across oil, major bulks, and dry cargo, reached 8.7 billion tons in 2011 (see Figure 1). The majority of dry cargo is carried in containers. Container trade is the fastest-growing cargo segment, growing at an average annual rate of 8.2 percent between 1990 and 2011. Container trade volumes reached 151 million 20-foot equivalent units (TEU) in 2011, or more than 1.4 billion tons. The total fuel consumed for oceanic freight transportation has also increased. Buhaug et al. (2009) report that the total annual fuel consumption grew to approximately 300 million tons, accounting for 3.3 percent of global carbon emissions in 2007. This is more than double the amount of fuel consumption in the previous decade (Corbett and Koehler 2003). According to the World



	1980	1985	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012
▮ Container	102	162	234	371	698	969	1,076	1,193	1,249	1,127	1,276	1,385	1,498
▨ Other dry cargo	1,123	810	1,031	1,125	1,928	2,009	2,112	2,141	2,173	2,004	2,027	2,090	2,219
▤ Five major bulks	600	900	985	1,105	1,296	1,709	1,514	1,963	2,065	2,086	2,336	2,477	2,547
■ Oil and gas	1,871	1,459	1,755	2,050	2,163	2,622	2,698	2,747	2,767	2,642	2,772	2,796	3,003

Figure 1: International seaborne trade has grown steadily across all cargo types. All units are in millions of tons loaded.

Shipping Council (2008), fuel costs represent as much as 50–60 percent of total operating costs.

In view of the economic importance of oceanic freight transportation and the impact it has on the environment, planning its operations significantly impacts its performance, and consequently the world economy. The converse relationship also holds; as a result of the recent financial crisis, shipping lines have been forced to slow down their ships to transport a lower amount of international freight. Oceanic freight transportation is confronted with many different challenges. In the *Network Design and Management* section next, we discuss these challenges and present some of the studies (mostly applied in practice).

Network Design and Management

Two important problems that shipping companies face are (1) network design and routing, and (2) scheduling ships that transport cargo. In the network design problem, given the demands, costs, and revenues of visiting different ports, a shipping company determines the ports a ship will visit. In the routing problem, the main decision is the sequence of ports that the ship must visit; in the scheduling problem, temporal and spatial aspects are considered simultaneously. Note that these problems are also coupled with the operational problem of cargo routing, in which the cargo to transport and the route the ship should take are determined. Indeed, the decisions made in each level affect each other. Because of specific characteristics of industrial (shipper-owned, usually liquid and dry bulk), tramp (volume-based contracts, tankers, and dry bulk), and liner (container and general cargo) shipping, the corresponding network design and management problems require different constraints and objective functions. Furthermore, such problems differ from those in other transport modes, because ships do not necessarily return to their originating location or operate 24 hours per day, seven days per week; in addition, the draft of a ship is a function of the load, as described by the overview papers Christiansen et al. (2004, 2007).

Furman et al. (2011) report that ExxonMobil typically charters between 60 and 70 ships to transport vacuum gas oil (VGO) from Europe to the United States. They developed a mixed-integer programming formulation for VGO routing and inventory management that enabled ExxonMobil to substantially improve its performance. As another example, the

Norwegian company Omya Hustadmarmor has saved $14 million per year by developing a decision support system to solve its fleet inventory routing problem. Its optimization problem is solved using a hybrid genetic algorithm (Dauzère-Pérès et al. 2007).

Speed is one key element in the problems we mention here. High-travel speed comes at a cost of increased fuel consumption and emissions. Recently, with higher fuel prices and a decrease in international demand, shipping lines have adopted a slow-steaming strategy and have reduced speed from 26 to 21 knots per hour (Dekker et al. 2012). This has resulted in a balance between demand and supply, as well as lower fuel consumption and emissions. Psaraftis and Kontovas (2010) look at the trade-offs between the environmental benefits associated with speed reduction and changes in the in-transit inventory holding cost and fuel cost, and conclude that reducing speed is beneficial if the market price of cargo at the destination is low. Corbett et al. (2009) explore the impacts of a fuel tax and a speed reduction mandate on CO_2 emissions. Using a profit maximization function that considers opportunity costs associated with speed reduction, they conclude that CO_2 emissions can be reduced by more than 70 percent in some routes when speed is halved, but the fleet must be increased.

Mobile Asset Planning and Management

Mobile asset planning. The design of the fleet size and mix is a major strategic decision in oceanic freight transportation. The objective is to minimize the fixed and variable costs of the operating fleet subject to practical constraints, such as satisfying the supply and demand. Sambracos et al. (2004) address the fleet size issue using a vehicle routing problem formulation for short-sea freight services with a homogeneous fleet; Fagerholt and Lindstad (2000) develop a model to plan deliveries to Norwegian petroleum platforms in the North Sea for a heterogeneous fleet, and find savings of several million U.S. dollars.

Mobile asset management. Empty-container deficits exist in exporting countries such as China, whereas the United States and European countries have excess empty containers. Compañí a Sud Americana de Vapores (CSAV), one of the world's largest shipping companies, has saved $81 million by optimizing its empty-container logistics (Epstein et al. 2012). CSAV developed a multicommodity, multiperiod model to manage container repositioning, and an inventory model to determine the safety stock required at each location. The company uses safety stock to ensure high service levels despite uncertainties, particularly in the demand for containers. A hybrid forecasting system supports both the inventory and the multicommodity network flow model.

Terminal Management

Terminals provide the necessary infrastructure for handling cargo, storing cargo, offering a maritime and land interface for export, import, and distribution activities, and providing extended transport links with the hinterland. In recent years, ports and terminals have been struggling to match capacity with increasing trade volume, and inefficiencies and congestion have become critical issues. Models are used to support decision making in many areas, such as terminal design and expansion, pre- and postarrival operations, storage, and terminal truck and rail interfaces; see Gharehgozli et al. (2013) for a recent review of OR models.

Terminal design and expansion. The terminal design process determines the dimensions of the terminal, including the length of the quay wall, handling technologies used at the quay side, internal transport and stack, vehicle transport paths, and the stack layout and size (number of blocks, and bays, rows, and tiers per block). Simulation is used most commonly in evaluating designs (Saanen and Valkengoed 2005). TBA, a terminal consultancy and software development company, has developed CONtainer TeRminal Optimized Logistics Simulation (CONTROLS), which aims to provide a simulated virtual-container terminal (Boer and Saanen 2012). It emulates the physical processes at a terminal, such as equipment and driver behavior, and generates operational scenarios that typically occur in practice. Using this tool to optimize terminal settings, they were able to reduce the truck turnaround time and improve straddle carrier productivity; however, optimization models are also successfully used to design and expand terminals. Kroes et al. (2013) discuss their development of cost-optimization models to estimate the container freight demand and analyze the viability of three port expansion strategies at the Port of Davisville. Their analysis supports establishing a short-sea shipping service between the Port of New York and New Jersey and the Port of Davisville.

Terminal management. Terminal operations planning and management can be split as the pre- and postarrival of ships, and integrated. Prearrival ship arrivals involve several tactical and operational decisions, such as allocating berthing space and time, and assigning and scheduling quay cranes (QCs) to handle containers. These three problems—berth allocation (BAP), QC allocation (QCAP), and QC scheduling (QCSP)—are solved using optimization models with the objective of minimizing the sum of ship waiting and handling times (port stay times, demurrage costs), subject to spatial, handling, temporal, and crane interference constraints (Bierwirth and Meisel 2010). Although these decisions have significant interrelationships, the three problems are often solved sequentially and in isolation. OR methods have found their way into practice here; Pasley and Race (2012) report about the use of berth-scheduling methods at tank terminals by Sabic and BP in Asia and Europe.

Postarrival, vehicles are assigned and scheduled to transfer containers from the quay side to the stack side (import), and containers are also transferred from the stack side to the quay side (export containers). At the stack, containers are stored temporarily to wait for their targeted departure. Yard cranes (YCs) or straddle carriers are used to handle containers in this area. A survey by Wiese et al. (2010) using the data of 114 container terminals worldwide shows that 63.2 percent of all terminals use YCs for stacking.

Murty et al. (2005) explore integrated pre- and postarrival planning; they developed a decision support system for terminal operations at Hongkong International Terminals (HIT). The decision-making modules, which address problems in pre- and post-vessel arrival, internal transport, and storage and landside operations, are implemented in HIT's productivity plus program (3P) for daily operations. HIT has observed performance benefits in all areas of its terminal operations. Notably, HIT was able to handle an increase of approximately 50 percent in annual throughput without investing in additional infrastructure, thus saving approximately US$333 million in additional infrastructure costs. The turnaround time for external trucks (unloading or loading containers) decreased by 33 percent—from 60 to 40 minutes.

Load Management (Stowage Planning)

To gain economies of scale and increase ship utilization, containerships sail from one port to another (up to 20 ports) using a fixed route. At each port, thousands of containers may be loaded, unloaded, or repositioned. Shipping containers in such large quantities poses a difficult operational problem, which we call the container stowage problem (CSP). A stowage plan includes the placement of a container on a ship slot, which is described by a combination of the stack, bay, and tier numbers. The objectives of a good stowage plan are to minimize the port stay times of ships, ensure stability, obey stress operating limits of ships, and maximize the utilization of quay cranes.

To deal with the complexity of the CSP, most successful studies hierarchically decompose the problem into a multiple-port master-planning phase and a slot-planning phase (Kang and Kim 2002, Wilson and Roach 1999). They develop mixed-integer programming formulations and use (meta-)heuristics to obtain solutions. In practice, visualization and simulation tools are available for stowage planning. Aye et al. (2010) develop an automated stowage plan generation system that provides different options for visualizing the stowage and analyzing the allocation sequence. The heuristic algorithm embedded in the tool generates plans that maximize the stability of a ship and minimize its port stay time.

Unique Areas of Research: Integration with Land Transportation

The ever-increasing container transport volumes handled in seaports also lead to increases in hinterland transport. Veenstra et al. (2012) describe an extended gate project in Rotterdam. An extended gate is an inland intermodal terminal directly connected to a seaport terminal(s) with high-capacity transport connections. By closely collaborating with hinterland terminals, deep-sea terminals can balance flows and workload more efficiently over time and prevent negative external effects from the transport, including congestion in seaports or on motorways as a result of too much trucking.

Barge, truck, and train are the three main modes of hinterland container transportation. During the past decades, truck transport has been the dominant mode of transportation. At the terminal landside, many trucks must be loaded and unloaded every day. As a result, terminals often have long queues of trucks. Giuliano et al. (2008) report that the gate appointment system, in conjunction with extended gate operating hours, implemented at the Port of Los Angeles and Long Beach, reduced truck congestion by shifting 20 percent of the drayage movement from peak to off-peak hours.

Port authorities are currently prompting a modal shift from road to barge or train to reduce the pressure on the current road infrastructure and reduce greenhouse gas emissions. For example, one of the aims of the Port of Rotterdam Authority is to change the current truck-barge-rail split of 45-40-15 percent to 35-45-20 percent by 2035 (Port of Rotterdam Authority 2012).

For a country with easy access to waterways, barge transport is a competitive alternative to road and rail transport because of its ability to offer cheap and reliable transport services. Because barge and ship freight transportation are similar, the strategic, tactical, and operational problems (i.e., scheduling and routing) are comparable; however, specific practical constraints for barge transportation require new analytical methods (see Christiansen et al. 2004). One crucial condition for successful barge freight transportation is the alignment of terminal and barge operators. Currently, information exchange is lacking and agreements and schedules are often not kept. Neither terminal nor barge operators are willing to accept a centralized decision-making method in which a trusted party coordinates the activities of all barges and terminals. They are unwilling to share information and want to be autonomous. Therefore, online decentralized decision-making methods are much more suitable in this case. To achieve this goal, Douma et al. (2009) model the problem using agent-based planning systems and compare their approach with a central approach. Their experiments suggest that exchanging information on expected quay wait times can reduce the average tardiness per barge by almost 80 percent compared to a process in which no information exchange takes place. Further, their approach performs well compared to the centralized approach. The authors extend this idea in their later studies (Douma et al. 2011a, b). The insights from these studies are currently imbedded in a project entitled Barge Terminal Multiagent Network (BATMAN) that was implemented in the Port of Rotterdam (Mes et al. 2013).

Rail freight transportation has been considered comprehensively in both theory and practice, as we discuss in the following sections. However, rail operations occurring inside a terminal have hardly been studied; successful implementations of OR research are scarce. According to Boysen and Fliedner (2010), the main decision areas related to rail operations inside a terminal are (1) determining the bundles of trains and their sequence for entering the yard, (2) assigning each train to a railway track, (3) determining positions of the loading units on trains, (4) assigning moves of loading units to gantry cranes, and (5) determining the sequence of moves per crane. Each terminal operating system uses a different heuristic algorithm to make such decisions; see, for example, the Navis Rail Autostow software (Navis 2014).

Areas of Opportunity for Practical Research

Recently, many shipping companies have merged and share their fleets in a pool to increase their market power and flexibility (Sheppard Seidman 2001). In such a situation, they could apply cooperative game-theory modeling that analyzes the split of income and costs (Ergun et al. 2007). Furthermore, controlling large fleets, which are the result of mergers and pool collaborations, creates the need to modify and expand previous models on strategic, tactical, and operational decisions in oceanic freight transportation. Environmental routing and weather-routing modeling also hold promise; Lo et al. (1991) estimate that by exploiting ocean currents, the world's commercial fleet could reduce its annual fuel costs by at least \$70 million. According to the International Maritime Organization (IMO), a fuel and emission reduction of two to four percent could be achieved by weather routing (Bazari and Longva 2011).

Conversely, new terminals are being expanded with faster cargo- and container-handling equipment (larger and faster quay cranes with multiple hoists, lifting transport vehicles, and multiple yard cranes per stack). Technological advancements also require the development of new analytical models to test system performance during the design conceptualization process. Likewise, the effect of increasing drop sizes for large post-Panamax vessels (up to 18,000 TEU containers) on operational planning and port-handling requirements needs to be well understood. At an operational level, mathematical models are needed to study integrated port operations.

When studying the new terminals that are being developed, we notice that the layout of the internal transport area and the stack-block organization varies. Some terminals (e.g., the terminal at Pusan) use a stack-block orientation that is parallel to the quay, whereas the terminals in Rotterdam use a stack-block orientation perpendicular to the quay. Research is needed to understand the design trade-offs and the implications of design parameter settings on system performance (Roy et al. 2014).

Freight Rail and Intermodal

In the United States, freight rail is the most successful mode; in the past three decades, it has grown steadily as a result of the growth of internationalization, increase in fuel prices, and deregulation of railroads. In particular, intermodal (internationally, ship-rail and domestically, truck-rail) has grown, stressing the rail infrastructure.

Rail freight is the most capital intensive of the modes, because it is the only mode responsible for the physical plant (i.e., the rail and yard network); other modes do require maintenance of oceans, roads, and air—only the ports, airports, and trucking terminals in the network. For this reason, rail executives face constant pressure to wisely allocate resources among the five major rail asset and expense categories: line, yard, car, locomotive, and crew. With varying degrees of success, analytical models have been deployed in each of these areas to improve the efficient use of these assets; Gorman and Harrod (2010) and Harrod and Gorman (2011) provide background reading on rail operations and OR.

Network Design and Management

In freight rail, service design describes the assignment of cars to trains, and the trip plan (which is akin to an air freight itinerary) for each car in the railroad is the heart of rail operations planning, especially in the mixed-freight or merchandise business in which single rail cars are scheduled en masse across multiple trains.

Many attempts at sophisticated optimization approaches to service design have been developed and published; however, only a few recent works have been implemented. In practice, the standard service-design application in the rail industry is the multirail product described in the Canadian Pacific (CP) application in Ireland et al. (2004). The application undertakes a series of discrete steps, starting with forecasting, then a blocking (i.e., car aggregation) plan, then a train plan with day-of-week considerations, and finally a crew plan. This iterative, human-in-the-loop approach decomposes a complex problem into a series of simpler and more easily solved ones. The CP application reports to have saved the railroad US$170 million in fuel, crew, locomotive savings, and increased railcar velocity. More recently, Ahuja et al. (2007) discuss a sophisticated optimization approach used at the Burlington Northern Santa Fe (BNSF), CSX Transportation (CSX), and Norfolk Southern Corporation (NS) railroads for radical redesign of services, but do not discuss gains realized from the use of their tool.

Service design deals more with the planning of services; service execution deals with exception management. Because of the high flexibility of rail service and short horizons for decision making, OR models have been scarcely used to support such decisions.

Mobile Asset Planning and Management

Mobile assets—locomotives, crews, and railcars—have received a great deal of attention in the application of OR models in freight rail.

Mobile asset planning: *Locomotives.* The assignment of locomotives to trains is perhaps the most difficult problem in railroad modeling. Each locomotive has different attributes (e.g., horsepower, tractive effort) that make it more or less suitable for trains of specific lengths and weights, and for use with other locomotives of different attributes (i.e., consists). Because of the potential value to railroads (new locomotives cost about $2 million apiece), many railroads have tried implementING locomotive planning systems, but few have succeeded.

Ahuja et al. (2005) describe an application at the CSX railroad using very large-scale neighborhood search on a mixed-integer programming problem, which identified potential for higher locomotive utilization. The result was a fleet savings opportunity of 400 locomotives based on their modeling;

however, this exercise identified only the potential benefit of using a modeling approach. A notable current application in real-time locomotive management using approximate dynamic programming approach is being implemented at Norfolk Southern Railroad (Powell et al. 2012). This model is used for strategic planning to conduct sensitivity analysis of the relationship of locomotive fleet size to response variables, such as train delays and congestion. Powell et al. (2012) reports that the model is conducive to real-time planning, but claims no implemented benefits.

Mobile asset management: *Railcars and containers.* Empty-car distribution (the movement of an empty car to a shipper for its use) is likely the most successful and widespread use of optimization in freight rail. The problem is suitable for optimization techniques, because it is often modeled simply as a transportation or assignment problem (Gorman et al. 2011). Tight integration with production systems allows model results to be updated and disseminated rapidly as new information (e.g., new orders or empty-car releases) becomes available. It is an important and valuable problem, because empty-car distribution is essential for achieving good customer service and reducing empty-car miles, which are expensive and consume valuable train space.

The major U.S. railroads have all deployed successful railcar distribution systems (Gorman et al. 2011, 2010; Narisetty et al. 2008), and all report sizable savings. The CSX implementation reported in Gorman et al. (2010) saved CSX $51 million annually ($510 million since inception), and a reported $1.4 billion in capital avoidance from avoiding the purchase of new railcars. They also report a benefit to the U.S. public through reduced pollution and congestion, and improved safety. Narisetty et al. (2008) report a 35 percent return on investment from implementing an empty-car distribution system at the Union Pacific Railroad. Intermodal rail transportation combines multiple modes of transportation, often truck and rail. Railroads have implemented various decision-support tools for planning rail operations, and more recently, intermodal marketing companies (IMCs), which handle the sales and intermodal handoffs (rail and local trucking, known as dray, and container management) have implemented successful tools.

IMCs have shown considerable activity in OR, having recently deployed systems to help with near-term (one-to-two week) capacity planning and the assignment of container capacity to shipping companies and rail carriers. Particularly notable applications are the systems implemented by Schneider National, which Simão et al. (2010) report has saved $39 million per year and reduced late deliveries by 50 percent, and the Hub Group for which Gorman (2010) reports a three percent increase in revenue, a five percent increase in container velocity, and $11 million per year of cost savings.

Manpower management: *Rail crew scheduling.* Crew (manpower assignment to trains) modeling received little attention in U.S. freight rail until the past decade. Although the crew-modeling problem can appear to be relatively simple, it is drastically affected by labor rules, deviations in train schedules, and the expense of manpower imbalances, which cause held-away-from-home pay and repositioning (i.e., deadheading). Gorman and Sarrafzadeh (2000) was the first published work in U.S. freight rail on this subject; for a simple class of the crew-planning problem, the Santa Fe Railway implemented a dynamic programming approach. Gorman and Sarrafzadeh (2000) report a four percent savings on a set of crew districts through more advanced planning that allows a reduction in chronic imbalances and a lower-cost means of deadheading. Subsequently, Vaidyanathan et al. (2007) developed a more comprehensive methodology using multicommodity network-flow modeling; they claim promising results for a North American railroad based on case studies and strategic sensitivity analyses; however, at this point, it may not be implemented widely. In Europe, scheduled operations are more consistent; Jütte et al. (2011) describe a successful application of crew planning at DB Schenker. They report that the use of column-generation techniques (Desaulniers et al. 2005) quickly produces practical schedules, reducing the human effort required to create and modify schedules. They demonstrated to management that integrated planning with a model across business units resulted in potential savings of 12 percent over autonomous planning.

Terminal and Yard Management

Intermodal terminals, where truck meets rail, and rail yard operations, where trains are constructed, have received relatively little attention from the OR community.

Yard modeling has been based predominantly on queuing and simulation methods. Queuing models simplify many yard-operation complexities, but produce results that are not utilized widely in practice. Simulating yard operations requires carefully detailed and customized models to produce accurate results. For example, Lin and Cheng (2009) model a specific yard at the Norfolk Southern railroad and discuss operating rules and capital investment strategies based on their simulation. Because custom models such as these, which accurately match unique physical yard specifications, capabilities, and work content, are often required and accurate results are difficult to attain, the cost of building such models increases; however, the benefit decreases. Thus, practical yard modeling has been curtailed. Yard operations are often included only as delays in broader network models because they relate to the transference of cars between trains. Most research is either theoretical, dated, or both. Yards truly remain the black hole of practical OR and rail operations; most published theoretical research has done little for the practice of OR in rail yards.

Load Management (Train Makeup)

Relatively little research has been applied to the area of train makeup. One successful example of OR in practice in U.S. intermodal transport is known as the Oasis system (Feo and González-Velarde 1995); the Oasis system maximizes train capacity utilization through careful assignment of trailers to trains. Recent research by Lai et al. (2008) evaluates the fuel-saving benefit of building intermodal trains that are more aerodynamic through better assignment of containers to train slots. They estimate potential for millions of dollars of fuel savings on a major U.S. freight railroad through their approach.

Research Areas Unique to Rail: Rail Line Modeling

Only freight rail needs to manage congestion and plan capacity on the arcs (rail lines) in its network. Because line capacity is extremely expensive to maintain and add, rail line congestion is a constant challenge, and one that OR modeling can aid significantly.

Implemented rail modeling has successfully leveraged optimization and simulation techniques. Optimization methods are typically not used in any long-term planning (i.e., rail timetables) sense in freight rail because of schedule deviations, which are common, particularly in U.S. freight rail. The best example of optimization-based long-term schedule planning is the discussion by Kroon et al. (2009) of passenger rail in the Netherlands.

In U.S. freight rail in particular, optimization, known as computer aided dispatching (CAD), is typically used over a 3-to-24-hour horizon to help dispatchers plan the paths of currently moving trains through a train district. The objective function is generally to minimize (weighted) delay among the trains. The models are typically large-scale time-space networks that are solved via mixed-integer programming techniques. Because of the demanding systems and process integration requirements for such a real-time system, the most ubiquitous application is associated with Union Switch and Signal's (also known as Ansaldo STS USA) dispatching system, the optimizing traffic planner that Morariu et al. (2008) patented.

Simulation techniques are used to understand the long-term impact on train operations of significant changes, including adding new tracks, sidings, and crossovers, which give a train district additional capacity, or the impact of a significant change in train schedules. The rail industry has several standard rail-line simulation packages in wide use; however, few recent advances in methodology or application have been published. Welch and Gussow (1986) describe a notable but dated success in this area, a capital spending deferral of C$350 million at the Canadian National Railroad; this deferral is partly a result of rail-line simulation work.

Freight Rail and Intermodal Research Opportunities

By far the greatest challenge to OR modeling of freight rail problems is accounting for the variability and uncertainty of rail operations, particularly in the United States. Research has largely focused on deterministic problems, and its applicability and advisability in a practical setting can be questioned. As a result, planning tools have become less useful and implementable, and tactical decision support tools have become more short term and operationally focused. Models and decision support systems that can incorporate this uncertainty would be more useful for freight railroads.

The greatest opportunities for freight rail-based modeling lie in the integration of planning tools that have focused, up to now, on optimizing individual assets. To the extent service design can integrate locomotive, crew, car, yard, and line considerations in a more comprehensive and integrated fashion, natural frictions among the planning tools can be better resolved. As rail assets continue to be heavily utilized, the ability to price services as they relate to tight capacity constraints along multiple dimensions will be a modeling approach to improve rail profitability.

Truckload and Less Than Truckload

The truckload (TL) market is a large industry ($300 billion in 2012) in which many carriers operate profitably; the average operating margin for public carriers in the first quarter of 2012 was twice (6.6 percent) what it was in 2009 (three percent). The LTL market in the United States, however, is much smaller ($32 billion in 2012), and carriers are operating far less profitably; the average operating margin for public carriers was only 0.7 percent in the first quarter of 2012.

The primary distinction between TL and LTL freight is shipment size. A TL carrier typically deals with customer shipments (or sets of shipments) that (nearly) fill a trailer; thus, the carrier can dedicate a driver to the task of picking up a shipment at the customer's origin location and then transporting it directly to the customer's desired destination. TL freight is typically handled only at customer pickup and delivery locations, and its time in transit is primarily a function of the driving distance between those locations.

LTL shipments are typically much smaller than TL shipments, often requiring less than five percent of trailer capacity. To achieve high levels of trailer utilization, a LTL carrier must load a trailer with shipments from multiple customers (referred to as consolidation). The carrier accomplishes this by routing the trailer through a multilevel network of consolidation terminals that traditionally follow a hub-and-spoke structure. Thus, LTL freight often spends much more time in transit than TL freight, because it is routed through and held for consolidation with other freight at different consolidation terminals. Braklow et al. (1992) provide a more complete description of LTL operations. With customer demands for shorter service times (often one or two days as opposed to five business days in the 1980s), achieving high utilization through consolidation and meeting service demands become more challenging. Similarly, LTL freight may be transferred between trailers multiple times, increasing the risk of mishandling or breakage.

Network Design and Management

Powell and Sheffi (1989) discuss the design and implementation of a system for a load-plan design—the routing of LTL freight through a network of consolidation terminals to achieve high utilization. Their commercialized system, which is still available (and used) today, is based on a heuristic that repeatedly considers adding or removing transportation services between two terminals and evaluating the impact of doing so. One appealing aspect of this system to practitioners is that its add-drop nature enables it to be run in an interactive mode. Planners can review and accept or reject the freight-routing changes that the system suggests, and can quickly see estimates of how costs could change if their ideas for changes are implemented.

Prior et al. (2004) discuss how network-optimization software enabled Menlo Worldwide Forwarding (a freight forwarder whose transportation network includes both truck and air) to succeed in an environment of decreasing shipment volumes and complicated operating environments as a result of the events of September 11, 2001. They discuss how the company and Menlo Worldwide Technologies developed custom network-optimization software to integrate its truck and air networks when routing freight, and also consider service levels, weekday and weekend schedules, and other operational issues.

The software uses a two-phase approach. The first phase produces weekly schedules for aircraft with an assignment-type model that incorporates four of the five problems commonly present in airline planning: schedule development, fleet assignment, aircraft routing, and crew scheduling. Feasible aircraft routes, an input to this model, are generated based on origin-destination location pairs, freight volume projections, and other business and operational constraints. The second phase uses those weekly schedules and more accurate estimates of origin-destination freight volumes to determine shipment routes over the integrated air and truck network. By using this software, Menlo Worldwide Forwarding was able to increase its utilization by 30 percent, reduce its operating costs by 21 percent, and respond quickly to business disruptions.

Fleuren et al. (2013) discuss several OR-driven projects undertaken at TNT Express N.V., a business-to-business express delivery company that operates the largest express road and air network in Europe and also has networks in China, South America, Asia-Pacific, and the Middle East. The authors discuss the development of decision support tools for routing freight, designing customer-facing pickup-and-delivery routes, and sizing the company's air network with an understanding of the capabilities that the road network provides. Many of these tools use flow-based optimization models; using one tool, they solve (heuristically) the classical multicommodity flow model defined on a time-space network; using another tool, they solve a tactical service-network design model. Between 2008 and 2011, these projects saved TNT 207 million euros, and the team won the Edelman Award in 2012. The paper is particularly interesting for its description of how TNT introduced and integrated the use of OR techniques into its corporate culture and planning process, such that "OR is now an effective part of the core values at TNT Express" (Fleuren et al. 2013, p. 5).

Because TL shipments are typically routed directly from customer origin to destination, these shipments do not present the same network-design problem as LTL shipments; however, because of the chronically high driver turnover rates that carriers face, researchers (Üster and Kewcharoenwong 2011) began to look at designing networks of relay terminals (in which loads are handed off from one driver to another) that will yield more consistent routes for drivers and bring them home more often. The researchers propose a Benders decomposition-based algorithm that enables them to solve large-scale instances and derive insights into situations in which relay networks should be used.

Mobile Asset Allocation and Management

Mobile asset management: *Container fleet management.* For a LTL carrier, positioning empty containers for future shipments is a critical fleet-management issue. Because the position of containers is often dictated by the load plan, systems that design load plans often recognize how a change in the load plan will impact future empty movements when they are evaluating such a change. Although some systems (e.g., Powell and Sheffi 1989) recognize the impact of these changes through estimates (often based on dual variables), more recent research efforts (Jarrah et al. 2009, Erera et al. 2013) have explicitly modeled how routing freight impacts empty-container movements. The nature of many LTL operations is such that all freight located at a terminal and destined for the same terminal will visit the same intermediate terminals on their route to their destination. Mathematically speaking, this operating structure means that LTL service networks form directed in-trees, with a different in-tree for each destination terminal. These last two efforts are mathematical programming-based and exploit this structure; the first employs a column-generation-based heuristic (Desaulniers et al. 2005), wherein columns correspond to in-trees; the second uses a heuristic that repeatedly solves mixed-integer programs to generate new in-trees.

Manpower management. The route for a truckload shipment or load is typically fixed a priori; however, the driver to assign to deliver (or cover) that load from its origin to its destination must be determined. Typically, a carrier seeks to minimize the empty miles traveled by a driver to cover the load; choosing the right driver is often referred to as the load-matching problem. At any point in time, a large carrier may need to cover hundreds of loads and may have hundreds of drivers available for assignment. Also, the problem is inherently dynamic because shippers often make requests for transportation only a few days in advance. More realistic models of the problem consider issues such as drivers needing to return home on a regular basis and (or) restrictions on the skills a driver must have to cover a load.

Powell et al. (2002) discuss what they deem a moderately successful project to implement a real-time dispatching tool at Burlington Motor Carriers; the tool allows the company to rank drivers who can cover loads. The paper is particularly notable for its focus on the challenges associated with convincing dispatchers to accept the tool's recommendations and the carrier to fully realize the predicted savings. They conclude that dispatchers ignored the tool's recommendations primarily because they possessed information that (1) the tool did not have (e.g., a driver has requested a specific destination), or (2) the tool could not model accurately (e.g., a soft time window based on a customer request).

Powell et al. (2002) also developed the capability to resimulate a day's worth of dispatches and compare the tool's recommendations with the decisions made by dispatchers. Because the objective function of the model is a weighted aggregation of different objectives, this capability enabled them to tune the weights without relying on oral feedback. They were also able to study the sensitivity of the savings that the carrier realized to the rate at which dispatchers adopted the tool's recommendations. With a detailed analysis, they found that using a normal acceptance rate (i.e., 70 percent), the tool's recommendations did not yield significantly greater savings than the dispatcher's own decisions.

Simão et al. (2010) also focus on the load-matching problem, albeit from a different perspective. Instead of a real-time decision support tool, they discuss an approximate dynamic programming-based (Powell 2007) simulation model of Schneider National's operations (Schneider is one of the three largest TL carriers in the United States); the model captures dispatcher decisions, driver behaviors, and load requests. Using this simulation model, Schneider was able to determine that a driver retention strategy that would allow drivers to spend more time at home would have a negative impact of $30 million on operating costs. By using the model, Schneider was able to derive a policy that had a similar effect, but at a cost of only $6 million. Similarly, the model enabled Schneider to quickly evaluate the impact of new rules from the U.S. Department of Transportation regarding driver work schedules. It improved its annual profits by $5 million by implementing hiring practices for new drivers based on an understanding of the cost of needing to return a driver to his (her) home. Although this paper and its companion (Simão et al. 2009) represent a significant advancement in solution methodology, it is also notable for its emphasis on model calibration to historical performance.

Terminal and Hub Management

At LTL terminals, shipments are often cross-docked or unloaded from inbound trailers, parked at docks, and then moved (often by forklift) to docks where they are then loaded onto outbound trailers. Thus, the layout of such a terminal and the dock to which an inbound trailer is assigned can have a significant impact on the cost and time required for cross-docking.

Terminal design. Bartholdi and Gue (2000) propose a model for designing the layout of a terminal where freight is sorted and transferred between trailers. The goal of this model is to minimize congestion, thus increasing worker productivity and reducing labor costs. They report that the implementation of a layout prescribed by their model in one terminal yielded annual savings of $67,000.

Terminal management. Rosales et al. (2009) focus on the truck-to-door assignment problem for Transfreight, LLC, a third-party logistics provider that specializes in lean logistics and traditionally used a manual planning process for assigning trailers to docks. The authors propose a mixed-integer linear program for allocating inbound trailers to docks at cross-dock facilities. They report that using their model for one facility resulted in annual savings of $60,000, not including the savings related to a much less labor-intensive planning process. They also compare a spreadsheet implementation of their model, which is closer to Transfreight's current planning process, and an implementation involving more sophisticated optimization software, which shows that significantly greater savings can be achieved by using the more sophisticated approach. These results have persuaded Transfreight to consider using this software in other operational contexts.

Unique Areas of Research: Covering the Last Mile with a Flexible Infrastructure

Truckload transportation is somewhat unique to ground transportation. This is partially a result of economics; one customer's shipments will rarely fill enough containers to make it economical to transport them directly from origin to destination by air, rail, or sea. In addition, ground is often the only mode that can carry freight the last mile to the customer's door. Carriers can see this as an opportunity to interact with customers. Because of this opportunity, researchers have begun to expand cost-based planning models to include customer service-related objectives or constraints. As an example, the work on the consistent vehicle routing problem (Gröer et al. 2009) considers both transportation costs and the desire of the organization to develop and nurture relationships between its customers and drivers. Also, this last mile may require delivery in an urban environment, an environment that often necessitates different strategies for cost-effective and socially acceptable transportation. The field of city logistics (Crainic et al. 2009) focuses on planning models and methods for freight transport (typically ground based) in this context.

Ground transportation also provides more opportunities to alter the underlying network used to transport freight than other modes do. For both LTL and TL carriers, some terminals used for driver-management activities may require a very small capital investment (Üster and Kewcharoenwong 2011). For example, carriers can use highway rest areas as meet-and-turn or relay locations at which drivers swap trucks or loads (often so both drivers can then turn back and return home). Also, for a LTL carrier, adding or reducing capacity to a cross-docking terminal is often inexpensive and easily done (relative to air and sea transport). As a result, a ground-based consolidation network often has many more transfer points or terminals and many more potential routes for freight than other transportation modes. Ultimately, the relative ease with which a terminal network can be adapted suggests an opportunity for planning models that jointly look at how the terminal network is structured and freight or trucks are routed; however, little work has been done on such models.

Areas of Opportunity for Practical Research

The financial performance of the TL and LTL carriers we mention previously is a snapshot; however, it is also representative of the types of profits these carriers have seen over the past decade. Because many LTL carriers have struggled consistently to turn a healthy profit, the opportunity for operations researchers to make an impact in this space is still significant. The majority of published research and development activity in the LTL space still focuses on deterministic models and does not model uncertainty with respect to shipment volumes. One approach to dealing with uncertainty is to look at LTL freight routing as a dynamic problem, where routing decisions are reoptimized daily, instead of as a static planning problem that is solved only at weekly (or possibly longer) intervals. Such a tool could also help carriers better deal with significant disruptions to their transportation networks because of weather or other unforeseen events. Finally, LTL carriers consistently rate driver shortages as a concern. Yet, few planning methodologies for LTL freight routing accurately capture the impact of freight routes on driver retention, nor does there appear to be a tool comparable to the one that Simão et al. (2010) propose for evaluating driver retention policies.

Air Freight

Air freight, more commonly referred to as air cargo, is an enabler of economic growth in communities that do not have easy access to an ocean-navigable waterway, the traditional enabler of trade (Miller and Clarke 2002). Additionally, air cargo has historically been the primary catalyst for the growth of the aviation industry—similar to the ships, stagecoaches, and trains that preceded it; aircraft were used to transport cargo (in the first instance, mail) long before they were used to transport people. Further, in times of war, the vast majority of the sorties that are flown involve either transporting material to forward bases or bombing enemy targets, which is also a form of cargo delivery.

Air cargo is also without question the most energy intensive and (on a per-unit-mass and per-unit-volume basis) the most expensive freight transportation mode. Thus, most of the cargo that is transported by air is either perishable and time critical from the perspective of a larger production process, or is of high value and relatively low density. As Clarke (2006) reports, more than 40 percent by value of global freight is transported by air, although the corresponding weight and volume of those goods are significantly less.

From an OR perspective, the vast majority of air cargo-specific innovations have been in the areas of revenue management and network optimization. More recently, OR has been applied to the intermediary-hub-location problem. There has been little to no air cargo-specific innovations in the areas of fleet planning and crew scheduling over the past two decades. The former is in large part because of the standardization of air cargo fleet sizes based on four business models: (1) the piggyback model in which cargo is carried on passenger flights alongside passenger baggage; (2) the trunk-route model in which cargos from various freight modes are aggregated and disaggregated at airport hubs (i.e., nodes in the multimodal freight network) and transported by air along the trunk route that links the two hubs; (3) the feeder-route model in which smaller aircraft are used to transport cargo between a given location and a node in the multimodal freight network; and (4) the UPS integrated-provider model, which has a combined trunk-and-feeder-route network, or Lufthansa and other major international carriers that have combined piggyback and trunk-route networks. The latter is because crew scheduling between passenger and cargo carriers is virtually the same; thus the crew-scheduling models that are developed for passenger carriers can be applied to the easier air cargo crew-scheduling problem.

Network Design and Management

Network design: *Hub location.* Although a plethora of work has been done on the hub location problem, the placement of air cargo hubs has not received as much attention as the placement of hubs in other transportation modes or in other industries such as telecommunications. In large part, this is a result of the complexity of aviation; in determining where to place an air cargo hub, one has to consider several issues, including weather and future airport capacity, which are difficult to model in a deterministic fashion. An examination of the attributes of the main hubs of the domestic air cargo service providers that offer overnight delivery reveals that the overriding considerations in their selection were their location relative to the sources of cargo, weather, and their excess capacity at the time they were selected.

That said, recent work has been done to understand how the current networks might change through additional stopovers. For example, Kuby and Gray (1993) introduce a network-planning problem called the hub network-design problem with stopovers and feeders; they apply their model to the western U.S. portion of the network used by the Federal Express Co., where most flights to and from the hub make one or more stopovers, and many smaller cities are served by feeder aircraft that connect to other nonhub cities. They explore the trade-offs and savings involved with stopovers and feeders, and develop a mixed-integer program to design the least-cost single-hub air network, assuming that the primary hub location is already determined. They compare their resulting network to the preexisting Federal Express network to illustrate (through the similarities) that their model has captured the important design criteria and identified the differences that are necessary to improve efficiency.

Network management. Network optimization is another area in which air cargo and air passenger services differ. When providing air passenger services, operators must offer specific flight segments at specific times of the day and on specific days of the week, because this is part of the basis on which passengers determine whether to purchase a ticket. Those requiring air cargo services often care most about the latest time for pickup, which determines the time that the goods to be transported must be ready, and the earliest time for delivery that must be prior to the time that the goods are required for use. Thus, air cargo service providers have flexibility in how they can route mail, packages, and freight, and by extension, how they can configure their network and deploy the aircraft at their disposal to deliver the aforementioned goods.

Operations researchers have made significant contributions in this area. Most notably, two of the finalists in the competition for the 2003 Edelman Award addressed the problem of network optimization. Armacost et al. (2004) created a system to optimize the design of service networks for delivering express packages. It simultaneously determines aircraft routes, fleet assignments, and package routings to ensure overnight delivery at minimal cost. This is achieved through the introduction of composite variable formulations to reduce the problem size and enhance tractability, and the redefinition of the decision variables to produce a network-design formulation whose LP relaxation is provably stronger. The system has become central to the UPS planning process. “UPS management credits the system with identifying operational changes that have saved over $87 million between 2000 and 2002" (Armacost et al. 2004, p. 15).

Prior et al. (2004) developed a network-routing-optimization model to optimize the North American transportation network of Menlo Worldwide Forwarding (formerly Emery Worldwide) in the aftermath of the terrorist attack of September 11, 2001, and the subsequent drastic decline in the demand for air cargo services. The solution is achieved via decomposition in two phases; phase 1 optimizes aircraft schedules; phase 2 optimizes the routing of the integrated aircraft-and-truck network. Using this model, Menlo Worldwide Forwarding increased its profitability and reduced its operating costs, while maintaining high service levels. In 2002, Menlo Worldwide Forwarding reduced its operating costs by 21 percent, increased operating margin by 41 percent, and improved financial results by $80 million in the North American aircraft transportation operation.

Unique Areas of Research: Revenue Management

Given the significant and very costly energy requirements and the perishable nature of the good that is produced (i.e., the service of transportation cannot be stored for future use), much of the optimization work in air cargo has focused on maximizing the revenue that can be obtained, given the cargo capacity of a specific aircraft flying a specific fight segment or a set of aircraft flying several flight segments.

One of the most influential articles on air cargo revenue management over the past two decades (at least in terms of practice) is by Kasilingam (1996); the author describes the unique nature of the revenue management problem for air cargo relative to the revenue (i.e., yield) management problem for air passengers, and by extension other modes of freight transportation. That is, because both the weight and volume of the payload that an aircraft can carry have stringent limitations, which are a function of the distance to be flown, both the weight and volume of the cargo to be carried must be carefully monitored and managed relative to the revenue being offered. This is in contrast to revenue management for passengers and other freight modes, where either weight or volume is the binding constraint—but not both. However, despite his articulation of the multidimensional nature of the problem, Kasilingam (1997) initially developed only a one-dimensional solution.

In terms of substantive subsequent milestones, Pak and Dekker (2004) were the first to fully address the multidimensional nature of air cargo capacity; they modeled the problem as a multidimensional online knapsack problem and proposed a heuristic to determine the bid prices based on a greedy algorithm proposed in Rinnooy et al. (1993). In 2006, air cargo service providers were faced with the very real issue of no-shows because they typically had long-term contracts with freight forwarders, which guaranteed a specific amount of capacity; Popescu et al. (2006) developed a model to estimate overbooking based on a discrete show-up-rate distribution.

Later, Luo et al. (2009) extended the one-dimensional model initially developed by Kasilingam (1997) to two dimensions under cost minimization, which Moussawi and Cakanyildirim (2012) then reformulated as a profit-maximization problem. Somewhat in parallel, Xiao and Yang (2010) modeled the problem as a continuous-time stochastic-control model, and derived structural properties for the case in which the remaining capacities in two dimensions are equal or differ. When they are equal, they show that the optimal policy is not featured by the nested price structure (if a fare class is open, then all classes with higher fares should also be open) as in the one-dimensional case.

Most recently, Popescu et al. (2013) developed an effective approach to determining bid prices—where the bid price for a specific piece of cargo is the minimum offer to accept from a customer or alternately the minimum price to quote to the customer in the case of a mixed demand pattern that includes individual and batch bookings. Specifically, they decompose the demand into small and large bookings based on weight; they use dynamic programming for the large bookings, and a fast, high-quality approximation for the small bookings. This is an improvement relative to most prior literature and existing applications for making accept or reject decisions, where the arrival stream is modeled as individual bookings, because air cargo is often separated into two categories—mail and packages (small cargo) and freight (large cargo).

Revenue management has had a significant positive impact on the profitability of cargo operations. For example, Boonekamp (2013) reports that a simple static two-parameter bid-price model, in which the minimum revenue per kilogram and a minimum revenue per m^3 required to accept a shipment are specified, provides an 11 percent increase in revenue relative to a first-come, first-served decision policy, which is the traditional practice with respect to accepting bookings. Interestingly, this model does not require booking forecasts or real-time adjustments. If optimal booking limits for individual demand sequences are used, much larger revenue increases would be realized. From another perspective, according to Jeffrey Johnson, an executive with Sabre, Lufthansa estimates it realized six million euros in increased revenues just six months after implementing its cargo overbooking model in 2002 (Johnson 2014).

Air Freight Research Opportunities

As with passenger carriers, researchers have been giving increasing attention to integrated problems, where two or more of the problems that have traditionally been solved sequentially (in large part because of problem size) are solved simultaneously, in the hope of achieving greater optimality. Recently, Derigs and Friederichs (2013) proposed a framework for solving the air cargo scheduling problem; in their framework, the flight selection, fleet assignment, rotation planning, and cargo routing problems are solved simultaneously.

Similarly, researchers have begun to study how the differential pricing practices that are applied to passengers may be extended to air cargo pricing to increase yields. For example, Vinod and Narayan (2008) present a framework for optimizing cargo rates based on a customer's willingness to pay and the underlying market strategy. They determine the optimal prices per unit mass and volume (i.e., rates) for different commodities using a nonlinear optimization model with decision variables, such as market, day of the week, bulk versus container, customer service level, and commodity type. They show via a numerical study that by addressing cargo rates, which are a fundamental input into the revenue management process, cargo yields can be improved by determining the optimal published rate tariff structure for commodities.

The passenger-cargo relationship is also increasingly of interest within the context of an airline that flies both passengers and cargo over a network of locations on a fixed periodic schedule (i.e., the piggyback business model). Such airlines must control cargo accept-or-reject decisions to maximize expected profits, while ensuring effective dispatch of accepted shipments through the network. To this end, Levina et al. (2011) proposed a model for the problem in which bookings for cargo shipments between origin-destination pairs in a network are made in advance, but the weight and volume of aircraft capacity available for cargo and the exact weight and volume of each shipment are not known at the time of booking.

Another area with great potential from the perspective of air cargo service providers (broadly defined) is the optimal routing of cargo across competing networks and modes, especially within the context of varying energy costs. Additionally, the subset of entities that actually own and operate the hubs and links in the air cargo transportation network must make very consequential infrastructure investment decisions in the face of extreme volatility in demand. Thus, they have a great need for stochastic programming algorithms and tools to help them make such decisions.

Conclusion

OR has played a major role in multiple areas of freight transportation. Scheduling, the most fundamental need and perhaps the most challenging problem, is of keen interest across the modes of freight transportation. Scheduling spans across multiple considerations, including shipper service requirements, major-asset allocation, manpower planning, and hub operations (i.e., rail yard, truck terminal, oceanic shipping port). All have dabbled in some degree of yield-management techniques, given limited, ephemeral capacity to be sold and uncertain demand. In many notable cases, the investment in OR technology has had pervasive influence and tremendous financial value across all the modes.

The modes have differences. Only rail must build, maintain, and manage congestion on its arcs—the rail lines. Oceanic freight has the longest delivery distances, largest shipment aggregation, and the most uncertainty of delivery dates. Air freight, at the opposite end of the spectrum, has precisely the opposite characteristics. Truck has by far the lowest capital costs and the most flexibility of operations.

Like many industries, all freight transportation modes are dealing with improved information. The completeness of coverage, improvement in accuracy, and increase in the detail of data have resulted from electronic collection and dissemination. These data provide opportunities for improved OR modeling and performance tracking. Further, they create the need for new data-centric OR techniques for a wide variety of decisions that were not previously considered because of lack of data coverage or detail.

Opportunities for OR in freight transportation are great. The application of OR is hampered in all modes of transportation by uncertainty of demand, shipping times, and scheduling across modes. Robust stochastic methods are needed to expand the effectiveness of OR in practice. In many cases, shipments are multimodal. OR modeling that can assist in improving the design and operations of multimodal shipments has great potential.

In summary, OR has played a major role in enhancing the efficiency and profitability of freight transportation, and the future for applying OR in freight transportation is bright.

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