Fifty Years of Operational Research 1972-2022

1 Euro Gold Medal Presentation
July 2022

Gilbert Laporte, Professor Emeritus, HEC Montréal, CIRRELT, GERAD. Canada
Professor, University of Bath, United Kingdom
Professor II, Molde University College, Norway

Thank you for awarding me the EURO Gold Medal!

- Thank you to all my friends in the OR community
  - > 420 coauthors
  - 47 Ph.D students
  - 55 Master's students
  - 32 Postdoctoral fellows

- And to some very special coauthors, including 7 EURO Gold Medal recipients
  - Jacek Błazewicz 1991
  - Pierre Hansen 1986
  - Martine Labbé 2019
  - Ailsa H. Land 2021
  - Silvano Martello 2018
  - Paolo Toth 1998
  - Jan Węglarz 1991

Aim: *"To present some of [my] major and recent contributions to the body of knowledge in Operational Research"*
(Sarah Fores, May 2022)

#10 The Seriation Problem

- How to sequence grave sites based on the archeological artefacts found in them?

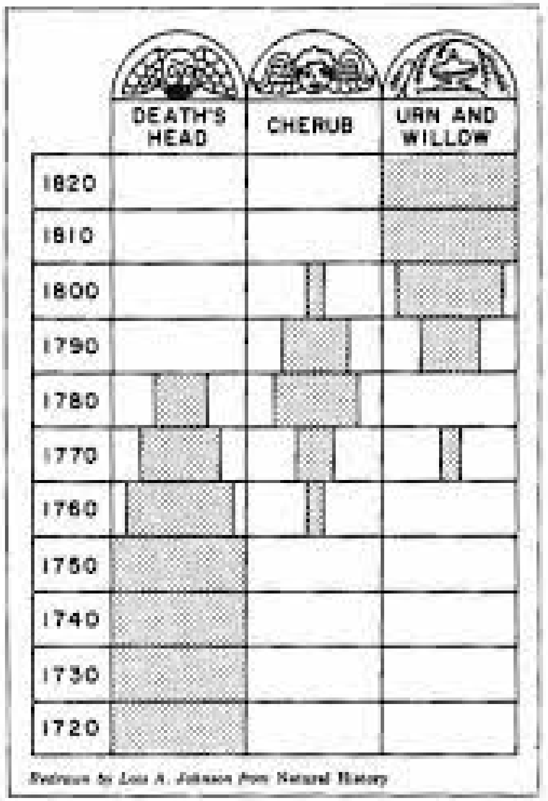
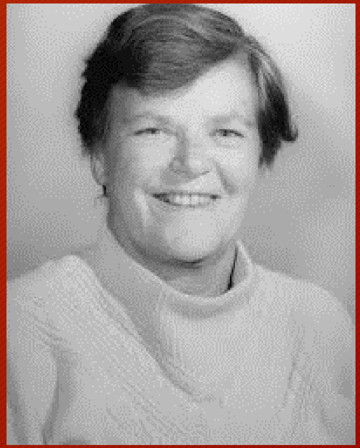


FIGURE 1. Stylistic Sequence from a Cemetery in Stoneham, Massachusetts.

PhD Thesis: 1972-1975
London School of Economics

Supervisor: Ailsa H. Land



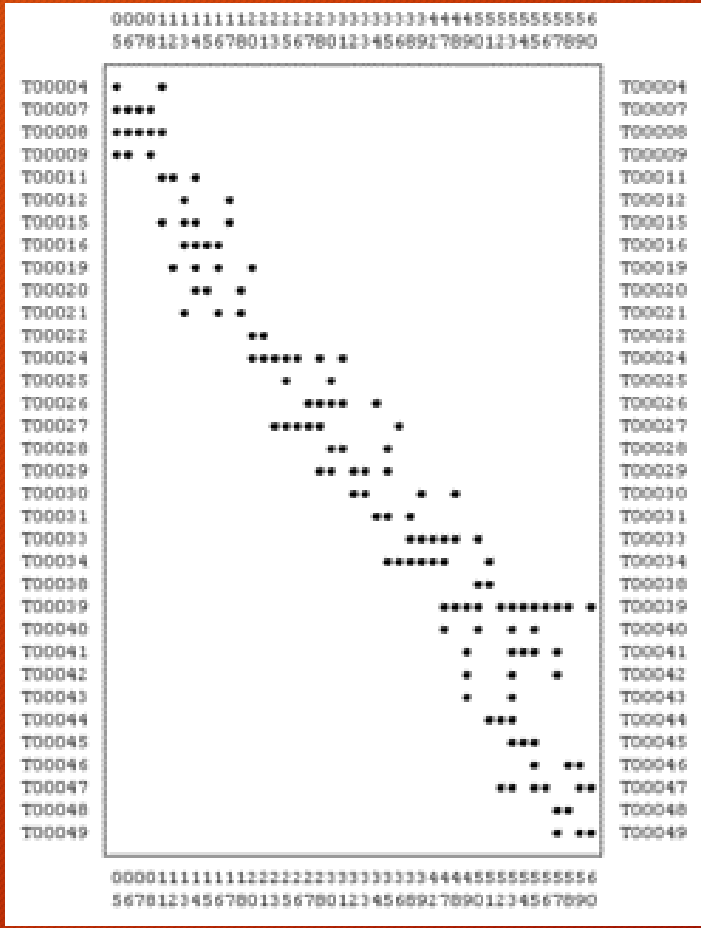
#10 The Seriation Problem (continued)

How to sequence grave sites based on the archeological artefacts found in them?

Permute the rows to minimize the total spread of 1s over the columns

Methodologies

- Combinatorial Bounds
- Integer Linear Programming
- Dynamic Programming



Laporte, G. (1976). A comparison of two norms in archaeological seriation. *Journal of Archaeological Science*, 3(3), 249-255.

#9 Rotating Work Schedules

- How to create rotating schedules for police and firefighters?

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	X	X	X	D	D	D	D
2	X	X	E	E	E	X	X
3	D	D	D	X	X	E	E
4	E	E	X	X	N	N	N
5	N	N	N	N	X	X	X

Figure 1 Schedule 1. A five week cycle with uniform workload requirements.

N = Night; E = Evening; D = Day; X = Off

Maximize number of full weekends off and control spacing
All employees follow the same cyclical schedule
Average number of weekly work hours is controlled
Constraints on number of consecutive days on and off

#9 Rotating Work Schedules (continued)

- How to create rotating schedules for police and firefighters?

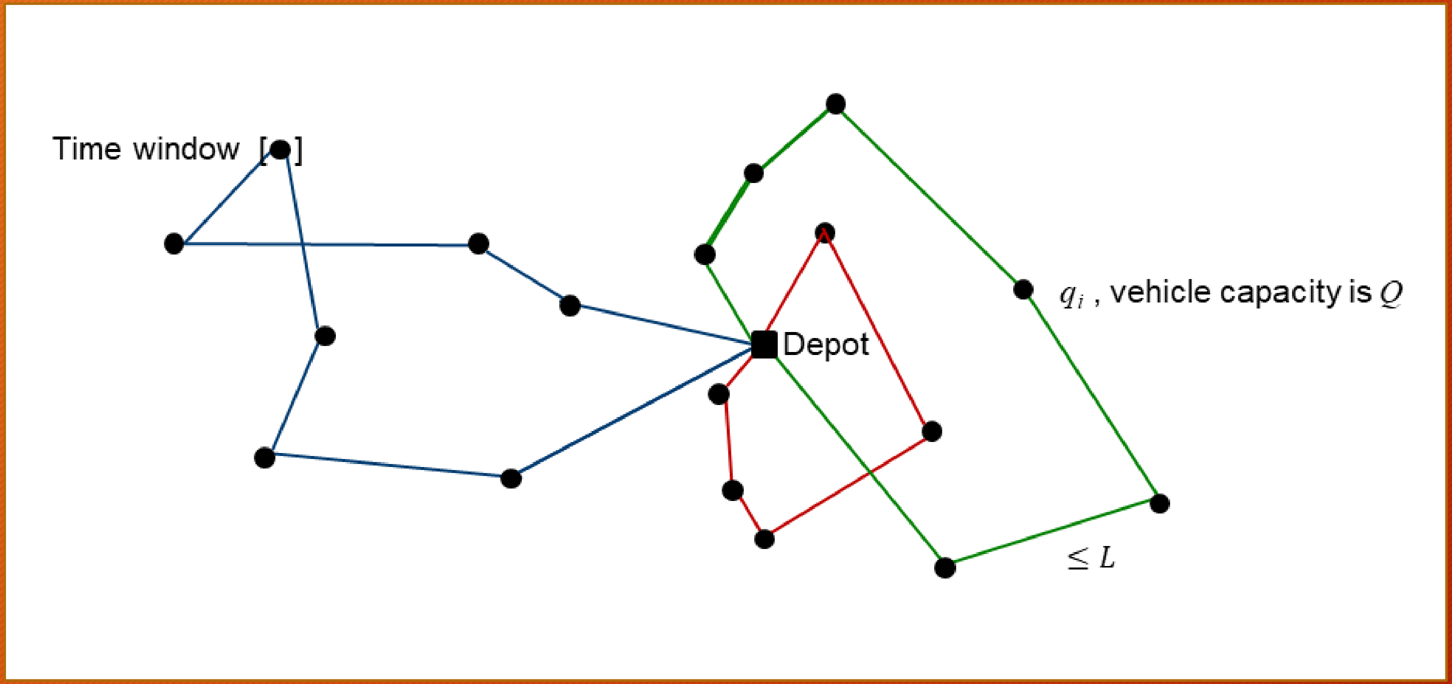
Fraternité des policiers et policières de Montréal

- Started as consulting project Montreal police union 1975-76
- Became scientific project
  - Hand-made solutions
  - Integer linear programming
  - Constraint programming

Laporte, G. (1999). The art and science of designing rotating schedules. *Journal of the Operational Research Society*, 50(10), 1011-1017.

#8 Vehicle Routing

- How to create optimal vehicle routes?



- Here there are n = 18 customers and m = 3 vehicles
- Typical constraints: 1) capacity, 2) route length (duration), 3) time windows
- The Traveling Salesman Problem has only one vehicle and no constraints

#8 Vehicle Routing (continued)

- How to create optimal vehicle routes?

MANY APPLICATIONS

- Parcel delivery (Amazon; Alibaba)
- Food delivery (e-groceries)
- Mailbox collection
- Beer distribution
- Dial-a-ride problems
- Maritime routing

MANY VARIANTS

- Heterogenous vehicle fleets
- Pickup and delivery problems
- Several depots
- Multiple time windows
- Flexible time windows
- Cross-docking
- Optional customers
- Multiple compartments
- Stochasticity (demand, travel time)

#8 Vehicle Routing (continued)

$$\min \sum_{(i,j)\in E} c_{ij}x_{ij} + fm$$

$$\text{s.t.} \begin{cases} \sum_{j\in V\setminus\{0\}} x_{0j} = 2m & \\ \sum_{i<k} x_{ik} + \sum_{j>k} x_{kj} = 2 & k \in V \setminus \{0\} \\ \sum_{\substack{i\in S, j\in V\setminus S \\ \text{or } i\in V\setminus S, j\in S}} x_{ij} \geq \left\lceil \sum_{i\in S} q_i/Q \right\rceil & S \subset V \setminus \{0\} \\ x_{0j} = 0,1,2 & j \in V \setminus \{0\} \\ x_{ij} = 0,1 & i,j \in V \setminus \{0\}. \end{cases}$$

How to create optimal vehicle routes?

- Branch-and-cut works well on loosely constrained instances, but not on tightly constrained instances
- Several TSP valid inequalities can be adapted to the VRP, e.g., comb inequalities

Laporte, G., Nobert, Y., & Desrochers, M. (1985). Optimal routing under capacity and distance restrictions. *Operations Research*, 33(5), 1050-1073.

#7 Examination Timetabling

How to create construct examination schedules?

Exam Schedule as of March 31st for **Spring 2022**

Please visit go.sfu.ca for the latest date/time

ACMA	201	D100	B.Sanders	MON	25-Apr	12:00-15:00	R	SWH10061
ACMA	340	D100	R.Wang	MON	25-Apr	15:30-18:30	R	SWH10075
ACMA	401	D100	C.Tsai	TUE	26-Apr	19:00-22:00	R	RCB5120
ACMA	470	E100	J.Giles	TUE	19-Apr	23:59-23:59	R	TAKE-HOME
ARAB	100	D100	R.Mehri	MON	25-Apr	08:30-11:30	R	WMC2532
ARCH	100	D100	F.Berna	SUN	24-Apr	12:00-15:00	R	RCBIMAGTH
ARCH	100	OL01	D.Maxwell	SAT	23-Apr	15:30-16:30	R	REMOTE
ARCH	101	C100	D.Maxwell	TUE	12-Apr	08:30-11:30	R	REMOTE
ARCH	131	D100	D.Sandgathe	MON	25-Apr	19:00-21:00	R	WMC3520
ARCH	131	D200	M.Collard	TUE	26-Apr	12:00-15:00	R	WMC3260
ARCH	131	OL01	D.Sandgathe	TUE	26-Apr	08:30-10:30	R	REMOTE
ARCH	226	C100	D.Maxwell	TUE	12-Apr	12:00-15:00	R	REMOTE
ARCH	226	D100	D.Maxwell	SUN	24-Apr	12:00-15:00	R	AQ3181
ARCH	285	D100	F.Berna	THU	14-Apr	22:30-22:30	R	TAKE-HOME

- Assign exams to slots in a grid
- Avoid conflicts
- Space out exams by the same student
- Several side constraints

#7 Examination Timetabling (continued)

How to create construct examination schedules?

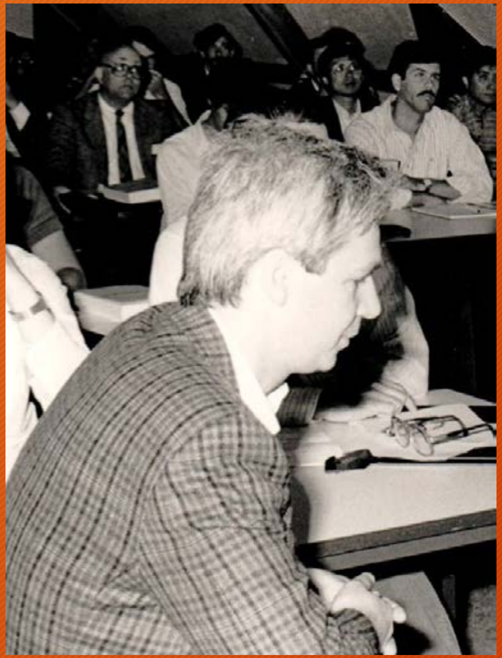
- Methodology: Initial solution & local search
- EXAMINE software developed with Michael W. Carter (U. of Toronto) and distributed in several universities
- Practice Prize 1992, *Canadian Operational Research Society*

Michael W Carter

Carter, M. W., Laporte, G., & Chinneck, J. W. (1994). A general examination scheduling system. *Interfaces*, 24(3), 109-120.

#6 Stochastic Programming

How to solve stochastic integer programs?



François V. Louveaux

Integer L-Shaped Method (Extension of Benders)

- Three steps: (1) planned solution x; (2) random event; (3) apply recourse action of expected cost Q(x)
- Compute lower bound θ on Q(x) associated with solution x
- Compute Q(x): if Q(x) > θ, add optimality cut to force a new solution

Laporte, G., & Louveaux, F. V. (1993). The integer L-shaped method for stochastic integer programs with complete recourse. *Operations Research Letters*, 13(3), 133-142.

#6 Stochastic Programming (continued)

How to solve stochastic integer programs?

AN INTEGER *L*-SHAPED ALGORITHM FOR THE CAPACITATED VEHICLE ROUTING PROBLEM WITH STOCHASTIC DEMANDS

GILBERT LAPORTE

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LUC VAN HAMME

OM Partners, Michielssendreef 40/42, B-2130 Brasschaat, Belgium, lvanhamme@ompartners.com

(Received October 2000; revision received January 2001; accepted January 2001)

The classical Vehicle Routing Problem consists of determining optimal routes for m identical vehicles, starting and leaving at the depot, such that every customer is visited exactly once. In the capacitated version (CVRP) the total demand collected along a route cannot exceed the vehicle capacity. This article considers the situation where some of the demands are stochastic. This implies that the level of demand at each customer is not known before arriving at the customer. In some cases, the vehicle may thus be unable to load the customer's demand, even if the expected demand along the route does not exceed the vehicle capacity. Such a situation is referred to as a failure. The capacitated vehicle routing problem with stochastic demands (SVRP) then consists of minimizing the total cost of the planned routes and of expected failures. Here, penalties for failures correspond to return trips to the depot. The vehicle first returns to the depot to unload, then resumes its trip as originally planned. This article studies an implementation of the Integer *L*-shaped method for the exact solution of the SVRP. It develops new lower bounds on the expected penalty for failures. In addition, it provides variants of the optimality cuts for the SVRP that also hold at fractional solutions. Numerical experiments indicate that some instances involving up to 100 customers and few vehicles can be solved to optimality within a relatively short computing time.

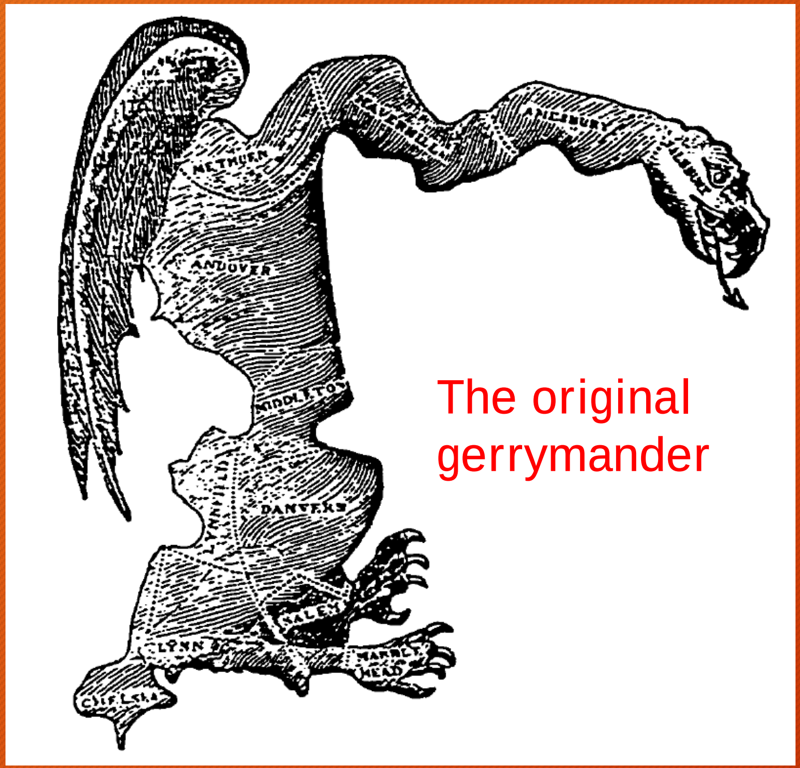
Has been applied to the solution of stochastic vehicle routing problems

- Stochastic travel times
- Stochastic demands

Best Paper Prize: Transportation Science and Logistics Section of INFORMS, for the article "An Integer L-Shaped Algorithm for the Capacitated Vehicle Routing Problem with Stochastic Demands", G. Laporte, F.V. Louveaux, L. Van hamme (*Operations Research*, 50, 415-423, 2002), 2004.

#5 Districting

How to partition a territory into districts?



The original gerrymander

- Partition a territory into districts by agglomerating small cells (census tracts)
- Used for electoral maps, sales territories, etc.
- Contiguous, equitable and compact districts
- NO GERRYMANDERING!
- Multicriteria problem solved by tabu search

#5 Districting (continued)

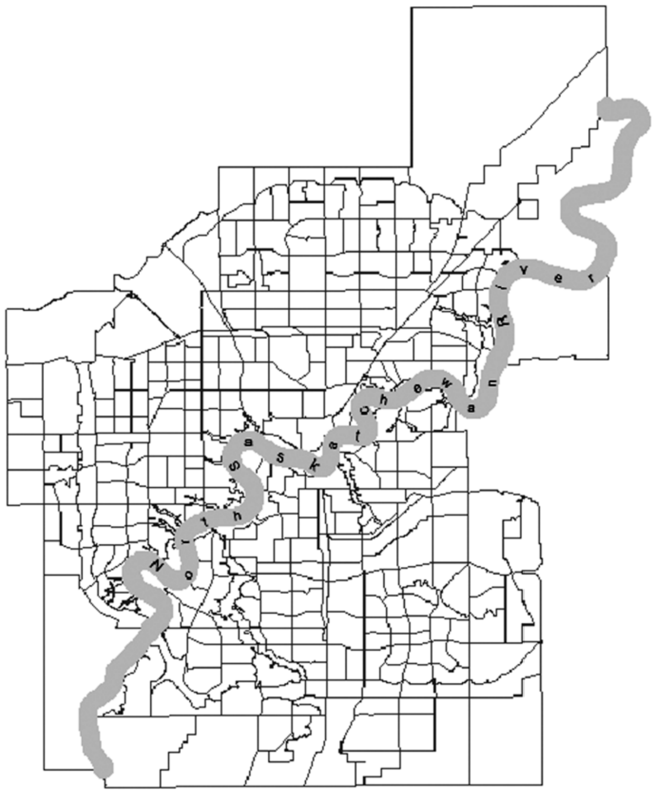


Figure 8: The map shows Edmonton neighborhoods used as basic units for districting.

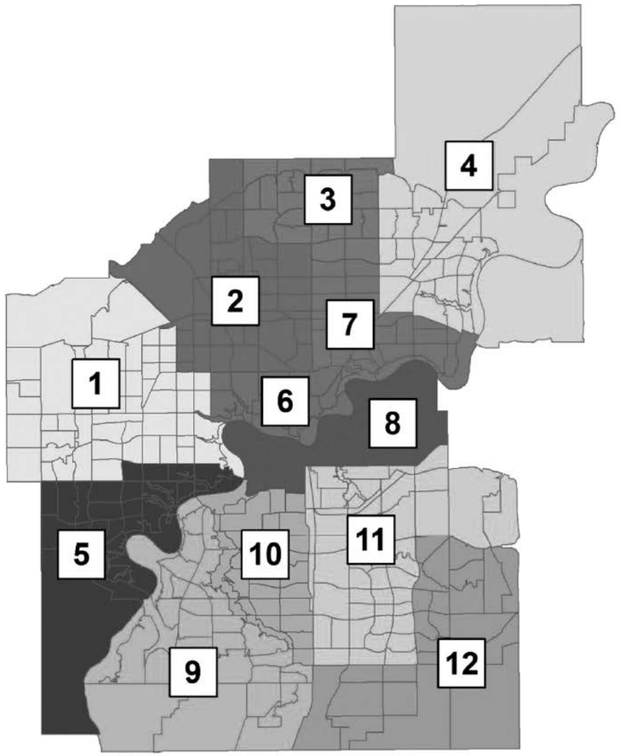


Figure 10: This proposed district plan for the city of Edmonton was recommended to the city council. Although this plan is similar to the plan in Figure 9, note the difference between districts 11 and 12.

How to partition a territory into districts?

Application to City of Edmonton, Alberta

- Practice Prize 2010, *Canadian Operational Research Society*

Bozkaya, B., Erkut, E., Haight, D., & Laporte, G. (2011). Designing new electoral districts for the city of Edmonton. *Interfaces, 41(6), 534-547.*

#4 Arc Routing & Waste Management

How to plan garbage collection routes?

- A lot more than arc routing
  - Districting
  - Facility location
  - Scheduling
  - Vehicle fleet composition
  - Inventory control
- Very large scale problems
- Heuristics needed
- Difficulty in measuring departure from optimality

Sanne Wøhlk

Project funded by Danish Council for Independent Research - Social Sciences; Transportation issues in waste management

#3 Metro Network Design

How to design metro networks?

Very complex problem

- High cost
- Uncertainty
- Externalities
- Multiple decision makers

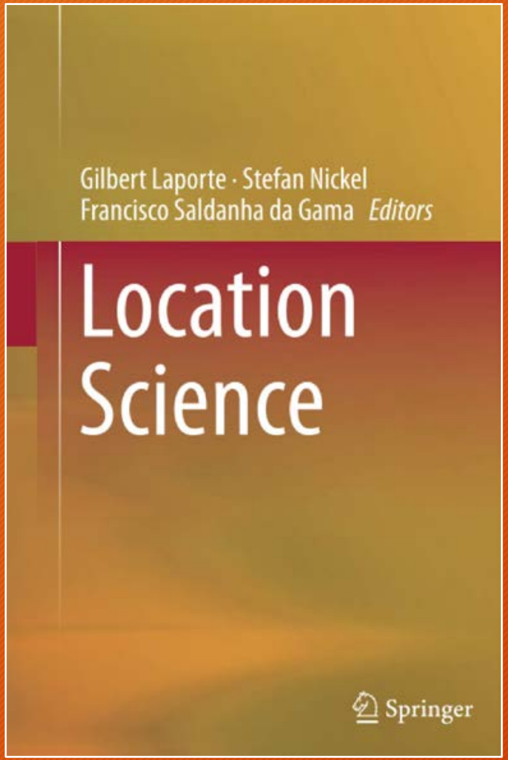
Operational research can help generate good networks

- Good interconnections
- Good coverage
- Budget constraint

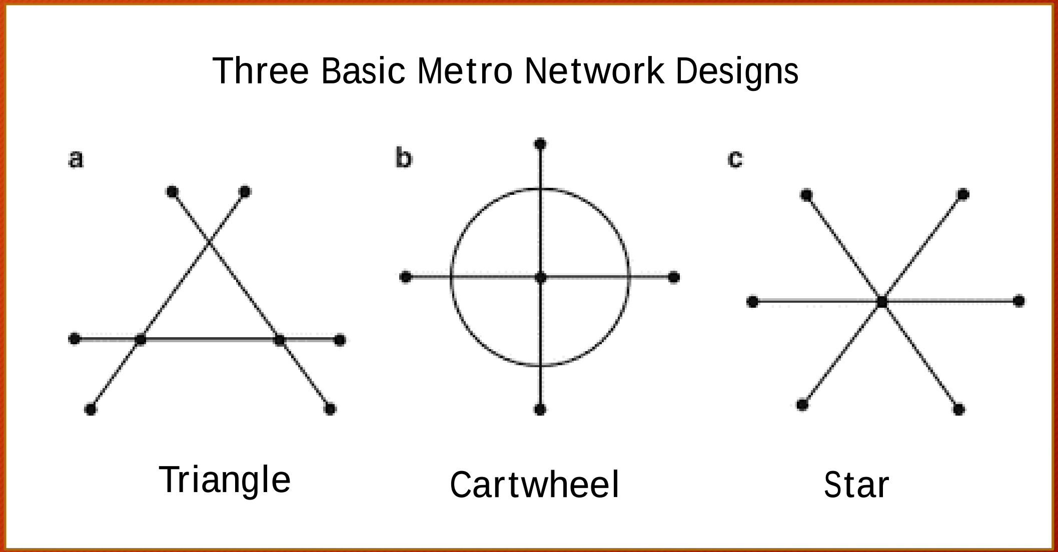
Juan A Mesa

#3 Metro Network Design (continued)

How to design metro networks?



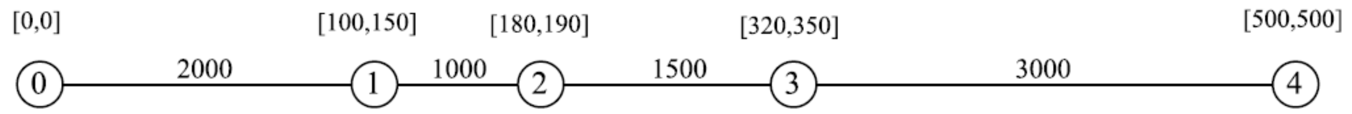
Laporte, G., Mesa, J.A., "The Design of Rapid Transit Networks", *Location Science* (Second Edition), G. Laporte, S. Nickel and F. Saldanha da Gama (eds.), Springer, Cham, 687-703, 2019.



- Define a shape and broad corridors
- Fine-tuning: local search or integer linear programming
- Produce several candidate solutions

#2 Green Transportation

How to design green transportation solutions?



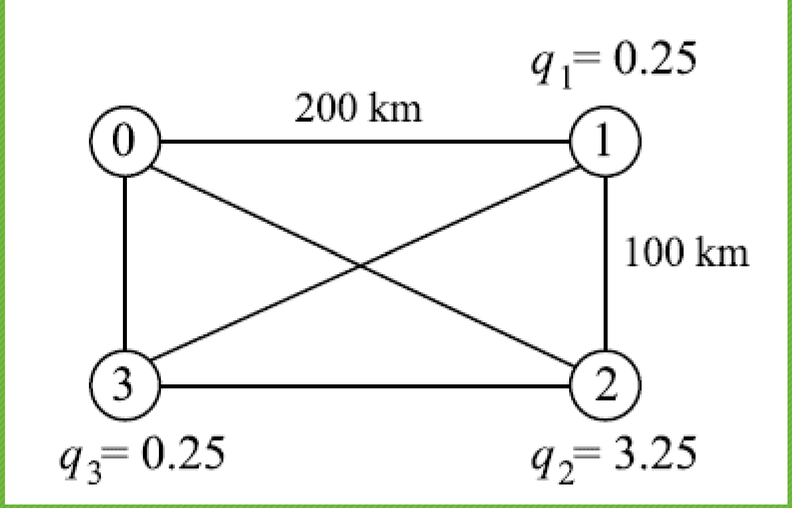
Fi p route with time windows

- In maritime shipping, emissions are a convex (cubic) function of speed
- Determine speed on each segment to minimize total emissions and satisfy time windows
- $O(n^2)$ exact algorithm

Hvattum, L. M., Norstad, I., Fagerholt, K., & Laporte, G. (2013). Analysis of an exact algorithm for the vessel speed optimization problem. *Networks*, 62(2), 132-135.

#2 Green Transportation (continued)

How to design green transportation solutions?



Pollution-routing problem

- Energy ≈ A(load x distance) + B(speed^2 x distance) if speed ≥ 40 km/h

- (0,1,2,3,0) distance = 600
  weighted load = 2950
- (0,2,1,3,0) distance = 647.21
  weighted load = 2886.07

- Time windows and travel time costs add further complications

Tolga Bektaş

Bektaş, T., & Laporte, G. (2011). The pollution-routing problem. *Transportation Research Part B: Methodological*, 45(8), 1232-1250.

#2 Green Transportation (continued)

How to design green transportation solutions?

Electric vehicles

- Where, when and by how much to recharge batteries?
- Incentives for EV adoption
- EVs have a higher purchase cost than conventional vehicles but lower running cost
- Robust solutions in stochastic contexts
- How to transition to an electric fleet

Pelletier, S., Jabali, O., & Laporte, G. (2016). Goods distribution with electric vehicles: review and research perspectives. *Transportation Science*, 50(1), 3-22.

Samuel Pelletier

Ola Jabali

Honourable Mention: Dartboard Design

How to design the most challenging dartboard?

Original dartboard designed by Brian Gamlin (Bury, Lancashire) in 1896; Risk level = 2480

Optimized dartboard designed by HA Eiselt and Gilbert Laporte in 1991; Risk level = 2642

Assumptions:

- Players hit their target or the one ajacent to it. All targets are equally likely
- Risk = sum of squared deviations from target position and obtained position
- Modeled as a Traveling Salesman Problem

HA Eiselt

Eiselt, H. A., & Laporte, G. (1991). A combinatorial optimization problem arising in dartboard design. Journal of the *Operational Research Society,* 42(2), 113-118.

#1 Humanitarian Logistics

How to restore the water supply network in Nepal following 2015 earthquakes?

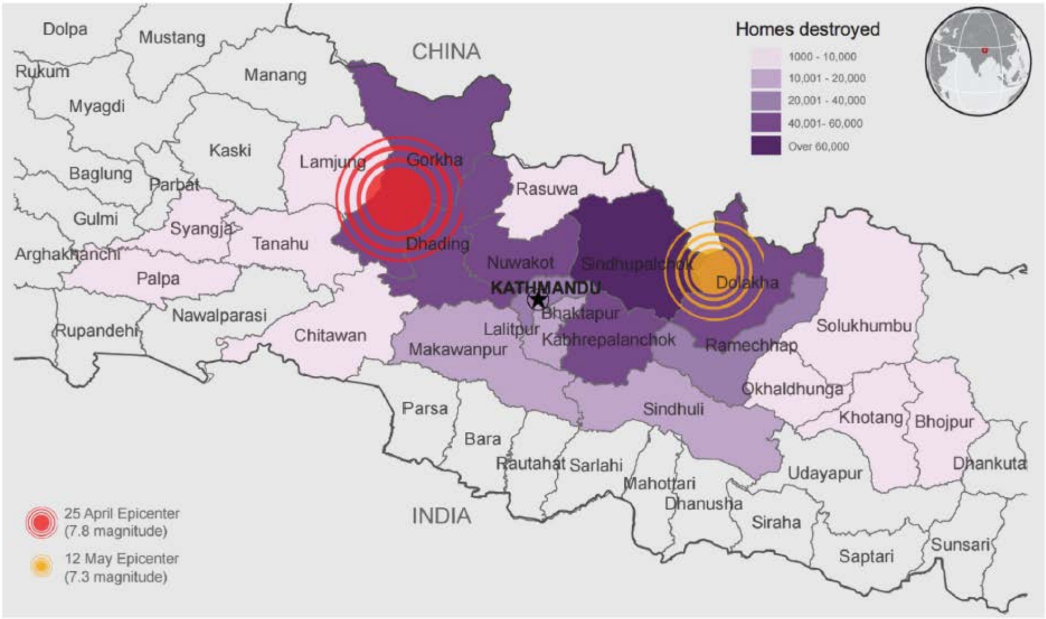
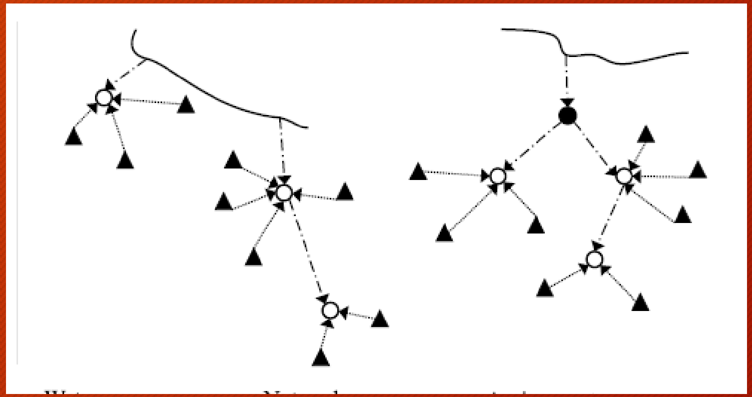


Fig. 1. Epicenters of the Gorkha and Dolakha earthquakes.
Source: Goldberg (2015).

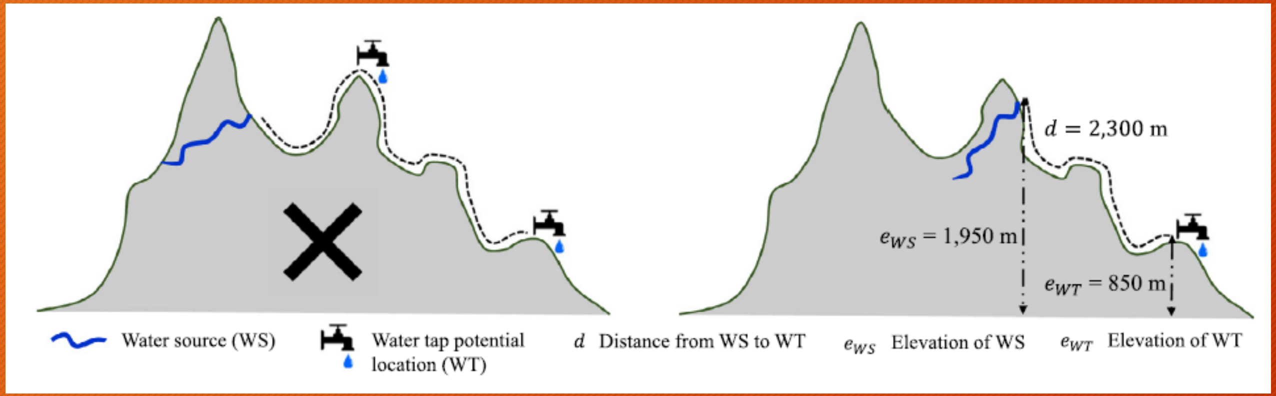
Locate water taps and connect them to water sources through a Steiner forest



- Locate water taps and assign users (fixed charge facility location problem solved exactly)
- Connect water taps with a Steiner Forest: simulated annealing

#1 Humanitarian Logistics (continued)

How to restore the water supply network in Nepal following 2015 earthquakes?

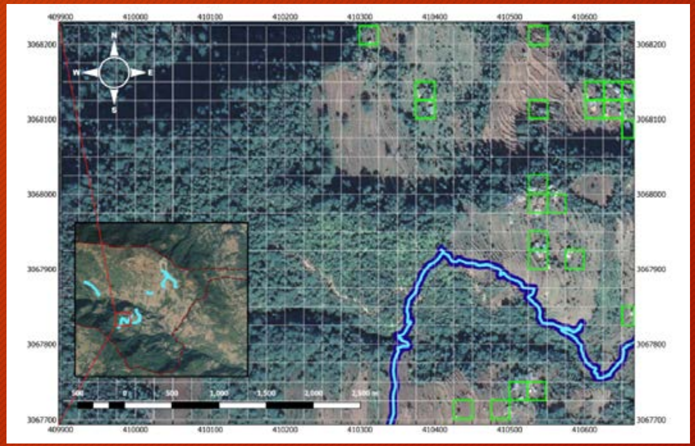


Gravity constraint (pumps are not used):

$$e_{ws} - e_v - \gamma\, d_{ws,\,v} \geq 0 \quad (\gamma = 0.1)$$

Williams and Hazen, 1933

Tests on two communities in Dolhaka District: Suspa Kshemawati (29,910 vertices, 75,200 arcs) and Lapilang (28,500 vertices, 68,300 arcs)



Marie-Ève Rancourt

Jessica Rodríguez-Pereira

Selene Silvestri

Laporte, G., Rancourt, M.-È., Rodríguez-Pereira, J., & Silvestri, S. (2022). Optimizing access to drinking water in remote areas. Application to Nepal. *Computers & Operations Research*, 140, 105669.

Thank you for your attention!