We consider the problem of determining good policies for route design and inventory management of inbound parts. In particular, a facility wishes to coordinate the delivery of parts from multiple suppliers in an efficient and cost-effective manner, but has a limited amount of storage space in which to house inventory. The frequency with which suppliers are visited and the quantity that is picked up must be coordinated with the operations schedule of the facility, the storage space it has allocated, and the capacity restrictions for the vehicles used to transport the parts. We develop two heuristics that consider the inventory and routing decisions in alternating order which allows us to evaluate the benefits of incorporating the storage constraint at different stages. Additionally, we simultaneously consider both transportation and inventory functions in order to make effective logistics-related decisions. We show that combining less than full truckload shipments from multiple suppliers can result in substantial savings by taking advantage of economies of proximity. Further, we quantify the benefit of considering storage capacity in the determination of routes and pickup quantities rather than simply adjusting pickup quantities in order to satisfy the storage constraint. In this manner we are able to achieve a good balance between constructing efficient routes and retaining near-optimal pickup quantities from suppliers.

1. Introduction

Inventory routing is perhaps one of the most fundamental topics of manufacturing and transportation logistics. It is in this problem context that we determine how the transportation of products should be organized to support manufacturing, processing, and distribution operations. Transportation can be outbound to distributors or directly to retailers or, in this case, inbound from suppliers to the manufacturer. We exploit economies of proximity and show that combining LTL shipments from multiple suppliers can result in substantial savings.

We develop two heuristics that consider the inventory and routing decisions in alternating order which allows us to evaluate the benefits of incorporating the storage constraint at different stages in the planning process. We simultaneously consider both transportation and inventory functions in order to make effective logistics-related decisions. We quantify the benefit of
considering storage capacity in the determination of pickup quantities rather than adjusting quantities to satisfy the storage constraint. We are able to achieve a good balance between constructing efficient routes and retaining near-optimal pickup quantities from the suppliers.

2. Problem Context and Assumptions

We examine the inventory routing problem (IRP) of an assembly plant that wishes to coordinate pickups from suppliers in an efficient and cost-effective manner. As in the typical IRP, we simultaneously consider the pickup routes and inventory management at the assembly plant. The addition of storage capacity constraints differentiates this particular problem as there is limited storage space available for parts at the assembly facility. Therefore, the frequency with which suppliers are visited and the quantity that is picked up must be coordinated with the storage space that is available at the plant and the capacity of the vehicles used to transport the parts. A maximum number of suppliers will be allowed on any given route as a means of limiting the amount of time spent making stops.

Demand from each supplier is constant and deterministic. A homogeneous fleet of vehicles is available for running the routes, and stockouts are not allowed at the plant or at any of the suppliers. There is a holding cost associated with carrying inventory at the plant, and each truckload of inventory carries a supplier-specific inventory value. Along with inventory costs, there are transportation costs for this model. The structure of the transportation cost function is based on the maximum value of either a distance based per mile cost or a minimum charge for a route.

3. Routing Procedure

The Location Based Heuristic (LBH) introduced by Bramel and Simchi-Levi (1995) is the basis for our routing mechanism. We begin by calculating a setup cost for each supplier as a seed point. We then calculate the connection costs between the seed point supplier and every other supplier. Using these transportation based costs, we can determine the optimal cycle time for each route. However, this cycle time may not be feasible given the vehicle capacity, so we must also compute the optimal, feasible cycle time for each route. Once the feasible cycle times of the
routes have been computed, we can calculate the average daily cost per route. We can then calculate the additional cost associated with assigning a supplier to a seed point (site).

In the second phase, we solve the Capacitated Facility Location Problem (CFLP) to choose a subset of the seed points and connect all other suppliers to one seed point. In the final phase of the LBH, we translate the CFLP solution into a solution for the routing problem.

4. The Route/Size (RS) Heuristic

The RS Heuristic consists of three steps: solve the LBH to determine the routes, solve the Traveling Salesman Problem (TSP) to determine the sequence of stops, and finally calculate the frequency for each route that meets all capacity restrictions and minimizes the total cost. We are now able to recalculate the transportation cost for the sequenced route and compute the optimal cycle time, maximum cycle time based on vehicle capacity, and optimal feasible cycle time.

Given the optimal feasible cycle times, we must calculate the total space needed at the plant to accommodate the resulting pickup quantities. We can then determine if the chosen cycle times and pickup quantities are feasible. If so, the storage space restriction is satisfied and we have a feasible solution. However, if the solution is infeasible, then too much inventory is being carried and we must decrease the route cycle times using a Lagrange multiplier for plant capacity. We restate and calculate the cycle time equations with the inclusion of the Lagrange multiplier. Next, we perform a bisection search over the Lagrange multiplier until the relative difference between the capacity needed and the capacity available is less than 0.1%.

5. The Size/Route/Size (SRS) Heuristic

The SRS Heuristic is different in that it incorporates the storage capacity constraint in the first step of the solution procedure. In this manner we are able to calculate the pickup frequencies for each supplier that meet the capacity restrictions and minimize the total cost. We then construct routes by combining the shipments of suppliers that do not fully utilize a vehicle independently.

The SRS Heuristic consists of four steps: calculate independent pickup frequencies, solve the LBH with a supplier constraint to determine the routes, solve the TSP to determine the sequence of stops along each route, and finally recalculate the optimal frequency for each route that meets both plant and vehicle capacity restrictions and minimizes transportation and inventory costs.
Given the optimal, independent pickup frequencies and resulting pickup quantities, we check for feasibility with respect to the plant storage capacity.

Next, we use the CFLP formulation to construct the routes. In this case, we use a constraint to insure that vehicle capacity will not be exceeded. As in the RS Heuristic we can use the IRP interpretation of the CFLP solution to determine the seed point supplier for each route as well as the suppliers that are connected to each seed point.

We can now solve the TSP and adjust the cycle times and quantities for the routes with multiple suppliers. We follow the same cycle time calculations and adjustment procedure as described in the RS Heuristic. We perform a second search over the Lagrange multiplier to determine optimal, feasible cycle times for each route that meet the storage capacity restriction.

6. Evaluation of the Heuristics

We considered four factors and varied each factor at three levels in order to create various problem instances with which to test the performance of the heuristics. The factors are plant capacity, vehicle capacity, carrying cost, and the number of suppliers that are allowed per route.

The RS and SRS Heuristic solutions are compared based on five practical performance measures. The first three measures are transportation cost, inventory cost, and total cost where the lowest cost solution is deemed to be the best solution. The final two performance measures are storage capacity utilization and vehicle utilization where the solution with the highest utilization in each category is deemed to be the most efficient, and therefore, the best solution.

![Figure 1](transportation_cost_storage.png)

![Figure 2](transportation_cost_vehicle.png)
7. Computational Results

The computational results in Figures 1 and 2 show that the storage capacity has a more profound impact on the solutions than does the vehicle capacity. Overall we observe that the SRS heuristic produces solutions that have 7.03% lower total cost than the RS heuristic. We see the greatest difference in the two solution procedures at the highest level of storage capacity. At this level the RS heuristic provides inefficient solutions because the cost structure overestimates the benefit of combining suppliers onto routes.

Looking at the effects of storage capacity on storage utilization in Figure 3, we observe a large difference in the two heuristics at the highest level of storage capacity. For the SRS solutions we expect the storage utilization to be relatively high regardless of the capacity. On the other hand, the RS heuristic must modify the quantities for the routes once it considers the storage capacity. Given that each route has dedicated space in the facility, the maximum storage capacity that the solutions will require is equal to the number of routes multiplied by the vehicle capacity.

Looking at Figure 4 we see that there exists a correlation between vehicle utilization and storage capacity. As storage capacity increases, we are able to more efficiently utilize the vehicles by increasing the amount of product that is picked up until we reach the point of full vehicle utilization. As we are able to store more in the plant, we can make fewer trips by picking up more on each trip. Alternatively, as the storage capacity decreases, we run the routes more frequently while picking up less which means that less space will be required in the vehicles and utilization will decrease.
We also found that restricting the number of suppliers allowed on a route is significant only when the maximum number is low. Due to the significance of transportation costs, suppliers that are close to one another will often be combined. However, if the number of suppliers in this cluster is large and the maximum number of suppliers allowed on a route is small, additional routes must be formed causing the total number of routes to increase. This effect is most profound in the RS heuristic as the emphasis is on efficient routes rather than considering how the quantities will be affected.

8. Concluding Remarks
The heuristics developed in this research illustrate the benefits of making coordinated decisions within a supply chain. Cost savings in the areas of transportation and inventory can be realized by considering operational issues from a strategic standpoint. We illustrate the benefit of integrating practical constraints such as capacity limitations into the planning process.

The RS heuristic illustrates the benefits gained from taking advantage of economies of proximity to reduce transportation costs while still considering the storage constraint. The SRS heuristic provides a solution that retains near-optimal quantities while still utilizing economies of proximity; thereby balancing the savings of transportation and inventory costs. In general, the SRS heuristic is recommended as it most often produces lower cost solutions and provides a good balance between constructing efficient routes and retaining near-optimal pickup quantities. It effectively utilizes capacity and remains robust across different factor and level combinations.

References