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Case Article

Growing Pains: A Case Study for Large-Scale Vehicle Routing

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Abstract. This is a case study focused on the quantitative modeling of transportation services for use in undergraduate and graduate level transportation and logistics or optimization courses. The problem considered in the case is a capacitated vehicle routing problem (CVRP) with additional side constraints corresponding to delivery windows and United States Department of Transportation drive and duty time regulations. The case is presented in the context of a fictional company, Northeastern Home Goods (NHG), but is based on a problem encountered by a real organization. NHG is considering outsourcing its transportation services to a firm having logistics as a core competency. Specifically, NHG wishes to evaluate the transportation costs that will result if a single distribution center is used to serve all of NHG's current stores according to a preexisting store delivery schedule. The primary objective of the case is to provide students with hands-on experience developing and applying solution techniques for a large unstructured vehicle routing problem. Secondary objectives include requiring students to think logically through the process of creating good solutions, promoting continuous improvement, and encouraging students to consider the business implications of their recommendations.

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Keywords: vehicle routing problem • heuristic • operations research • logistics • teaching case

1. Introduction

"Growing Pains: A Case Study for Large-Scale Vehicle Routing" is a case developed to expose students to a large and unstructured logistics planning problem, similar to what may be encountered when working for a real logistics firm. Specifically, students are asked to solve a capacitated vehicle routing problem (CVRP) variant that incorporates a number of complicating real-world constraints often not included in classroom examples. For example, the United States Department of Transportation (DOT) regulations governing drive and duty time regulations for drivers must be respected when creating routes, as must delivery time windows at store locations. The case also asks the students to perform resource requirement analysis for the set of vehicle routes they construct. This encourages the students to think about the impact of their proposed solution in terms of numbers of drivers and equipment required for executing the routes, instead of limiting their analysis to transportation cost. In completing the case, students are exposed to a large data set and are required to implement approximate solution approaches for VRP in spreadsheet and/or programming software environments. A number of useful case studies for the quantitative modeling of logistics problems are available in the literature. We review those that focus on service network design and vehicle routing, due to their applicability in logistics engineering courses like the ones we have used our case in.

Drake et al. (2011) introduce a case that integrates logistics network design with an ethical decision-making process. Students are asked to determine the optimal logistics network design that incorporates zone skipping; an arrangement that is expected to save the company in the case money, but that comes with an ethical dilemma. After determining the optimal design and its associated cost, students follow an ethical decision-making process to recommend several courses of action for the company to consider. Koksalan and Sibel Salman (2003) propose a case study that introduces a multiperiod strategic planning problem in the context of a beer producer and distributor. Students must develop and solve a mixed-integer programming model to optimize brewery locations, capacity expansions, and malt and beer distribution decisions. Transportation costs are considered in both of these cases, as the radial distances between demand points and their assigned facilities comprise one determinant of total network costs. However, neither case requires students to create vehicle routes explicitly.

DePuy (2009) provides a game to improve student's integer programming formulation skills applied to the traveling salesman problem (TSP). The objective of the game is to find a route through a puzzle board that visits each symbol on the board exactly once. Unlike the TSP, the puzzle does not require a return to the starting point at the end of the tour. Drake (2014) introduces a vehicle routing case study that requires optimizing the logistics operations for a regional chain of discount stores. The firm supplies 15 store locations from a single distribution center (DC). The demand of each store location is known and three homogenous capacitated trucks are available. A route duration constraint is included in the case, as a driver can drive at most 11 hours in one day. Thus, the case requires solving a CVRP with one additional side constraint (the drive time limit). Students are provided with an initial feasible solution (set of routes) and are asked to improve it. The case does not specify whether students should use exact or heuristic methods.

Of the cases we identified in the literature, Drake (2014) is most closely related to our own. Our problem is also a single-depot CVRP with a drive time limit, but we have additional side constraints for an on-duty time limit and delivery windows at stores. Further complicating extensions are distributed in the teaching note for the interested instructor to use. The sizes of the problem instances are another major difference between the two cases. The instance in our case consists of 123 store locations and 262 deliveries (store orders) across a one-week horizon. Therefore, our case is a large-scale routing problem that cannot be solved in a reasonable amount of time with an exact solution technique. While it is very easy to come up with a naive initial feasible solution to our case (e.g., send individual trucks out-and-back to deliver each store order), students need to modify and implement VRP construction and improvement techniques to produce a solution with reasonable routing cost. Thus, they learn how to extend and implement VRP techniques learned in class for a problem of realistic size. No other cases in the literature of which we are aware provide students with the opportunity to do this.

The remainder of this article is organized as follows. Section 2 provides background material for the case, while Section 3 discusses the teaching objectives. Section 4 describes how the case can be used in various classroom environments. The final section discusses our experiences from several classroom implementations.

2. Case Background

In this case, students are asked to prepare an estimate of total transportation miles required to fulfill 262 weekly store orders (across 123 store locations) of Northeastern Home Goods (NHG) out of a single DC in Wilmington, Massachusetts. In developing a set of routes to estimate total transportation miles, a number of operational constraints must be considered: vehicle capacity, store delivery windows, and the United States DOT drive and duty time regulations. This requires solving a CVRP with additional side constraints. After producing a set of routes, the students are asked to determine the minimum number of drivers and the minimum number of vehicles required in order to operate the set of routes they developed. This is not a trivial task, as interactions among routes with respect to drive and duty time regulations must be considered. For example, a driver who completes a Monday route at 8:00 P.M and begins a DOT-mandated 10-hour break is not eligible for a Tuesday route that is dispatched earlier than 6:00 A.M. Requiring students to complete this additional step requires them to think critically about their solutions. In a business environment, it is important to be aware of the practical implications that may arise as recommendations are presented and discussed.

This case was developed in conjunction with a large transportation logistics firm that offers a variety of freight solutions to their customers, including but not limited to truckload, less than truckload, and intermodal delivery services. This case was inspired by a problem the logistics firm faced when partnering with a company to provide a customized transportation solution to meet the client's needs. Specifically, the potential client was considering the logistics firm as their sole provider of freight transportation services. If the contracting arrangement were to be finalized, the logistics firm would supply all of the client's demand locations from a distribution center already operated by the logistics firm, subject to operational constraints set forth by the client and other governmental regulations. The logistics firm needed to estimate resulting transportation costs in order to submit an appropriate bid to the client. In this case, the fictional companies NHG and Massachusetts Area Distribution (MAD) are introduced to represent the client and the logistics firm, respectively. These company names will be used throughout the remainder of this case article for simplicity of exposition.

The logistics firm we worked with to develop the case provided the data describing NHG's average weekly freight requirements. The data are based on an actual potential client. Instead of providing street addresses for the demand locations (i.e., store locations), NHG demands were aggregated to the zip code level to protect the identity of the client. The weekday delivery schedule was also altered for client protection, although the client did express a desire to maintain a fixed weekly delivery schedule as the case suggests.

One aspect of reality that is simplified in the case is the specification of the weekly delivery schedule. While NHG did prefer a fixed delivery schedule, MAD discovered inefficiencies in it. Specifically, MAD was able to offer an alternative delivery schedule that maintained the appropriate number of visits to each NHG store per week, but reduced overall transportation miles by clustering deliveries to proximal demand locations into the same weekday. The resulting delivery schedule still met the expectations of NHG because the conveniences of the fixed schedule were afforded (i.e., the ability to plan staffing levels for receiving, and the ability to notify customers when new items will arrive). Thus, MAD considered the visit-day decisions in their logistics analysis, in addition to the routing decisions. In the basic version of this case, students are asked only to address the routing decisions. However, the visit-day decisions are explicitly considered in one of the extensions distributed with the case, should an instructor wish to include that aspect.

Another way the case has been simplified is in assuming a homogenous vehicle fleet. In the original problem defined by MAD, two types of vehicles were available. They differed according to their physical capacities and unload times. Some NHG store orders required one of the vehicle types, while either vehicle type could service other orders. Explicitly considering the vehicle type decision for each store order requires solving a CVRP variant with a heterogeneous vehicle fleet and other side constraints. This is available as an optional extension distributed with the base version of the case.

Finally, the delivery windows in the case have been simplified. The case states that all stores must be visited between 8:00 A.M and 6:00 P.M on their day of delivery. These delivery windows can be modeled as time windows. While their introduction in the case does increase the complexity of the resulting problem (beyond a routing problem with no time windows), the case is not as complex as it would be if delivery windows differed among stores. For example, a problem instance where some stores require windows of [8:00 A.M, 6:00 P.M] while others require windows of [10:00 A.M, 2:00 P.M] and [12:00 P.M, 5:00 P.M] would require modeling the interactions between route sequencing decisions and individual store time windows explicitly. As it is, the base case only requires comparing the arrival times to the first and last store deliveries on a route to the 8:00 A.M and 6:00 P.M delivery windowendpoints.

The teaching note provides some evidence of what constitutes a "good" solution, as measured by the transportation cost of the associated routes. This evidence is taken from a number of the best submissions that have been received to date from students. It may be possible to develop solutions with even lower costs, but this is not known as the problem is NP-hard and the optimal solution is not easily obtained by common commercial optimization solvers such as CPLEX.

3. Teaching Objectives

The primary teaching objective of this case is to provide students with hands-on experience developing and applying solution techniques for large unstructured logistics planning problems; specifically, vehicle routing problems. The size of the problem instance is large enough to be similar to what they may face in their business careers. Often in quantitative courses, models and solution approaches are demonstrated using small examples that can easily be solved by hand. For example, when we cover vehicle routing problems in a transportation and logistics course taught by one of the authors of this case, simple methods for constructing initial solutions for the classic VRP are introduced. Two such methods we introduce are the Clarke-Wright Savings method (Clarke and Wright 1964) and the Sweep Algorithm (Gillett and Miller 1974). The students employ these constructive heuristics using an example instance comprised of 13 demand locations and a depot during an in-class exercise. While this practice has the benefit of helping students grasp the mechanics of well-known techniques, it does not ensure students can implement such an approach for a large-scale instance. The number of demand locations in this case is high enough so that at a minimum, students must use spreadsheet-based tools to evaluate the feasibility of candidate routes, and better yet, implement software to automate the process of route creation and evaluation.

A secondary objective is to require students to think logically through the process of creating good solutions, as opposed to relying solely on the decision structure of an existing technique. When we use this case, students are encouraged to use VRP construction and improvement techniques that we cover in class as a starting point, but the problem cannot be solved without modifying those techniques in some significant way. For example, to employ the Clarke-Wright Savings Heuristic, new conditions for checking the feasibility of combining two routes must be added to model side constraints such as DOT drive and duty time regulations and delivery time windows.

A third objective of the case is to promote continuous improvement. After obtaining an initial feasible solution, students are asked to use solution improvement techniques such as neighborhood search methods. It is well known in the VRP literature that classical heuristics such as Clarke-Wright do not produce high-quality solutions when compared with more advanced metaheuristics (Cordeau et al. 2002). Reviews of advanced heuristics and exact algorithms for the classic VRP and its variants can be found in a number of papers in the literature (e.g., Braekers et al. 2016, Toth and Vigo 2014, Baldacci et al. 2008, Kumar and Panneerselvam 2012, Laporte 2009, Yeun et al. 2008, Cordeau et al. 2002). For the students who would like to implement more sophisticated solution techniques, we refer them to the relevant literature. However, those students who do not possess the skills to implement advanced metaheuristics can still use a number of simple neighborhood move operators (e.g., 2-exchange, remove and reinsert, etc.) to improve their initial set of routes. In this way, the case promotes continuous improvement, as the best submissions will not be those where the students ceased their efforts as soon as a feasible solution was obtained.

The final objective is to encourage students to think through the business implications of their recommendations. There are often practical considerations that may render a minimum-cost solution undesirable, especially when traveling distance is the only type of cost considered. In a business environment, a student should be prepared to address concerns that may arise *before* approaching management with a recommendation. For example, in this case study, a particular set of routes may require overnight domiciles, and the company may or may not have labor agreements and proper vehicles for this situation. It may be preferable to recommend a higher-cost solution that does not include overnight domiciles, or at least provide an analysis of the resource requirements induced by including them. By requiring students to evaluate the driver and equipment resources required by the set of route they recommend, students must view the operational planning problem using a systems-based perspective.

4. Suggested Classroom Use

This case is appropriate for a variety of optimization and transportation logistics courses. We have used this case in both graduate and undergraduate engineering courses that focus on quantitative modeling of logistics planning problems. It would additionally be appropriate for any course that emphasizes modeling, solving, and interpreting the outputs of mixed-integer programs, such as graduate courses in optimization.

The case is flexible with respect to the quantitative techniques that can be applied to solve the problem. For example, in an undergraduate logistics course, students can adapt and employ heuristic techniques in an ad-hoc fashion to create potential routes and then use the provided spreadsheet-based solution check tool, GrowingPains.SolutionCheckTool.xlsx (available as supplemental material at https://doi.org/10.1287/ited.2016.0167ca) to evaluate their feasibility and cost. This tool is discussed in the teaching note. In contrast, students with computer programming knowledge can create software to implement heuristics to automate route creation and evaluation. In our experience, we have found that the programming skills required for the latter are more advanced than many undergraduate students possess, though this may vary depending on the curricula of other engineering programs. We do require software creation when using the case in graduate engineering courses.

Another option to obtain an approximate starting point solution that may be infeasible is to make use of the VRP Solver available at http://verolog.deis.unibo.it/vrp-spreadsheet-solver. If a user inputs a fixed number of vehicles and all instance data corresponding to a particular weekday, this tool will return a set of routes that satisfy vehicle capacity, delivery windows, and drive time constraints. Note however that our case does not set a fixed number of vehicles for each weekday. Additionally, the routes returned by the VRP Solver will not necessarily satisfy duty time constraints, because vehicle dispatch time is required as an input. In our case study, vehicle dispatch time is a decision variable. Furthermore, our case allows for the possibility of a driver taking a break on the way back to the depot from the last store delivery, if required because of drive and/or duty time constraints. The VRP Solver does not allow this flexibility, and thus eliminates a portion of the feasible region.

Instructors for graduate courses in operations research can assign students the task of developing a mixed-integer programming (MIP) representation of the problem presented in the case. The teaching note provides one such model. It should be noted that it will likely not be possible to directly use commercial optimization software on the market at the time of this writing to obtain optimal solutions to the MIP models. If an instructor wishes to ask students to go beyond the modeling effort and implement an exact approach, students could employ a sophisticated technique such as branch and cut and price for VRP (Fukasawa et al. 2006) or a variant of the set partitioning formulation proposed in Baldacci et al. (2008), but the teaching note does not contain any guidance to this effect.

The case is also flexible with respect to the complexity of the underlying problem the students are asked to solve. In its most basic classroom implementation, the case requires solving a CVRP with additional side constraints. Students can separate the underlying problem into five separate instances (one for each weekday), and solve each individually. To provide a problem that is even more complex, three implementation variants are available to instructors. The variants below can be implemented alone or in combination and are discussed in further detail in the teaching note:

- Heterogenous vehicle fleet. An additional vehicle type can be introduced, where the two vehicle types vary based on capacity and loading/unloading time. Certain store orders require delivery from a particular vehicle type, while either type of vehicle can serve remaining store orders.
- Overnight routes. Overnight routes that group store orders from consecutive days onto the same route (separated by an overnight domicile) are allowed.

- Delivery schedule generation. The weekday each store order is delivered can be a decision variable, and the requirement that store order be delivered within store operating hours on the selected day of service remains.

We recommend this case be assigned as a group project, with teams consisting of three to four students. Typically, we distribute the case document as a reading assignment and then devote 20 to 30 minutes of the next lecture period to discussing the case, highlighting instructor expectations, and answering student questions. The students are then given two to three weeks to complete the assignment. The typical student, in our experience, is pursuing a full course load while taking our class. Thus, the two to three week timeline is developed with the expectation that students will be balancing the efforts required for this case study with their other coursework and obligations. We recommend making class time available throughout the duration of the project period for students to ask questions and pick up valuable hints from the instructor and each other.

We require students to submit their routing plans using the Excel-based solution check tool that we provide so that we can validate the feasibility and cost of their proposed plans. We encourage each group to send in their current best routing plans frequently throughout the project period as they discover new and improved solutions. This helps to ensure that each team has at least one valid submission by the end of the project period. Additionally, we maintain a competition dashboard on the website for the course, displaying the objective value of each team's best feasible submission to date. We update this dashboard at least daily. This inspires friendly competition. We believe the learning process is greatly augmented, as students continue striving to improve their submissions up until the project deadline. In doing so, many teams experiment with a wider variety of strategies than they otherwise might use.

The final deliverable we require for the case is a memo accompanied by a technical appendix. In the memo, the students provide the details of their recommended solutions: the total cost of the set of routes, details and graphical representations of those routes (one figure per weekday), and a summary of the driver and vehicle resource requirements. In the technical appendix, students must describe the solution techniques they explored and discuss what approaches led to their final recommended solution. This helps us evaluate to what extent the VRP solution techniques we cover in class are adapted and employed. Other instructors may prefer an alternate deliverable; for example, an oral presentation. A sample grading rubric for the case can be found in the teaching note.

5. Classroom Experiences

To date, student feedback regarding the case has been collected through informal conversations with them. Both undergraduate and graduate students find this problem very interesting and enjoyable. Some students have mentioned that they spent a couple of hours working on this case study without even realizing it. Several students have told us this case is excellent and fun. They like that the case is based on a real-life problem, and they become excited that after hard work, they can obtain very good solutions to a complex, meaningful problem. Students especially like and appreciate the solution check tool. When we assigned the case in previous semesters, before having made the tool available, students spent too much time trying to develop their own spreadsheet-based applications to evaluate route feasibility and cost. They did not have enough time to focus on the application of VRP methodologies. Making this tool available to them has allowed them to focus on the true learning objectives of the case. It is worth noting that the students informally evaluate the project more highly now than students from previous semesters who did not have access to the tool.

We have implemented the case in its various formats in undergraduate and graduate engineering courses that focus on quantitative modeling of logistics planning problems. Our experiences with each are detailed below.

Undergraduate engineering course. We have used both the base case and more complex case extensions with undergraduate engineering students in past courses. Based on these experiences, we recommend use of the base case at this level. There are many complex considerations in the base case alone, such that students gain ample experience analyzing data, applying heuristic techniques, and presenting solutions. In past submissions, student groups have reported using both ad-hoc decision logic and constructive heuristics for VRP with adaptations (by hand and with assistance from the spreadsheet solution check tool). They have also reported applying improvement techniques such as neighborhood search. However, their use of neighborhood search has been manual in nature, limited to applying just a few iterations of improvements that were easy to detect via visual inspection of routes.

Graduate engineering course. Our recommendation for graduate student courses is a two-phase project assignment, where students are asked to first solve the base case and then move on to a specified extension. Graduate student groups have reported applying adaptations of constructive heuristics for VRP to obtain initial solutions, and sophisticated neighborhood search schemes such as simulated annealing and tabu search to improve the routes. As a result, the best graduate student submissions for the base version of the case typically have lower cost than the best undergraduate student submissions.

Instructors (or teaching assistants) can expect to engage in frequent communication with students at the beginning of the project period, as students begin developing routes and using the solution check tool to evaluate their feasibility. Many students will have questions regarding why some of the routes they create are flagged as infeasible by the solution check tool. This occurs when a student team fails to consider at least one of the problem constraints initially. The most common constraint missed by the students is the DOT drive time regulation. Because store deliveries are restricted to a 10-hour window (between 8:00 A.M and 6:00 P.M), students often make the mistake of assuming route durations will automatically fall below the 11-hour drive time specified as permissible according to DOT restrictions. However, accounting for the drive time between the depot and first and last store deliveries may cause routes to exceed the 11-hour limit. Graduate students typically do not need as much hands-on assistance with debugging their solutions and understanding the constraints in the problem.

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