Missing from the Model: Orders, Drivers, Tractors and Trailers and Non-Linear Loading

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ABSTRACT
The Vehicle Routing Problem (VRP) was originally defined in 1959. The model used was a simple one that was appropriate to the software and hardware systems of the time. Since then many hundreds of papers have been written addressing the VRP and variants on it. Almost all are based on the original model or extensions of it. In particular notions of *demand* and the *vehicle* are adopted, seemingly without question. Capacity constraints, including volume, are considered to be linear. But this model does not match that used in commercial software – such as Transport Management Systems (TMS). In particular the concepts of *Order* and separate resources corresponding to the *Driver,* the *Tractor Unit* and the *Trailer* in the TMS need to be properly addressed to solve a variety of common real-world problems. This paper shows, through examples taken from Optrak customers, how without these concepts some common aspects of the problem cannot be addressed and how any attempt to map them onto the standard VRP formulation will result in major inaccuracies in the model and hence the usefulness of the results.

Categories and Subject Descriptors
D.2.11 [**Software Architectures**]: Data abstraction

General Terms
Algorithms, Design

Keywords
Vehicle routing model, orders, resources.

1. INTRODUCTION
The Vehicle Routing Problem is a well-known and well-researched problem. It originated with the famous paper of Danzig (1959) [1] and has been the subject of many hundreds of papers – both in its original form, in "standard" variations, such as the CVRP and CVRPTW (Capacitated VRP and Capacitated VRP with Time Windows) and in a variety of forms as researchers attempt to examine different, but related, real-world problems. It is also addressed by tens of commercial products [7] that typically use a variety of heuristics to address real-world problems and produce routes and schedules for real trucks and drivers.

A relatively recent concept is that of the "Rich Vehicle Routing Problem" [4].This is the beginning of a concerted effort by a few writers – typically people working at border of academia and industry – to bring more real-world constraints into the academic sphere – or at least a recognition of those constraints.

This is laudable and very useful. However, it is this author's contention that the approach of "VRP plus" as a way of expanding problem understanding is fundamentally limited. One of the main problems with academic VRP is that it is all built on an initial formulation that, though revolutionary in its day, is actually quite distant from reality and that to get a better understanding and more useful solutions, we actually need to reconsider the fundamental structures of the VRP.

In this paper we will look at 3 particular areas where the standard model fails to describe a fundamental part of real-world systems: the concept of *demand* as opposed to the *order*, the treatment of a *vehicle* instead of acknowledgement of the independent drivers and vehicles – especially separate tractor and trailer units and the assumption that vehicle volumes can be treated linearly.

For each model component the paper will adopt the following approach: an explanation of the standard VRP model of the component, an explanation of the proposed alternative component or components, a discussion of the problems with the former together with real-life examples of where the models can and cannot be considered equivalent or equivalently useful.

The real-life examples are all taken from the customers of Optrak Distribution Software Ltd., a provider of Computerised Vehicle Routing and Scheduling software. We do not have permission to publish full details of Optrak customers and consequently the customers are referred to by a letter code. Further details on individual customers can be supplied on written request to the author subject to agreeing to confidentiality of source and customer names.

2. DEMAND OR ORDER?
2.1 What is demand?
We begin with a problem that is caused by a specific use of terminology. Toth and Vigo describe one of the characteristics of *customers* as the

"amount of goods (*demand*), possibly of different types, which must be delivered or collected at the customer".[6]

The problem is with the concept of demand. The use of the word has been borrowed from economic theory where it is normally

GECCO'13 Companion, July 6-10, 2013, Amsterdam, The Netherlands.

defined as something like "the quantity of a commodity or service wanted at a specified price and time" [8]. Now the VRP has no particular mention of "specified price" thus omitting a large part of the economist's definition. Here the word is clearly meant to convey an amount – as such it must be considered some form of scalar quantity.

2.2 Orders

With the exception of stochastic problems, the VRP is attempting to model specific delivery (or collection) operations. But in general people do not place demand with a supplier. They place one or more *orders* and goods are, by and large, delivered as orders. Paperwork or computer records are generated for orders, and delivery constraints or contractual obligations are typically related to the order. For example "goods will be delivered within three working days of receipt of order". Orders may be split – in which case there is a vocabulary with terms such as "back-order" and "consignment" to deal with the parts of the whole, but the order remains the keystone of most commercial transactions.

So why does it matter? There are two areas where it causes problems for the standard VRP models.

1. Where orders for the same customer may be subject to different constraints.
2. Where there is pre-packaging at the order level and this packaging affects how the vehicle is utilised (typically due to volumes and intermediate containers).

The first category is the most important. Orders within a given delivery problem may have different constraints for a number of reasons. The following are all real-world examples taken from Optrak customers.

1. The orders may be available at the dispatch depot at different times.
2. Orders can be delivered together or separately.
3. Orders may have different vehicle / order compatibilities.
4. Orders may be placed at different times or have different service levels.

These will be discussed in greater detail below. However, before we do so we will look at how multiple orders can be dealt with in the "classic" VRP model.

2.3 With the "Classic" VRP Model

When faced with multiple orders and maintaining the "classic" VRP model of customers with demand, there are essentially three strategies:

1. Aggregate the orders so we have a single "demand" per product per customer.
2. Treat each order as if it were being delivered to a separate customer.
3. Invent an abstraction that is an order in all but name.

The first strategy is completely effective when the customer wanted the goods to be delivered together or when the quantities are sufficiently small as to make it unlikely there is any better solution – so long as the aggregation is legitimate. Examples below show that this is not always the case.

The second strategy works so long as there is no synergistic advantage in delivering the orders together. But this is almost never the case. In particular when working with clients to establish the best simple model for calculating time spent at customer premises, Optrak analysts and clients have found the best method is a fixed time plus a variable amount per unit delivered. The fixed time corresponds to activities such as parking, going through security, finding someone to accept delivery and so forth. Failing to take either the fixed or the variable elements into account results in a significant loss in modelling accuracy. For example, customer M models the delivery time at a customer as 10 minutes fixed plus 2.5 minutes per pallet. Since quantities are typically one or two pallets the fixed component is important – in the above example two orders each of 1 pallet would take 15 minutes using a fixed + variable model, if orders could be combined or 25 minutes if not – a difference of 40%.

2.4 Example: Company Z: Weekend Newspaper Delivery

This problem exemplifies points 1 (different arrival times at the depot) and 2 (orders can be delivered together or separately).

Weekend papers are typically multi-part. The news and the various supplements may be divided into two types – those which can be pre-written – for example travel or gardening supplements – and those that are "news" – typically the main news, business and sport. The printing of the former usually happens a day or two in advance and they are delivered to the local distribution centres early – up to 48 hours before the news date. By contrast the live news may not arrive until 4am on the day of delivery.

Vans and smaller lorries are used to deliver papers to the shops.

Weekend papers are typically bulky compared to weekday papers and consequently the vans used for delivery (which have significantly lower cost) can easily run out of weight capacity.

The solution normally adopted is to manage "pre-runs" whereby many of the supplements are delivered in the early hours (i.e. between midnight and 4am) with the vans returning to deliver the live news. However, it does not make sense to go to every store twice – particularly out-of-the-way rural stores. So the best solution seems to be to focus the pre-runs on the urban areas and deliver non-news supplements and news together to outlying areas.

The problem for the standard VRP formulation without orders, is that the best solutions may require some co-delivery and some separate delivery of the two streams. Treating the orders as if to separate sites fails to correctly model the unload time (2 minutes fixed plus approximately 1 minute per 50 kg), whereas pre-aggregation would deny the opportunity of splitting the deliveries into pre-runs.

The time window for delivery of newspapers is very narrow. A simplified model of delivery times would result in a significant error in the model.

2.5 Example: Company N – Bulk and Packed Lubricants

This example illustrates point 3 – vehicle and product compatibilities.

This example comes from another Optrak client delivering industrial and automotive lubricants. Depending on products involved, customers may order bulk or packaged goods. For example, a motor repair workshop my order 1000 litres of bulk gear oil and a drum (approximately 250 litres) of transmission fluid. The shop will have a bulk tank for the gear oil.

The client has a choice of vehicles at its disposal – bulk tankers which can only deliver bulk, packed only tankers and hybrid vehicles that use *totes* (US terminology) or *IBCs* (UK terminology – meaning Intermediate Bulk Containers) which are essentially $1m^3$ plastic tanks that can be loaded onto the truck as temporary bulk compartments.

Orders for bulk and packed goods are separate (company policy).

There is a customer preference for delivery together. Also there is a fairly high fixed component to the delivery time due to difficulties of getting the lorry into the yard passed parked cars.

On the other hand, the hybrid vehicles are more expensive than either of the other two and the pumps less powerful than on the regular tankers, hence delivery can take longer. The client also has the opportunity to send the packed goods via a third-party carrier which may be cheaper but not bulk goods as no equivalent 3rd party bulk carrier operations are available.

Taking these items together it can be seen that there are circumstances when the orders would be better delivered together and circumstances where separate delivery or even use of the carrier for packaged goods may be a better option than co-delivery. But the fixed + variable time model precludes treating them as separate customers.

2.6 Other Examples of Vehicle/Product Compatibility

Two further examples of the same problem are:

Multi-temperature Food Some food distributors will a mixed fleet of chilled vehicles, ambient vehicles and mixed vehicles.

Waste Recycling Waste collection companies have the option of

1. collecting on compartmented vehicles, thus allowing separation of streams,
2. collecting on single compartment vehicles with separate collections and
3. colleting on single compartment vehicles with co-collection, in which case the goods will be mixed and need subsequent separation in a MRF (Materials Recycling Facility). This last technique leads to a considerable degradation in quality of "recyclate" with a consequent loss to income to the waste collection company.

Another factor to consider is that dual compartment vehicles are typically lower capacity, lacking compaction facilities on all product streams – or much more expensive if compaction is provided for all streams.

2.7 Different Service Levels or different times of order

These two issues are essentially similar. In the first case, the guaranteed lead time for products may be different and consequently the orders will have different associated latest delivery dates, in the second case the customer has simply placed orders at different times (typically on different days) each of which has the same delivery period.

The issue here is that the delivery planning system can elect to deliver together or on separate days. Efficiency would suggest the former but there may be a scarcity of delivery resources, resulting in the need to put off the orders with the longer delivery time horizon. Again the arguments for co-delivery include reduced fixed times. Examples occur in most industries with multi-day delivery time horizons including companies A & K (lubricants).

2.8 Packing Issues

Except for small and irregular items such as parcels, or large items like kegs, goods are rarely loose loaded onto vehicles. Normally they will be put into or onto some form of intermediate container – such as a pallet or a roll-cage.

But goods are rarely packed to minimize space consumption. Normally they are grouped onto the pallet in some way so as to facilitate handling – particularly the speed of unloading, because driver time is a scarce resource. For example Company B has a rule: *the number of roll cages used for a customer's goods must always be the minimum required for that customer* (i.e. no unnecessary splits).

This ensures that the driver undertakes the minimum number of journeys from vehicle to customer, reducing time-costly operations such as raising and lowering the tail-lift.

A consequence of this rule is that volumes of individual orders cannot be simply added up. We will discuss more of this non-linearity later. However, for the purposes of this discussion on orders, the problem is that due to information systems limitations or the origins of the goods, the assemblage of orders onto the intermediate container is often carried out in the absence of an overall view of all orders for a specific customer.

In these cases the sum of the volumes of all orders for the customer can exceed that which would have been obtained if the goods were amalgamated prior to packing. Without taking the orders into account, the volume of goods cannot be ascertained.

3. Vehicles or Resources?

VRP problems usually assume there is a single resource used for each trip. This may be referred to either as the driver or the vehicle. Even in papers that specifically address more complicated aspects of the driver rules such as Goel and Gruhn [3] will treat it as a single resource. Some work has been done on separate tractors and trailers – the Tractor Semi-Trailer Routing Problem – this is very recent (2012) and assumes a homogenous fleet of trailers – Li, Lu et al [5].

However, the driver is a separate entity from the vehicle and vehicles can be composed of two parts (tractor and trailer) which can be combined in different ways. Also vehicles are not necessarily manned by a single person – many industries use driver's mates or even second drivers – and the existence of these has an impact.

Below we give examples where the combination of resources needs to be considered in generating solutions, and where ignoring this will result in impractical models of the underlying problem.

3.1 Example: Company W Driver's Mates

Driver's mates are common in a number of industries. Company W operates a fleet of heterogeneous vehicles delivering beer. Some vehicles are regularly crewed by 2 people and some by one. But others are floating – a regular driver might be used without mate some days but with a mate from a pool of available labour on another.

3.1.1 Reasons for Mates

The company had several reasons for employing mates:

1. Some customer sites (UK pubs) have trap-door cellars and the barrels or kegs have to be lowered from above with someone guiding the barrel from below. This requires 2 people because customer staff cannot help for health and safety reasons.
2. Some customers are in high-crime areas and leaving a vehicle full of alcohol, while unloading, even if the vehicle is locked, is considered unwise.
3. Two crew working together will make the operation significantly faster (approximately 50%). For trips in dense urban areas this makes delivery with 2 crew economic as the crew and vehicle can return to base for a second (or even third) load.

3.1.2 Cost of Crew

Against this is the fact that a double-manned vehicle is clearly going to cost more to run than a single-manned vehicle – a cost that should be reflected in the optimization objective function.

3.1.3 Optimization

In this case the optimizer has the potential to select whether or not an additional crew member should be assigned, based on the relative cost of the crew member and the savings in vehicles or mileage.

3.1.4 Similar Example: Company C

A similar example is company C – a commercial waste collection company. Here, there are no security issues or requirements for additional crew for specific jobs. Nevertheless double crewing will considerably speed collection because the second crew member can assist in getting bins to the vehicle's rear bin-lift – a speedup of approximately 40% per visit on average.

However, for longer journeys with a greater distance between bins the second crew member is less useful. Also the second crew member is only really effective when there is more than one bin per customer site. This means the choice of crew member is a balance of route structure, order (bin) quantity per collection and cost of the second crewman.

3.2 Example: Company T – Second Driver

In this example, giving a double driving crew enables the vehicle to stay out longer. Certain trips to rural areas require journeys that cannot be accomplished by a single driver in one shift for legal work and driving reasons. However, a double crew is allowed to work for longer – subject to certain rules about the second driver "resting". Employing a two-man crew enables the trip to be accomplished within a single shift.

However, there is an alternative strategy – which is to allow a multi-day trip with the driver taking an overnight break.

The choice is an active one to be considered in optimization – to balance the additional crew member against running overnight shifts and thus using the vehicle for a longer period overall.

3.3 Example: Company L Double-shifting Drivers

In this example, drivers are double-shifted. That is the same vehicle is used on a day shift and a night shift.

This is a problem for two reasons:

1. If we treat it as a doubled resource (i.e. VehicleA-day, VehicleA-night) then there is no intrinsic mechanism to minimize overall vehicle usage across shifts. For example even if we balance the number of vehicles being used, in a heterogeneous vehicle environment (as most real-world routing problems are) we cannot necessarily ensure that the same set of vehicles is used in each shift.
2. If the vehicle usage associated with a shift could exceed 12 hours, then there is no intrinsic mechanism to ensure that one shift finishes before the next one starts. And it is highly likely that shifts could exceed 12 hours – taking into account vehicle reloading between shifts, re-fueling, vehicle checks, and an allowance for on-the-road delays.

3.4 Example: Company M – Drivers allocated to areas, heterogeneous fleet

In this case there is a strong preference to use a particular real driver in a particular area. This may be

a) Because he is familiar with the area (and therefore can navigate and park more effectively). As an example company P cited informal evidence that a parcels driver who did not know the area was less than 50% as effective as one who did.

b) Because he is familiar with the customers – he knows who to find to get sign-off or help with loading, and were to go within a facility.

c) Because the customer is familiar with the driver – and wants to see the same driver each time (considerations of trust and of the driver acting in an informal customer-relationship role).

But overall demand across the area is not necessarily constant. On same days a large vehicle is required, on others a smaller one will suffice. In this case we want to allocate the driver to the area but have flexible choice in vehicle. This may further complicated by the fact that the area is not completely fixed. The orders are likely to create variations on what is ordered on any particular day.

3.5 Example: Company R – Complex Driver, Tractor and Trailer Constraints

This is a complex example where full separate treatment of drivers, tractors and trailers proved to be absolutely essential.

The company concerned is a 3pl (third party logistics provider) that carries out petrol and diesel deliveries on behalf of several clients. Each of the clients operates its own oil terminals supplying oil and has its own customers. Company R carries out the deliveries using a combination of tractors, trailers and drivers that were transferred when it undertook the contracts, plus other tractors, trailers and drivers that were bought and recruited separately.

There are a number of constraints and constraint types:

3.5.1 Driver Training

1. Drivers must be trained to work at a particular oil terminal. Not every driver can collect from all (1 day safety training is typically required per terminal).

2. Drivers must be trained to carry certain product types – due to training in rules on spillage containment and other emergency procedures.
3. Drivers must be trained by client – as each of the client companies has its own paperwork and rules.

3.5.2 Liveries

The vehicles have different liveries (painted logos and writing on the side of the vehicle) that reflects the origin of the vehicle. Company R also has a livery but this is considered neutral.

1. You cannot combine a tractor unit from one client with a trailer unit from another (it gives a confusing marketing message).
2. You can combine a tractor unit from Company R's own fleet with a trailer unit from any client and vice versa.
3. Certain sites may only be delivered with a trailer that matches the client livery.
4. Many sites may only be delivered with tractors and trailers with Company R livery or the client livery.

3.5.3 Compatibility Issues

Product / Trailer Compatibility Only some products may be delivered on some trailers.

Tractor / Trailer Compatibility Not all tractors can be combined with all trailers. There are mismatches of equipment.

Tractor / Trailer / Product Compatibility Some combinations of tractor and trailer are good for some products but not others.

Tractor / Trailer / Customer Compatibility Some combinations of tractor, trailer will work at some customers but not others (typically relates to gravity off load or pumping).

3.6 Where you can use a single resource

The Company R example is extreme. But for all the above cases, the resources in the model need to be considered explicitly in order to achieve a satisfactory model.

However, the single resource case is valid in many cases – probably the majority of situations.

1. Where there is fixed allocation of driver to vehicle and tractor to trailer the attributes of driver and vehicle can be effectively merged.
2. Where there is free allocation of driver to vehicle but all drivers have the same effective constraints.
3. Where there is no effective limit on the number of drivers or vehicles – for example in strategic modelling of resources required for a given contract.

4. Non-Linear Loading

The standard variation on the VRP – the Capacitated Vehicle Routing Problem (CVRP) [6] considers the vehicle capacity and the demand as quantity. This can be trivially extended to 2 dimensions – weight and volume.

The primary characteristic is that, regardless of the dimension, the capacity of the vehicle in that dimension is compared to the sum of the demand for each customer on the trip. This the linear loading. It is close to correct for weight because packaging tends not to be very heavy. It is correct with respect to a bulk single liquid. However, it is quite a poor model for majority of loading situations.

Before discussing those, we need to consider compartments.

An extension of the standard model is the compartmented vehicle. This does get some academic consideration, although "*Despite the vast amount of literature about vehicle routing problems, only very little attention has been paid to vehicles with compartments that allow transportation of inhomogeneous products on the same vehicle, but in different compartments*" – Derigs, Gottleib et al [2]. But even when these authors do consider the compartmented model, they simply move the linear model to a second level of component – the compartment – this is fine for bulk liquids but not an answer to the real problem.

4.1 Example: Company B – Roll-cages and Pallets

In this case the customer has several causes for non-linearity of volume.

1. The vehicle has two temperature zones separated by a moveable lateral barrier which can be removed (folder up into the roof space) altogether. The front, frozen zone has a minimum size that occupies at least 1.1 pallet lengths. The vehicle is a standard 2 pallets in width. The goods are loaded onto pallets. Because the barrier is lateral, any small amount of frozen product will occupy 2.2 pallet spaces. Further frozen goods will be rounded up to 4, 6 or 8 pallet spaces.
2. Ambient and chilled goods are packed into roll cages or onto pallets depending on customer requirements and source of goods (there are multiple warehouses). Roll-cages are one third of the width of the truck, pallets half the width. A completely efficient packing thus requires a multiple of 3 roll cages and a multiple of 2 pallets – or it would if it were not for the fact that pallets cannot be placed two abreast if it causes a barrier preventing access to roll-cages from the rear door of the truck. As a consequence a corridor of space may need to be left – depending on the sequence of visits.
3. Goods are packed into roll cages by the customer – according to various rules that minimize mixing and facilitate unloading. These rules mean that empty space is left on the roll cage.

4.2 Example: Company N – Packed Lubricants

Packed lubricant vehicles carry lubricants pre-packed into drums, pails, cases and totes (see above). Totes and drums can be off-loaded direct at the customer. Alternatively they can retained on the vehicle and pumped off. Some of the packed vehicles have built-in pumps for this purpose. Others use a mobile pump. But the mobile pump takes a full pallet footprint which is then unavailable for goods. As a consequence one tote requiring pumping effectively occupies two spaces, and two totes occupy three spaces. A single drum requiring pumping will occupy 1 ¼ spaces (4 drums per pallet).

A further issue is that everything except the totes is always palletized and you cannot mix drums on a pallet with other products – so one drum occupies one pallet space and four drums also occupies one pallet space.

4.3 Example: Company G – Pipes

Company G delivers pipes and other products. To secure the pipes in transit they are stored in racks or *stillages*. Each stillage has the width of a pallet and can be from one to six pallet lengths. It has a capacity of approximately 50 pipes (depends on pipe diameter).

As a consequence one 4m pipe of 5cm diameter will require a 4-pallet length stillage and occupy 4 pallet spaces. The next 49 pipes will add no additional volume as they will slot into the existing stillage. The 51st pipe will add another 4 pallet spaces.

The author has been unable to find appropriate examples for modelling these problem types in the academic literature.

5. Conclusion

This paper presented 3 different areas which cannot be modelled with the conventional VRP and its standard variants. Some work has been made to model related problems in the literature, but in each case papers describe or re-iterate that the amount of work in each area is limited. And in none of the papers the author has identified is the problem that has been addressed nearly as complex as the real-world problem. These real-world problems, although addressed by the commercial Optrak software using relatively simple heuristics, are ignored by the academic research community. Modern techniques, including metaheuristics have not been applied to these problems. They are *missing from the model*.

6. Summary of Companies

Company A 3rd Party delivery of bulk lubricants. Orders to same location with different time horizons.

Company B A food services company.

Company C Waste collection. Illustrates requirement for orders.

Company G Delivers pipes and other long items, packed into *stillages* – a form of mobile racking.

Company N A lubricants delivery company delivering a mixture packed and bulk products.

Company P A parcel delivery company

Company R Delivery of petroleum products. Company R delivers petrol, diesel, aviation fuel and similar products to petrol stations, airports, lorry parks and other customers requiring large deliveries (10,000 litres or above). Illustrates requirement for flexible resource modelling.

Company W Brewer delivering beer, wines and spirits to pubs and restaurants.

Company Z Delivery of newspapers from depots to newsagents and other shops. Illustrates requirement for orders.

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