CIVIL-557

Decision Aid Methodologies In Transportation

Lecture 1: Introduction to operations research

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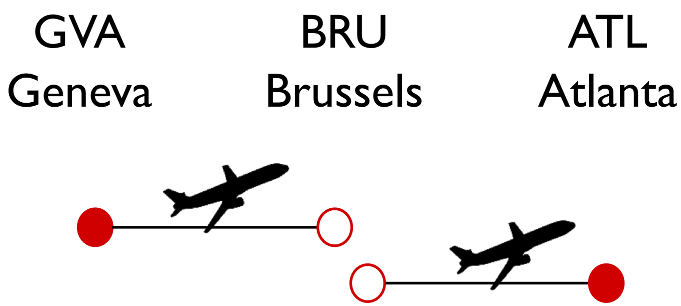
Transport and Mobility Laboratory TRANSP-OR
École Polytechnique Fédérale de Lausanne EPFL

Introduction

DELTA

Introduction



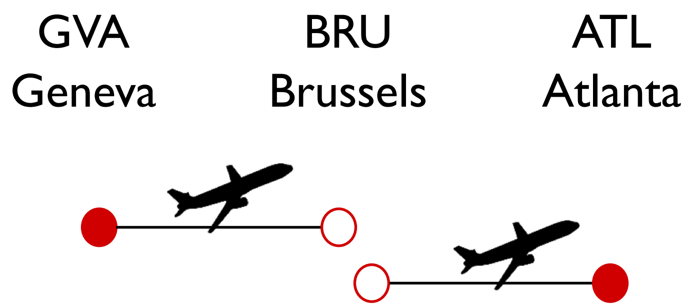
Which aircraft type should be assigned to each flight leg?

Airline fleet assignment problem

Maximize revenues from seats - finding the optimal balance:

1. Demand >> Capacity
2. Demand << Capacity

Introduction



Which aircraft type should be assigned to each flight leg?

Minimizing operating costs:

- Flight crew
- Fuel consumption
- Maintenance operations
- …

Under a variety of constraints:

- Cover constraint
- Balance constraint
- Availability constraint
- …

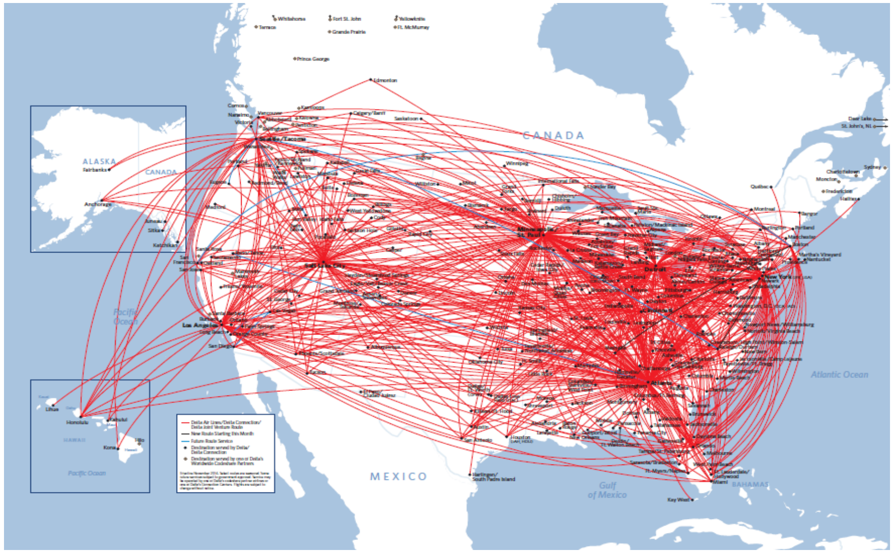
Introduction

Delta Air Lines international network:

- **325 destinations**
- **60 countries**
- **6 continents**

- Over **5,400 daily flights**
- More than **800 aircraft**
- **19 different fleets**

North America



Introduction

Fleet Assignment at Delta Air Lines:

- *September 1992:*

How to solve this problem ?

Coldstart system (1992)

- Use advances in mathematical programming and computer hardware
- Savings in the June 1, 1993 to August 31, 1993 schedule: **$220,000/day**

The Coldstart system is a successful real-world applications of Operation Research

Introduction

What is Operations Research?

*Operations Research (O.R.) is **a discipline** that deals with the **application of advanced analytical methods** to help make **better decisions**.*

INFORMS, *What is Operations Research ?*

*Operations research encompasses a wide range of **problem-solving techniques and methods** applied in the pursuit of **improved decision-making and efficiency** (…).*

INFORMS, *What is Operations Research ?*

*In its most basic form, Operations Research (O.R.) may be viewed as a **scientific approach to solving problems**; it abstracts the essential elements of the problem into **a model**, which is then **analyzed to yield an optimal solution for implementation.***

Jayant Rajgopal, *Principles and Applications of Operations Research*.

*OR: The **Science of Better**.*

INFORMS, http://www.scienceofbetter.org/.

Introduction

Agenda

- Lecture (8:15 – 10:00)
  - Course information
  - Operations research modeling approach

- Lab (10:15 – 12:00)
  - Practice examples

Course information

Course information

- 2 lecturers :
  - Dr. Nikola Obrenovic
  - Dr. Tim Hillel

- Course based on concrete case studies

- Class structure
  - Lectures: 2 hours per week and exercises: 2 hours per week
  - Interactive lectures: 4 hours per week

- 1 guest lectures session:
  - Dr. Iliya Markov and Dr. Marco Laumanns from BestMile
  - Dr. Alessandro Zanarini from ABB

Evaluation

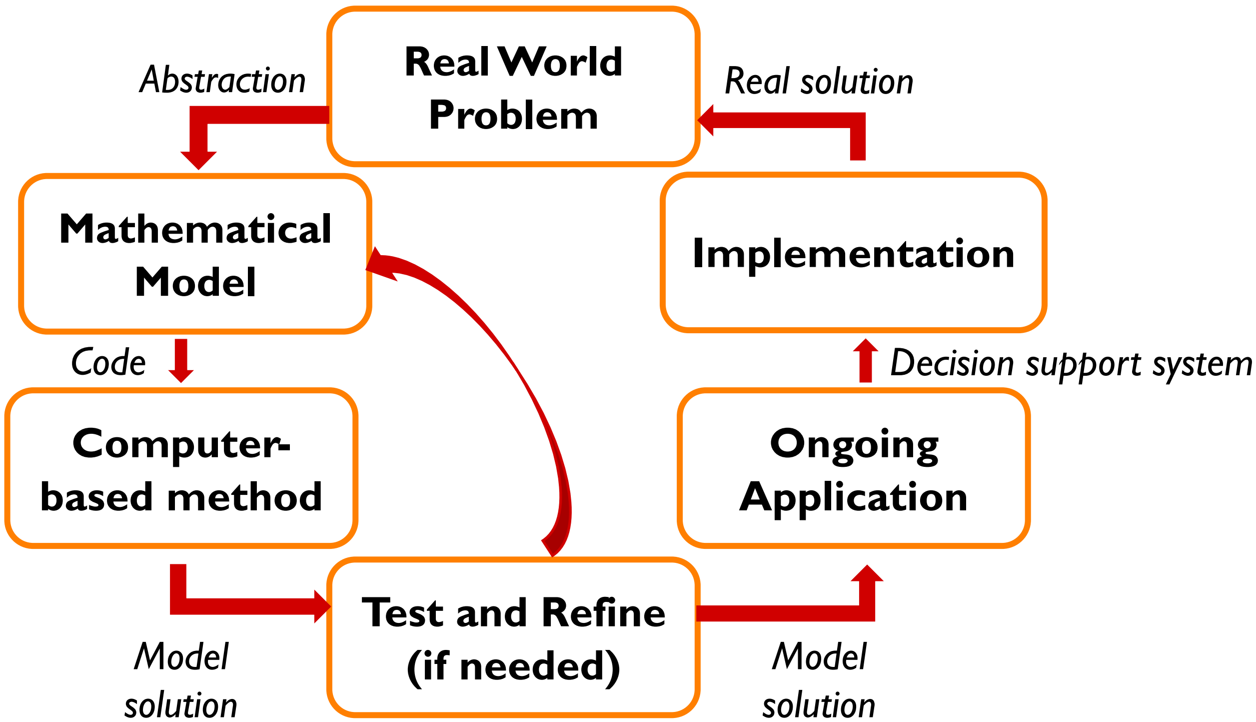
- **Mid-term exam (20%)**
  - **20 multiple choice questions**
- **Final exam (80%)**
  - **Groups of 2-3 members each**.
  - **Oral exam** organized in June
    - **Project-based**
    - **Presentation of maximum 20 minutes**
    - Questions about the presentation itself, but also on any material covered during the semester
    - **No authorized material**

Lectures

Date	Lecturer	Topic
Feb 19	Nikola Obrenovic	Introduction to decision science and linear optimization
Feb 26	Nikola Obrenovic	Linear Programming and Duality
Mar 5	Tim Hillel	Introduction to Python and data visualisation
Mar 12	Tim Hillel	Classification methods 1: Logistic regression and probabilistic metrics
Mar 19	Tim Hillel	Classification methods 2: Deterministic methods and discrete metrics
Mar 26	Guest Speaker	Operations Research in Practice
Apr 2		**Mid-term exam**
Apr 16	Nikola Obrenovic	Integer optimization
Apr 16	Nikola Obrenovic	Multicommodity Network Design I
Apr 23		**No Lecture (Easter Holidays)**
Apr 30	Nikola Obrenovic	Multicommodity Network Design II
May 7	Tim Hillel	Classification methods 3: Ensemble methods and hyperparameter search
May 14	Tim Hillel	Classification methods 4: Issues with performance validation
May 21	Hillel and Obrenovic	Research Topics from TRANSP-OR and Presentation of the Final Projects
May 28	Hillel and Obrenovic	Questions and Answers

Overview of the operations research modeling approach

6-steps O.R. Modeling Approach



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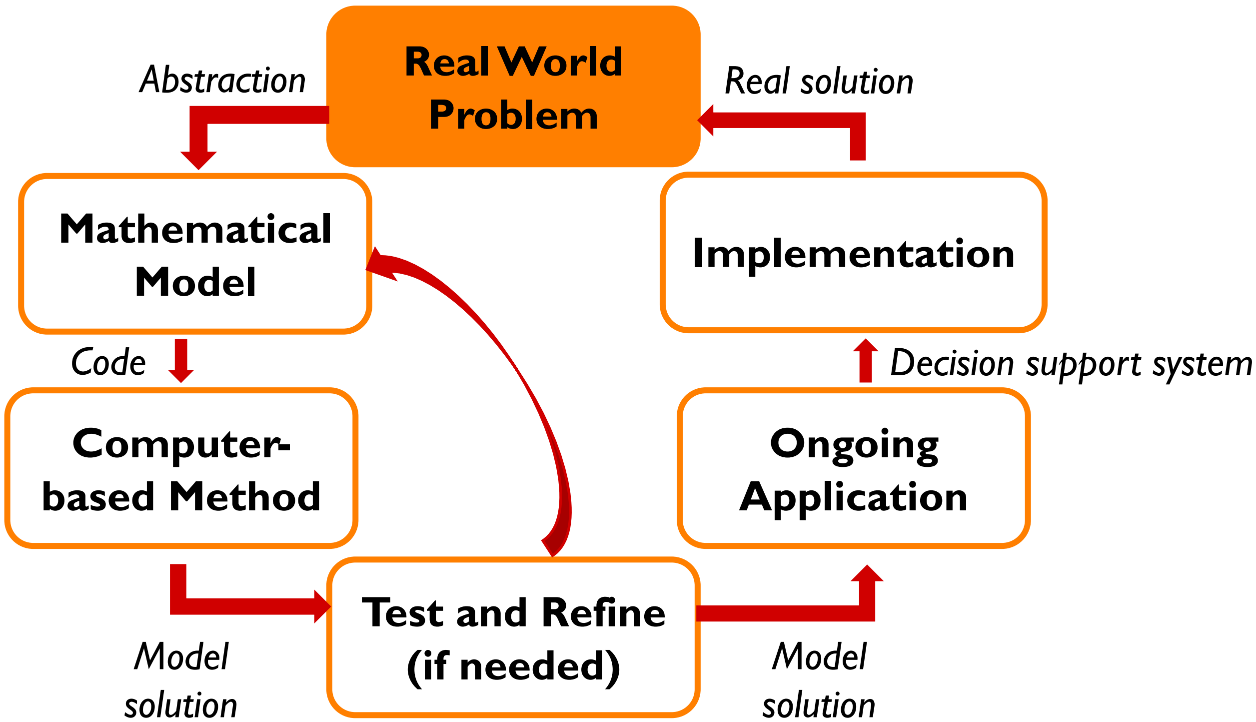
6-steps O.R. Modeling Approach



Defining the problem of interest

Textbook examples	Real-world problems
Described in a simple, precise way	Described in a vague, imprecise way

"It is difficult to extract a *right* answer from the *wrong* problem"

- Real-world problems are **complex**, **multi-dimensional problems**
- Importance of developing a **well-defined statement of the problem**

Delta Air Lines Example

- What are the appropriate objectives ?
- Are there constraints on what can be done ?
- What is the time horizon?
- Is there a time limit to make a decision?
- …

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Stakeholders

- OR team members are advising management
- OR should be concerned with the welfare of the entire organization
- Different parties with different objectives
  - Owners
  - Employees
  - Customers
  - Suppliers
  - Government
- Tradeoff between operational cost and quality of service provided to the users

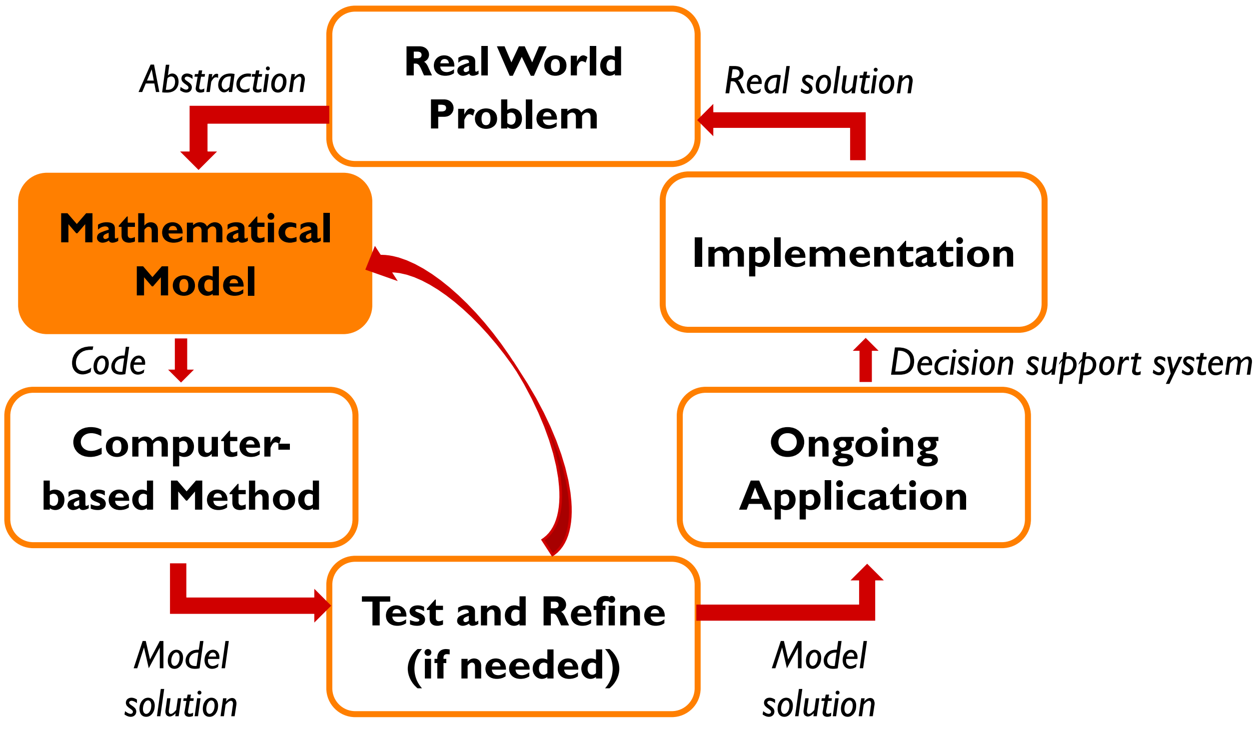
Delta Air Lines Example

Gathering relevant data

- Gathering relevant data is crucial but takes time
- Much data are needed to:
  - Gain an accurate understanding of the problem
  - Provide the input for the mathematical model
- Much data are not available when the study begins:
  - Information has never been kept
  - What was kept is outdated or in the wrong form
  - Information is confidential
- Much effort has to be devoted on gathering all the needed data
- Most of the time you only have rough estimates

Delta Air Lines Example

6-steps O.R. Modeling Approach



Formulating a mathematical model

- A mathematical model is used as an abstraction of the real-world
- There are pros and cons:
  - Standardized form of displaying a decision problem
  - Reveal cause-and-effect relationship
  - Indicate more clearly what data are relevant
  - Enable the use of high-powered mathematical techniques and computers

  - Abstract idealization of the problem
  - Require approximations and simplifying assumptions
  - Rely on the experience and judgment of the modeler
  - Are the result of a trade-off between precision and tractability

Main components of the mathematical model

Three main components:

1. **The decision variables**:
   - The decisions to be made
   - Their respective values have to be determined

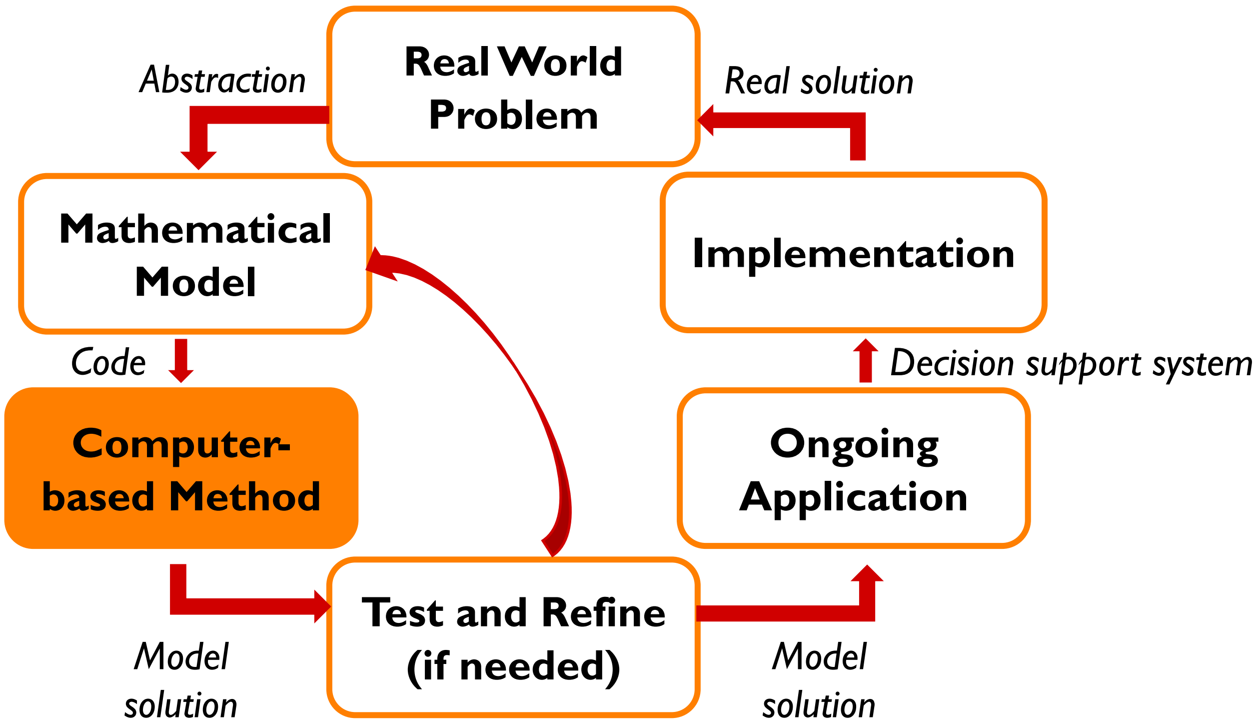
2. **The objective function**:
   - The goal to achieve
   - Mathematical function of the decision variables

3. **The constraints**:
   - Any restriction on the values that can be assigned to the decision variables
   - Mathematical expressions of the decision variables

Delta Air Lines Example

Determine the values of the decisions variables so as to minimize/maximize the objective function, subject to the specific constraints.

6-steps O.R. Modeling Approach



Developing a computer-based method

- A **computer-based algorithm** is used to solve the model
- Two main categories of optimization algorithms:

1. **Exact methods**
   - Guarantee to give an optimum solution of the problem
   - Can be very expensive in terms of computation time on large-size problem instances
2. **Heuristics**
   - Attempt to yield a good, but not necessarily optimum solution
   - Used for their speed

Balance between the quality of the solution and the time spent on computation

Post-optimality analysis

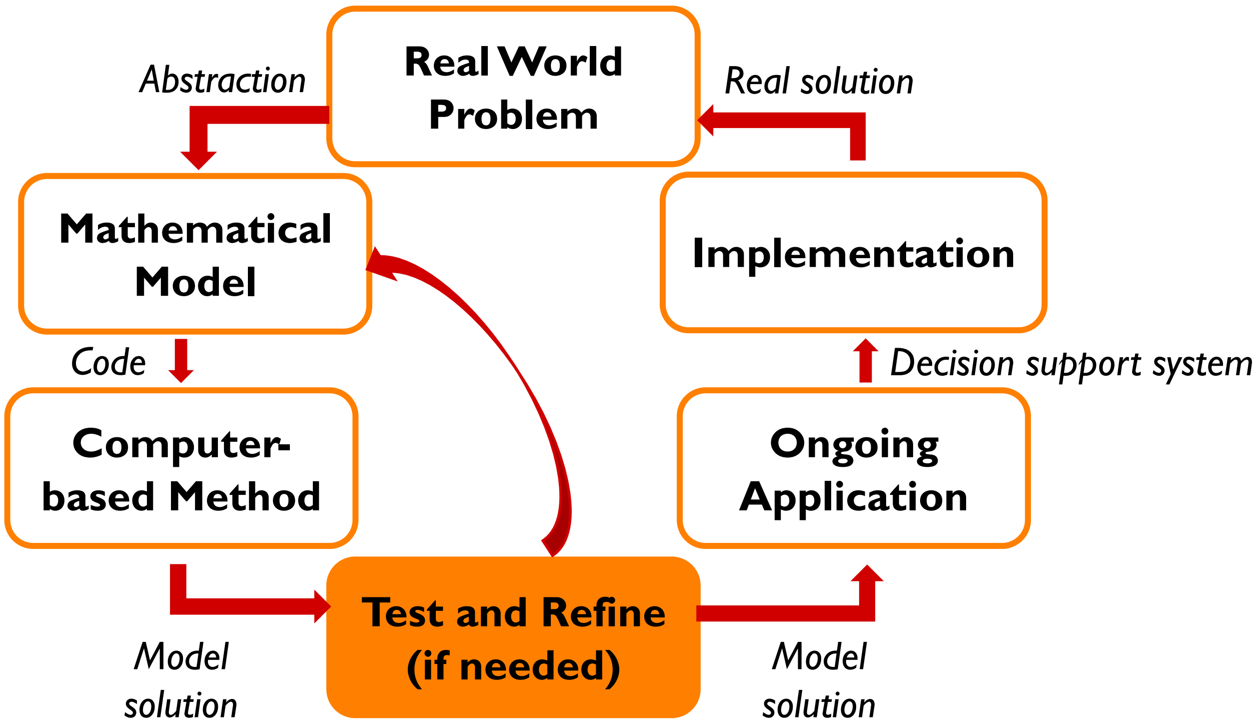
- Post-optimality analysis is important:
  - Sensitivity analysis:

    Delta Air Lines Example

    - What if the demand for some specific flights increases or decreases?
    - What if the cost of operating some flights increases or decreases?

  - Scenario analysis:
    - Analyzing possible future events by considering alternative possible outcomes
    - Different recommendations can be concluded for each scenario

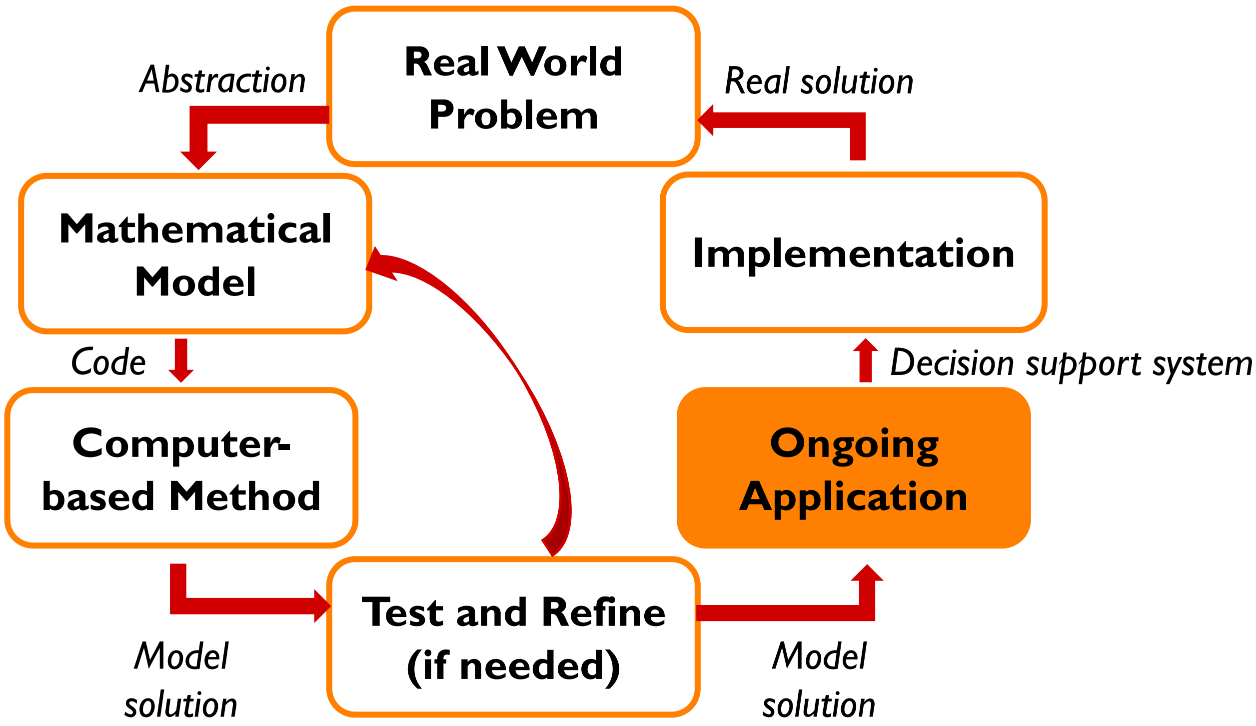
6-steps O.R. Modeling Approach



Model validation

- The first version of a computer program often contains bugs
- A long succession of tests is needed
  - Tests can reveal flaws in the mathematical model
  - Tests lead to a succession of improved models
- Model validation techniques:
  - Artificial test cases with known outcome
  - Interpretation of the results
- Documenting the process used for model validation is also very important

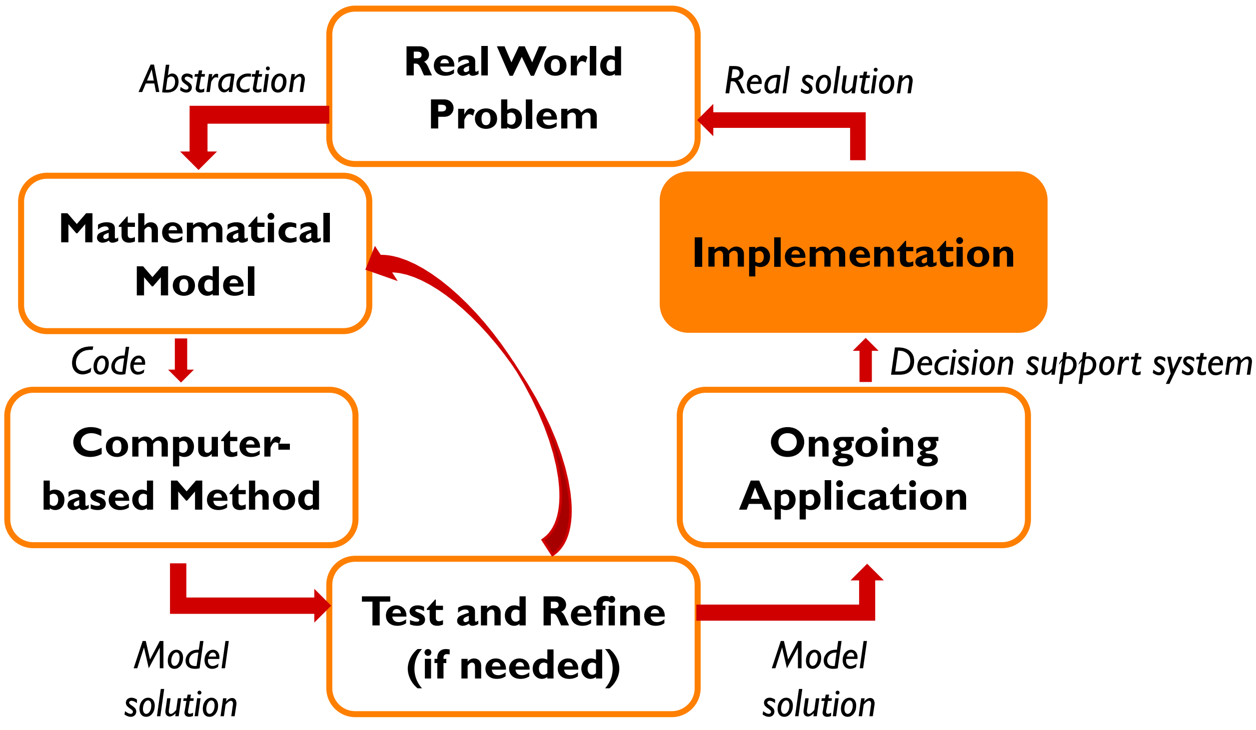
6-steps O.R. Modeling Approach



Preparing to apply the model

- Developing a **well-documented** **decision support system** is critical
- Usually part of a larger **information system (IS)**
  - Interactive and computer-based
- **Maintaining** this system throughout its future use is very important

6-steps O.R. Modeling Approach



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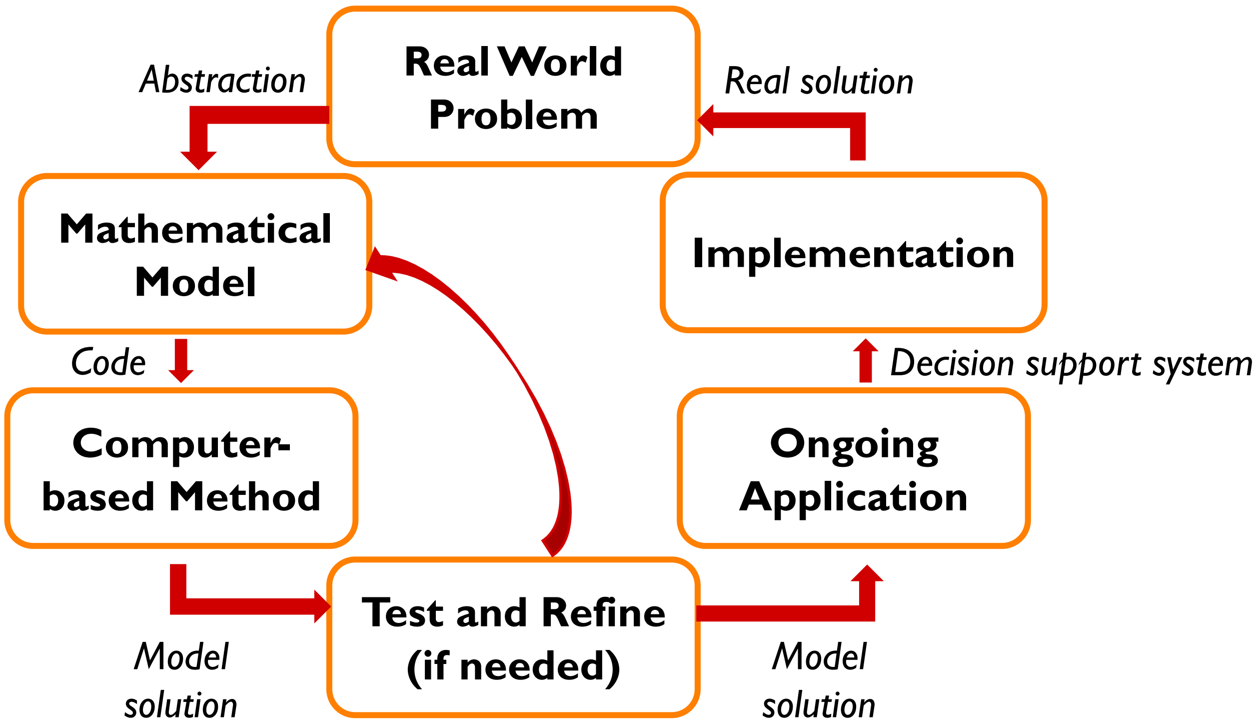
Implementation

- Implementation is a **critical phase**
- Success depends on the support of the top management:
  - Sell the concept
  - Demonstrate the effectiveness of the system
- Success depends on the support of the operation management:
  - Provide the needed support tools
  - Train the personnel who will use the system
  - Convince the personnel of the usefulness of the system

Implementation

- **Good communication** is needed
- **Continuous feedback** on:
  - How well the system is working
  - Whether the assumptions of the model continue to be satisfied

6-steps O.R. Modeling Approach



Practice examples

Decision Aid Methodologies in Transportation

Focus on the Transport & Logistics industry

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Transport and Mobility Laboratory

Cargo loading problem

How to optimally load a set of containers/pallets (ULDs) into a cargo aircraft that has to serve multiple destinations under some safety, structural, economical, environmental and maneuverability constraints?

Transport and Mobility Laboratory

Railway cargo network design problem

What is the optimal number and location of marshaling and shunting yards in a railway network in order to reduce freight transport and shunting costs?

Passenger centric train timetabling problem

How to optimally design a timetable?

Cyclicity?

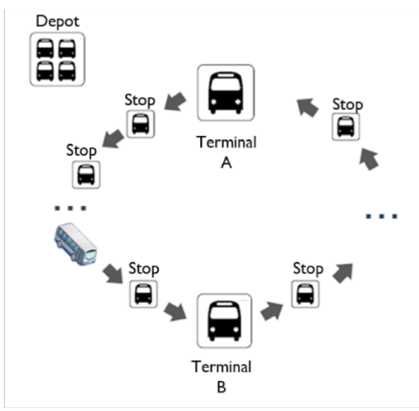
Profit

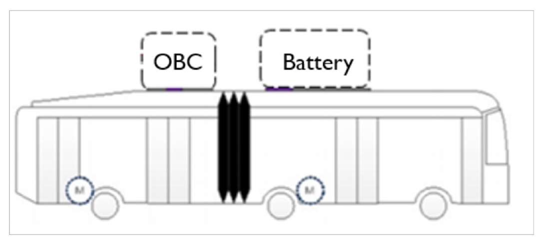
Passenger travel time

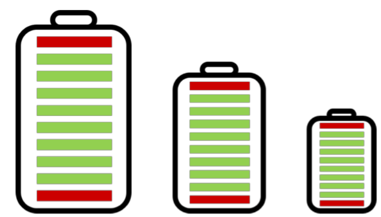
Transport and Mobility Laboratory

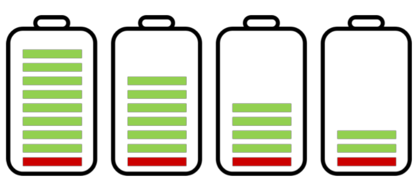
Network design problem for battery electric bus

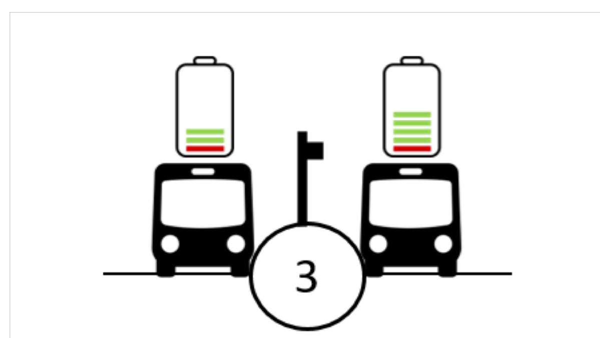
At which stations should we install a feeding station, which type of feeding station should be installed at these stations and with which battery should we equip the buses in order to minimize the total cost of the system ?











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Case Study

- **Container Storage Inside a Container Terminal**
- Project carried out at HIT (Hong Kong International Terminals) in Hong Kong Port

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Maritime Shipping

Maritime shipping

Specialized vessels

Shipping of bulk commodities (e.g., crude oil)

Container shipping

Shipping all other manufactured goods (e.g., textiles)

20 FT Container (TEU)

40 FT Container (TEU)

« Reefers » Container (Refrigerated)

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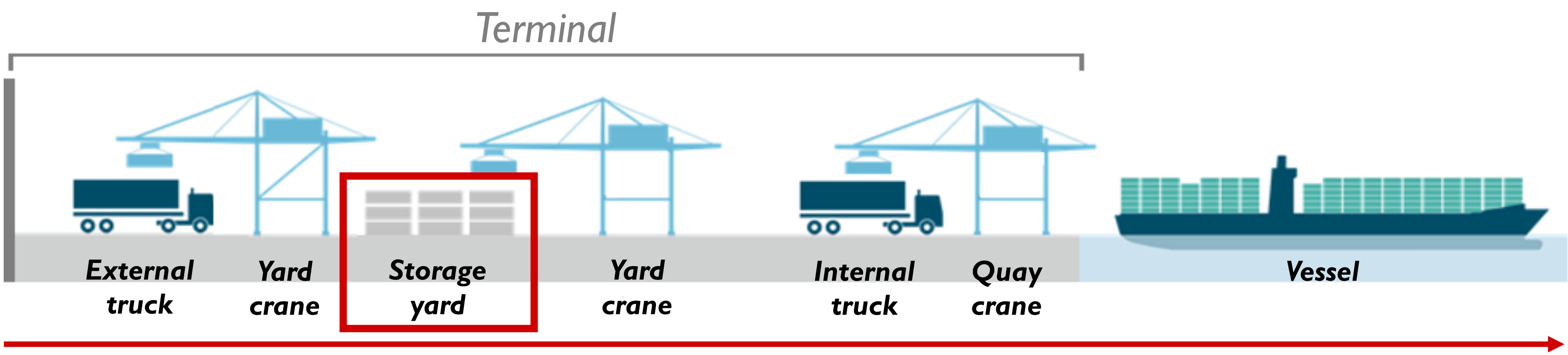
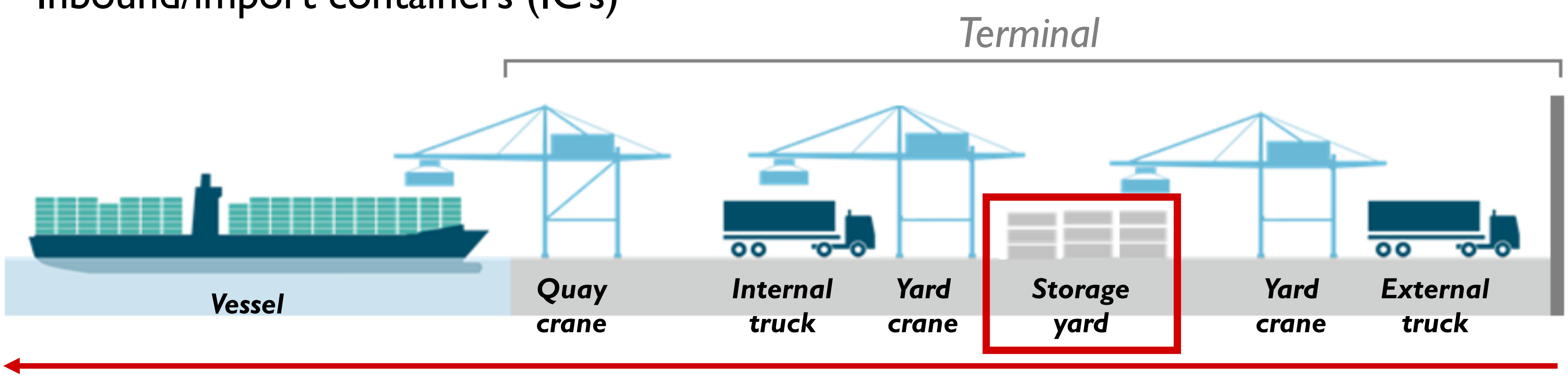
Container shipping

- Outbound/export containers (EC’s)

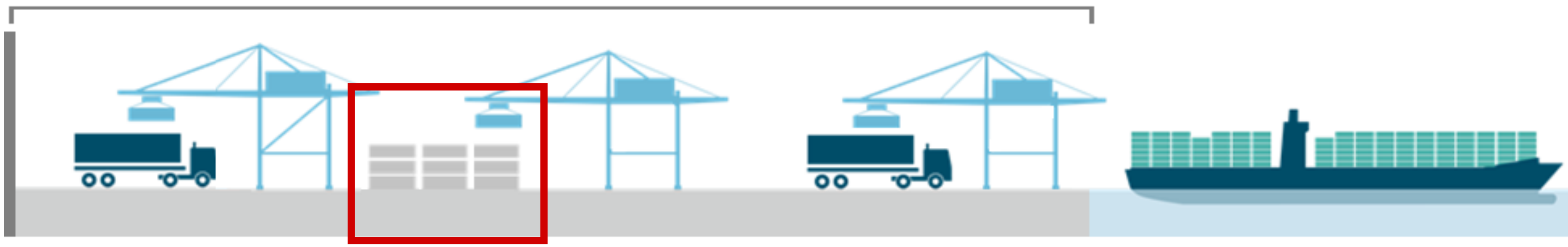


- Inbound/import containers (IC’s)



Storage yard

- **Storage yard** is the section of the terminal used for the **temporary storage** of containers between land and sea transportation



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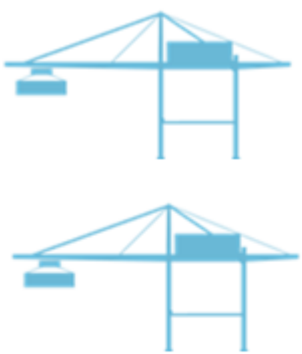
Storage blocks

- The Storage yard is divided into rectangular **storage blocks**.
- HIT case:
  - Each block is divided into 7 lanes (6 storage lanes + 1 line for trucks)
  - Each storage lane is divided into 26 storage spaces
  - Each storage space can accommodate up to 6 containers
  - Two or more yard cranes allocated to each storage block



Key service quality metrics

- About 40 major shipping lines in the world
- **Fierce** regional **competition** among terminal operators

Which container terminal to patronize ?

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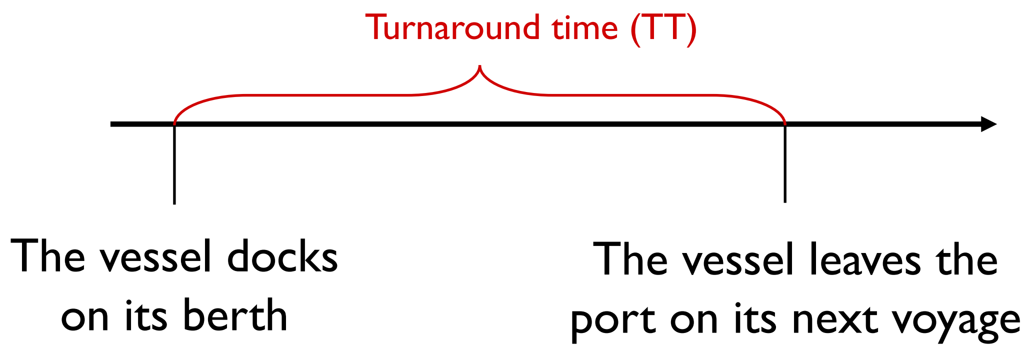
Vessel turnaround time

- The time needed for unloading, loading, and servicing the vessel



- Strong consideration to shorten the vessels' cycle time/ increase the vessels' utilization (sailing time)

➢ How to keep the **average vessel turnaround time** as low as possible ?

Gross crane rate (GCR)

- The average vessel turnaround time is directly influenced by the **gross crane rate** or quay crane rate

- The gross crane rate (GCR) is the **average lifts** achieved at the terminal per quay crane working hour

- A "lift" refers to either the unloading of an import container from the vessel, or the loading of an export container onto the vessel

- The higher the GCR, the better the service quality

➢ How to maximize the GCR ?

Hong Kong International Terminals

Situation in mid-1990s:

- Export boom in mid-1990s in China
- Remarkable demand for terminal services in Southern China
- Land scarce in Hong Kong: not possible to expand terminals
- Growing competition from new terminals opening along China's southern coast
- GCR in the upper 20s
- Losing market share in a growing market

How to survive?

- Provide premium service quality
- Establish HIT as the industry's benchmark

Traffic flow in container terminal

"Traffic flow in a container terminal is akin to the circulation of blood in the human body: life depends on it."

- Quay cranes have to wait for internal trucks
- GCR decreases

First idea: adding 2 additional trucks

✗ Increased traffic congestion

Decision support system

- Goal: increase gross crane rate by reducing congestion

- Means: develop a new decision support system for daily operations

Reducing congestion

- Reduce the number of working internal trucks

<u>Policy 1: *existing practice*</u>

- Having a separate batch of eight ITs to serve each QC

<u>Policy 2: *pooling system*</u>

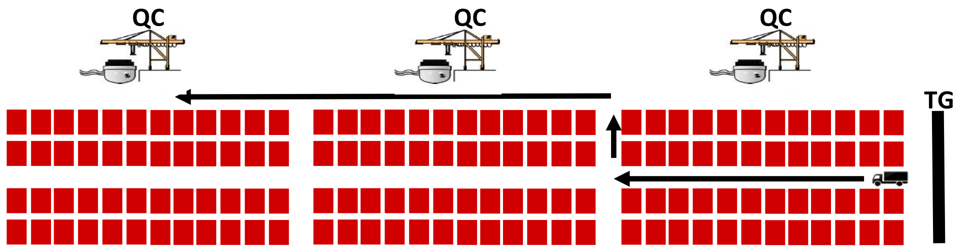
- All the ITs working in the terminal form a pool that collectively serves all the QCs
- New central dispatching unit

Reducing congestion

- Route container trucks optimally

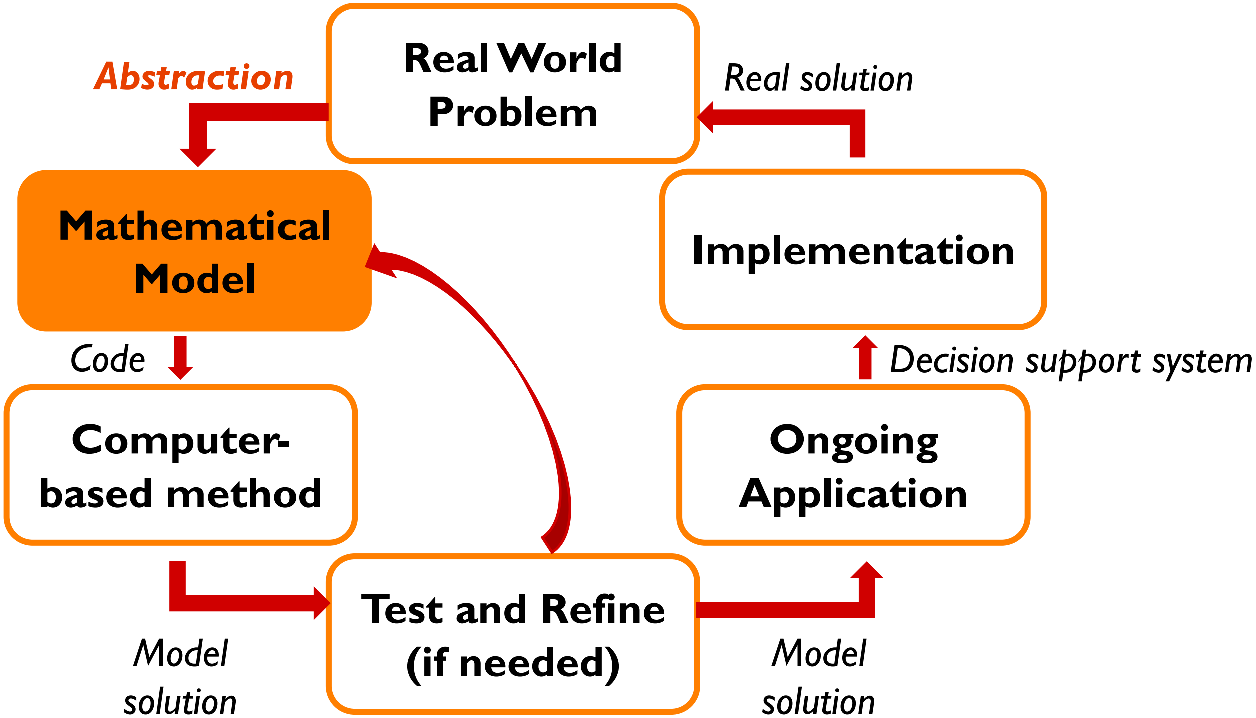
Hong Kong International Terminals:

- 10 berths
- Around 200 internal trucks
- 80,000 TEUs
- 10,000 truck passages through the terminal gate daily



Policy of allocating storage spaces in the storage yard to arriving containers is the key to achieve optimum routing

6-steps O.R. Modeling Approach



Allocating storage spaces in the storage yard

First model: a 0-1 model

- Decision variables:

$$x_{ijkl} = \begin{cases} 1 & \text{if the } i\text{th container from the } j\text{th QC is stored in the } k\text{th stack of block } l \\ 0 & \text{otherwise} \end{cases}$$

- Large model with many binary variables

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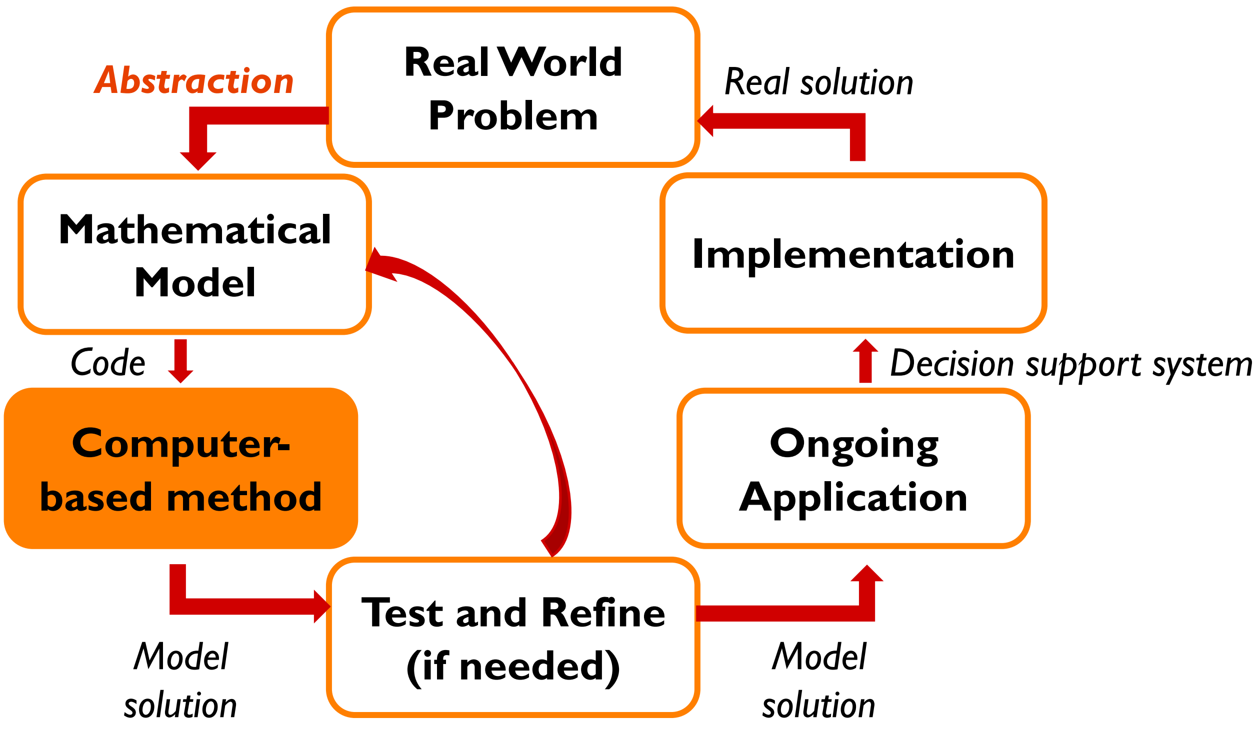

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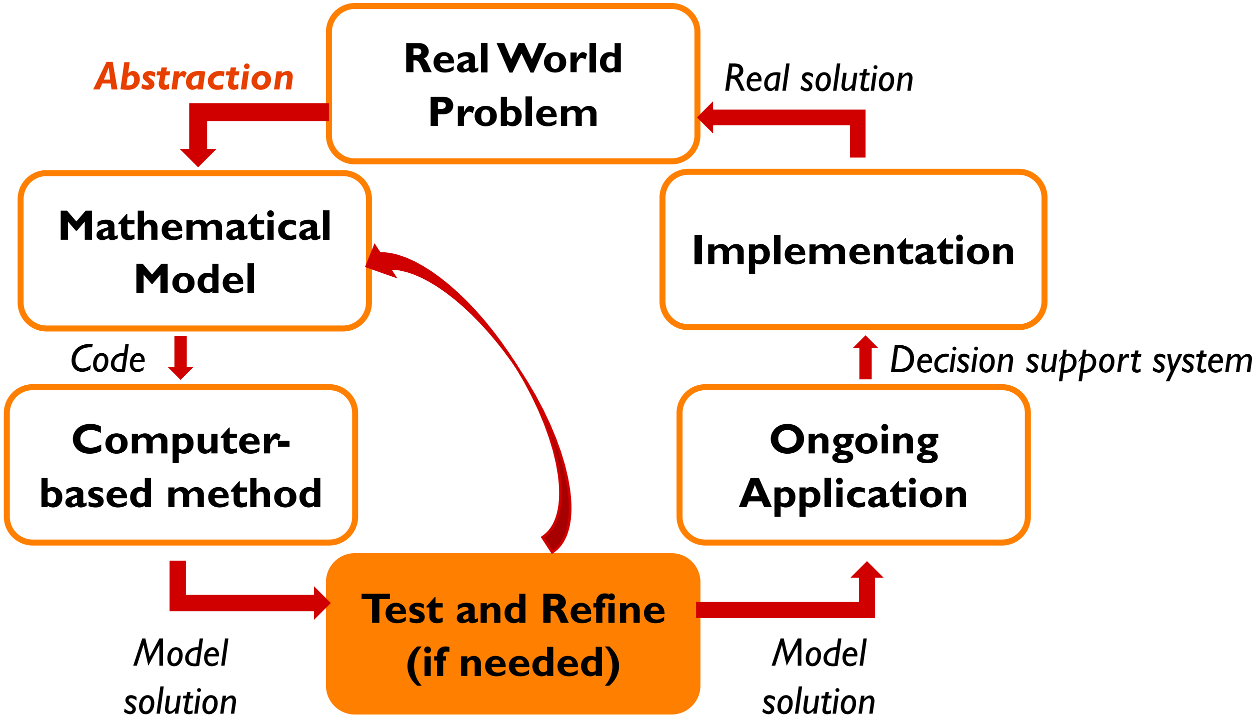


Allocating storage spaces in the storage yard

First model: a 0-1 model

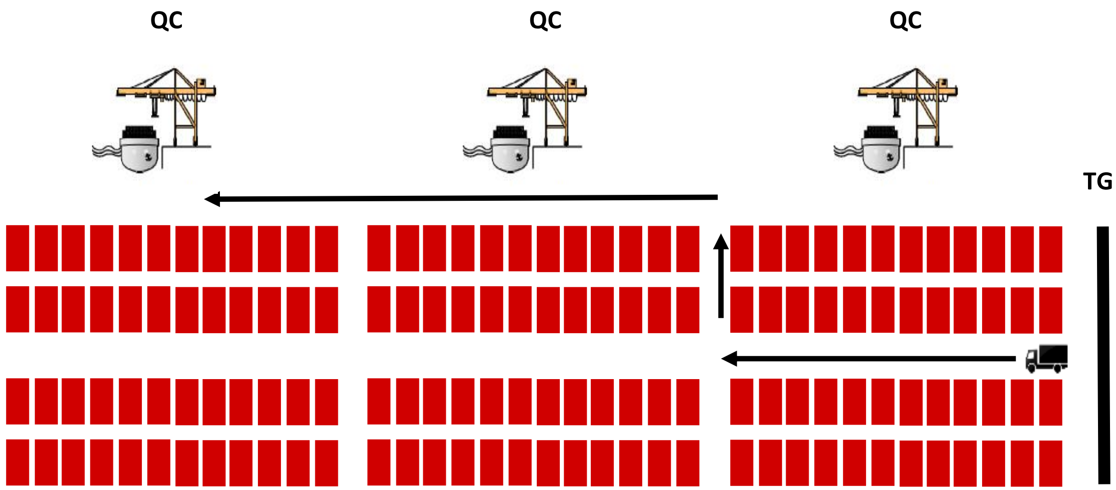
- Too granular modeling
- High computation time

➢ The binary variable model was **impractical** and **inappropriate**

Spreading the container truck traffic evenly

Second model: a multicommodity flow model

- Road congestion could be decreased by spreading the container truck traffic on all the road segments evenly



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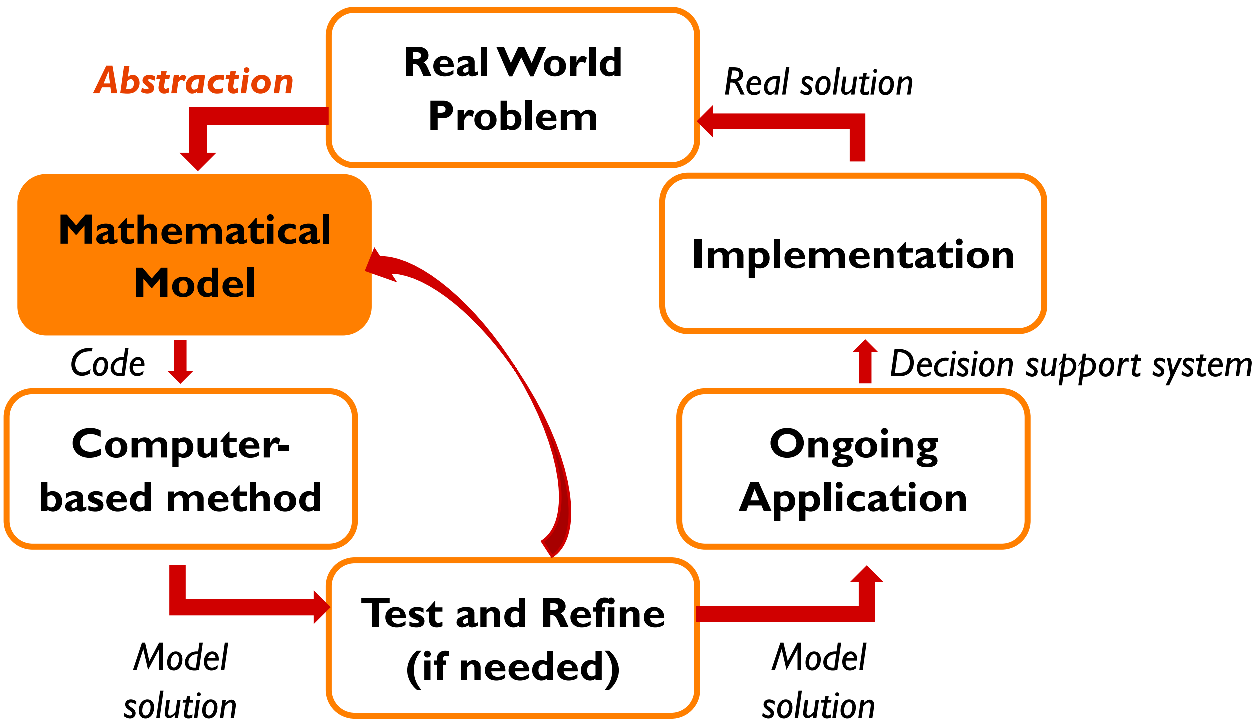
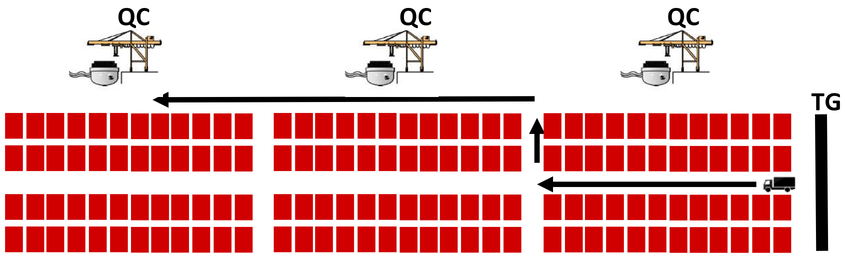


Spreading the container truck traffic evenly

Second model: a multicommodity flow model



- Decision variables:

  f_{ij}: the total number of container trucks flowing on arc (i, j) in the terminal road network during the planning period (4hrs)

- Objective function:

  Minimize $\theta - \mu$

  where $\theta = \text{maximum}\{f_{ij}: \text{over all arcs } (i, j)\}$
  $\mu = \text{minimum}\{f_{ij}: \text{over all arcs } (i, j)\}$

- Large-scale **linear programming model** for each period

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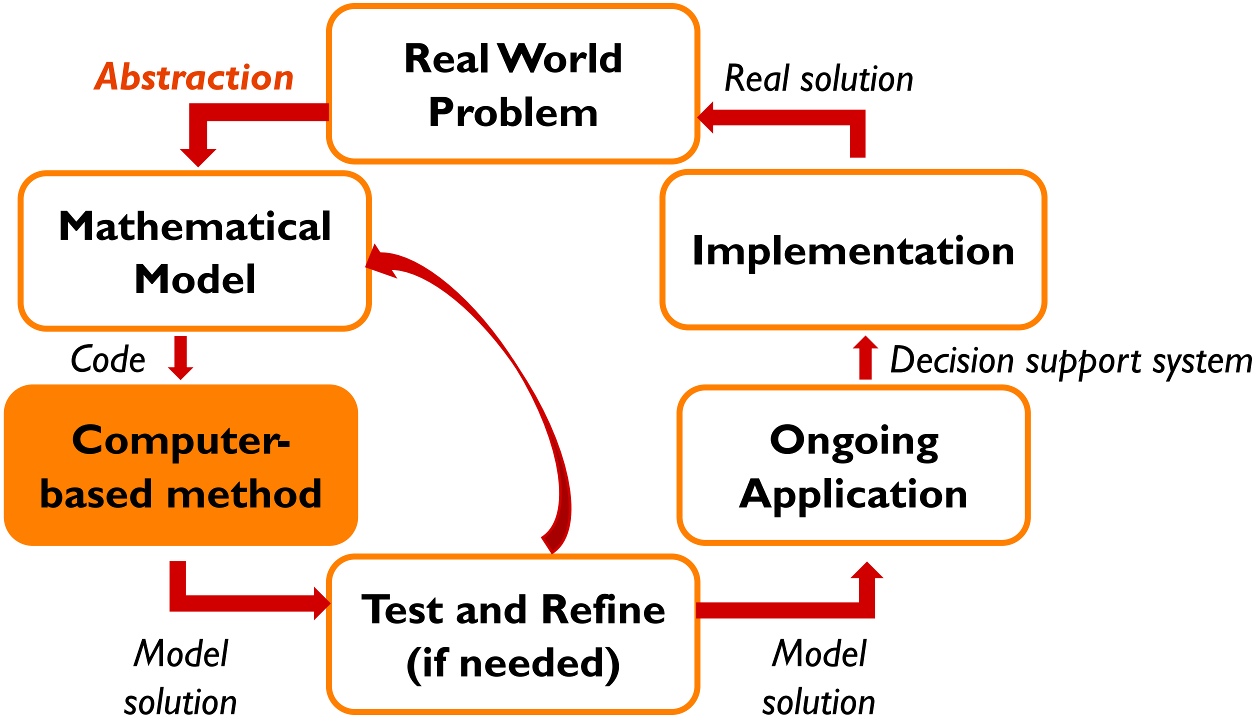
Spreading the container truck traffic evenly

Second model: a multicommodity flow model

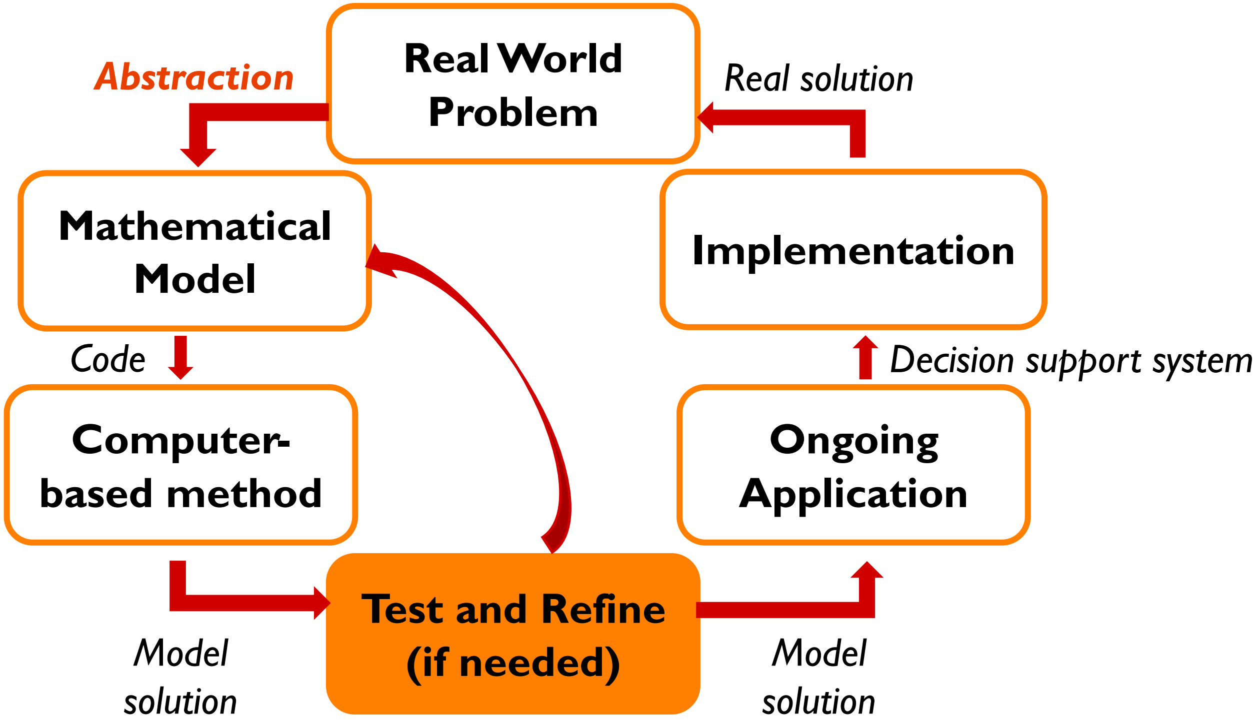
- Input data*:
  - At each QC position:
    - How many ICs to be unloaded and sent to the storage yard ?
    - How many ECs to be sent here from each block of the storage yard ?
  - At each block:
    - How many ECs to be dispatched to each QC position
    - How many ICs to be retrieved for leaving the terminal through the TG ?
  - At the TG:
    - How many ECs to arrive for entry into the terminal ?

*ICs: import containers - ECs: export containers – QC: quay crane – TG: terminal gate

6-steps O.R. Modeling Approach

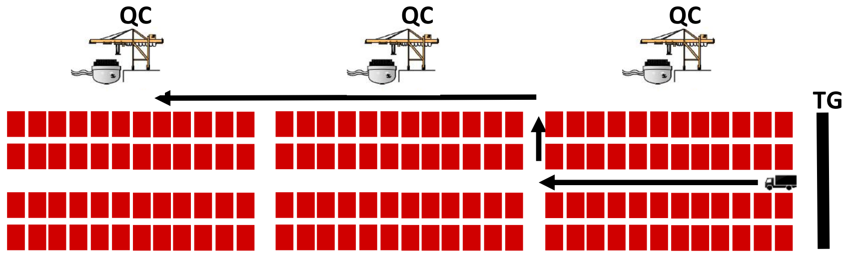


6-steps O.R. Modeling Approach



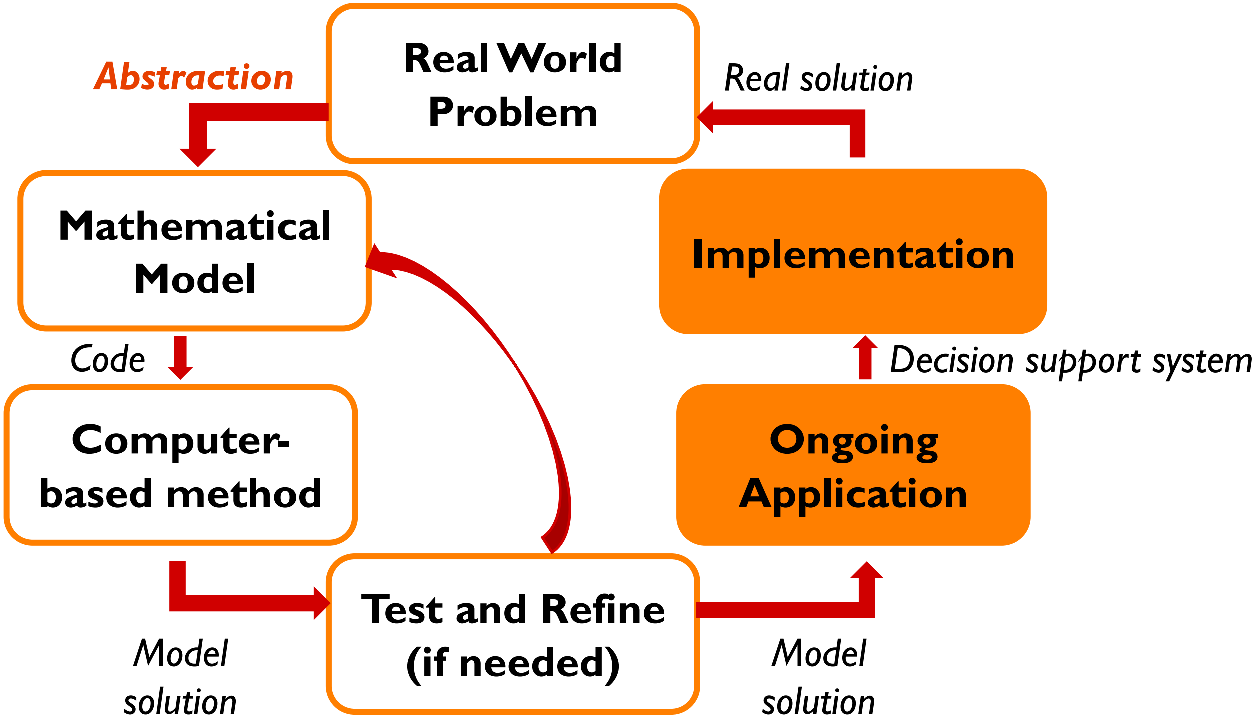
Spreading the container truck traffic evenly

Second model: a multicommodity flow model



- Model can be solved in a few minutes using the best available linear programming software system (at that time)
- Output: routes for container trucks that minimize congestion

6-steps O.R. Modeling Approach



Spreading the container truck traffic evenly

Second model: a multicommodity flow model

Issues when trying to implement the solution:

1. Truck drivers resented being told what routes to take.

   "**We** all **know** the terminal road network **well**, and can find the best route to get to any destination point by ourselves based on current traffic conditions"

2. Far-away roads equally favorized as the roads close to the QCs

➢ This model is also **inappropriate** !

Fill-ratio in a block

Third model: the successful one

- Blocks containing many containers have much more truck traffic around them

$$\text{Fill-ratio in a block} = \frac{\#\text{ containers in storage in the block}}{\#\text{ storage positions in the block}}$$

Equalizing the fill-ratios among blocks

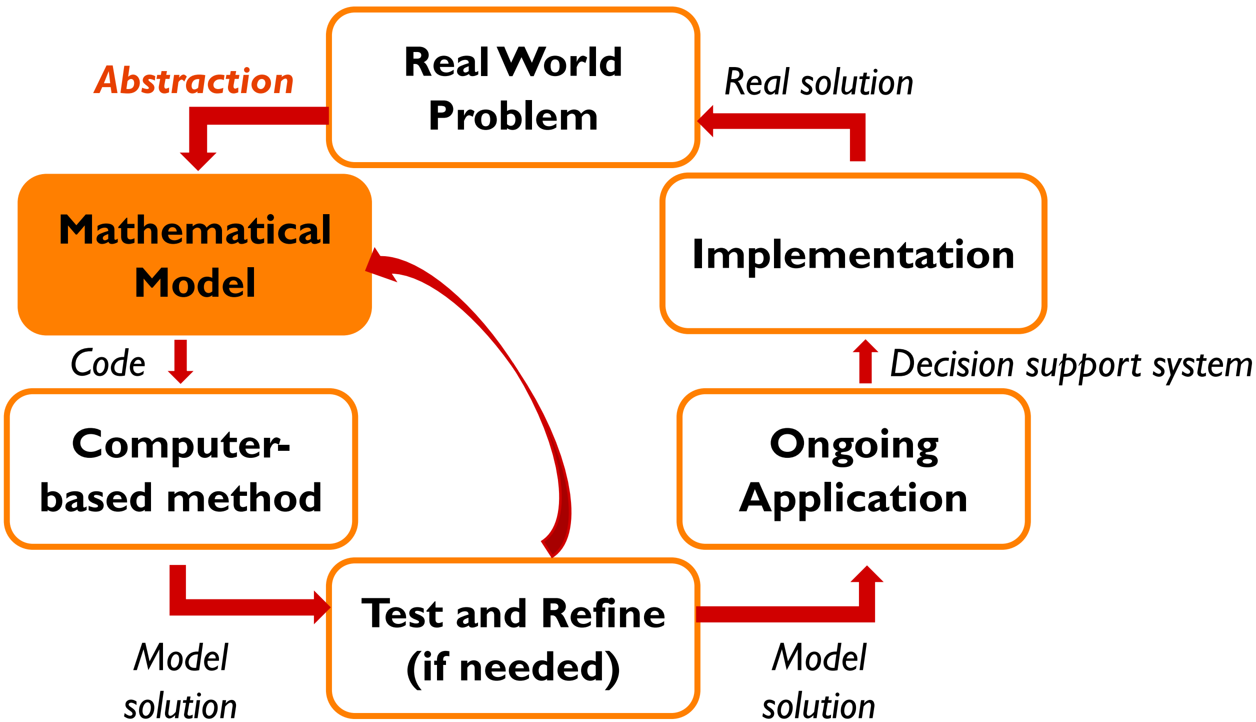
Third model: the successful one

- Blocks containing many containers have much more truck traffic around them
- The fill-ratios at HIT varied significantly over block

New idea:

- Equalizing the fill-ratios among blocks
- This will ensure an equal distribution of traffic on terminal roads
- As fill-ratios in blocks vary with time, the idea was to equalize the fill-ratio in all the blocks at the end of each planning period

6-steps O.R. Modeling Approach



Equalizing the fill-ratios among blocks

Third model: the good one

- Input data:

  a_i: Initial number of stored containers in block i

  N: Number of new containers expected to arrive for storage in this period

  B: Total number of blocks in the storage yard

  A: Number of storage positions in each block

- Decision variables:

  x_i: Number of arriving containers in this period to be stored to block i

Equalizing the fill-ratios among blocks

Third model: the good one

- Objective function:
  - The fill-ratio in the whole yard at the end of this period will be:

$$F = \frac{N + \sum_i a_i}{A \times B}$$

  - If the fill-ratios in all the blocks at the end of this period are all equal, they will all be equal to F
  - This policy determines x_i to guarantee that the fill-ratio in each block i will be as close to F as possible by the end of this period

$$f_i = \frac{a_i + \boldsymbol{x_i}}{A}$$

Equalizing the fill-ratios among blocks

Third model: the good one

- Objective function:
  - Fill-ratio in each block i ($\boldsymbol{f_i}$) should be as close as possible to $\boldsymbol{F}$:

$$\text{Minimize } |\boldsymbol{f_i} - \boldsymbol{F}| \text{ for all } i$$

$$\boldsymbol{f_i} = \frac{a_i + \boldsymbol{x_i}}{A} \qquad \boldsymbol{F} = \frac{N + \sum_i a_i}{A \times B}$$

$$\longleftrightarrow \text{ Minimize } \left|\frac{\boldsymbol{a_i} + \boldsymbol{x_i}}{\boldsymbol{A}} - \boldsymbol{F}\right| \text{ for all } i$$

$$\longleftrightarrow \text{ Minimize } \left|\frac{\boldsymbol{a_i} + \boldsymbol{x_i} - \boldsymbol{A} \times \boldsymbol{F}}{\boldsymbol{A}}\right| \text{ for all } i$$

$$\longleftrightarrow \text{ Minimize } |\boldsymbol{a_i} + \boldsymbol{x_i} - \boldsymbol{A} \times \boldsymbol{F}| \text{ for all } i$$

$$\longleftrightarrow \text{ Minimize } \sum_i |\boldsymbol{a_i} + \boldsymbol{x_i} - \boldsymbol{A} \times \boldsymbol{F}|$$

Equalizing the fill-ratios among blocks

Third model: the good one

- Objective function:

Minimize $\sum_i |a_i + x_i - A \times F|$

Minimize $\sum_i (\mu_i^+ + \mu_i^-)$

- Constraints:

$$\sum_i x_i = N$$

$$x_i \geq 0 \quad \forall i$$

$$\sum_i x_i = N$$

$$(a_i + x_i - A \times F) = \mu_i^+ - \mu_i^- \quad \forall i$$

$$x_i, \mu_i^+, \mu_i^- \geq 0 \quad \forall i$$

Nonlinear function

How to make it linear ?

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Linear programming

Canonical form of Linear Program (LP):

$$\min_{x \in} c^T x \quad \text{Linear objective function}$$

subject to $Ax \leq b$ — Linear inequalities

$x \geq 0,$ — Non-negativity constraints

where $A \in \mathbb{R}^{m \times n}$, $\mathrm{b} \in \mathbb{R}^m$, $\mathrm{c} \in \mathbb{R}^n$ — n variables, m constraints

Linear programming

Standard form of Linear Program (LP):

$$\min_{x \in \mathbb{R}^n} c^T x$$ Linear objective function

subject to $Ax = b$ Linear equalities

$x \geq 0,$ Non-negativity constraints

where $A \in \mathbb{R}^{m \times n}$, b $\in \mathbb{R}^m$, c $\in \mathbb{R}^n$ — n variables, m constraints

- Slack variables:

$$Ax \leq b \longleftrightarrow \begin{cases} Ax + y = b \\ y \geq 0 \end{cases} \qquad Ax \geq b \longleftrightarrow \begin{cases} Ax - y = b \\ y \geq 0 \end{cases}$$

How to solve a LP?

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Main references

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