Comparing observation satellite constellations – A novel approach using binary integer programming

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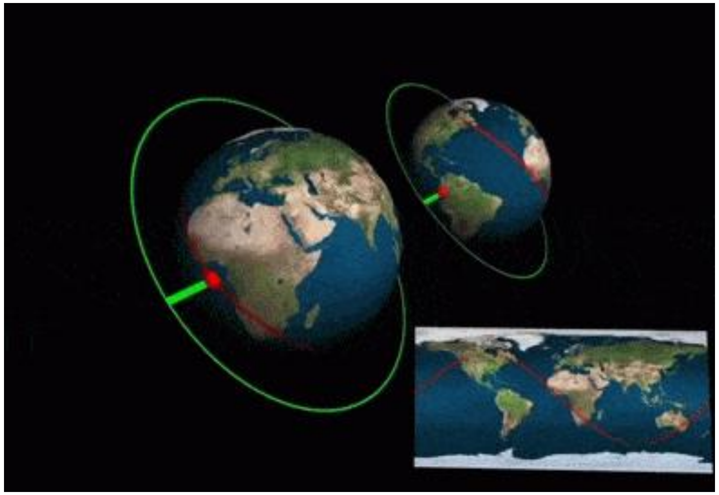
Introduction

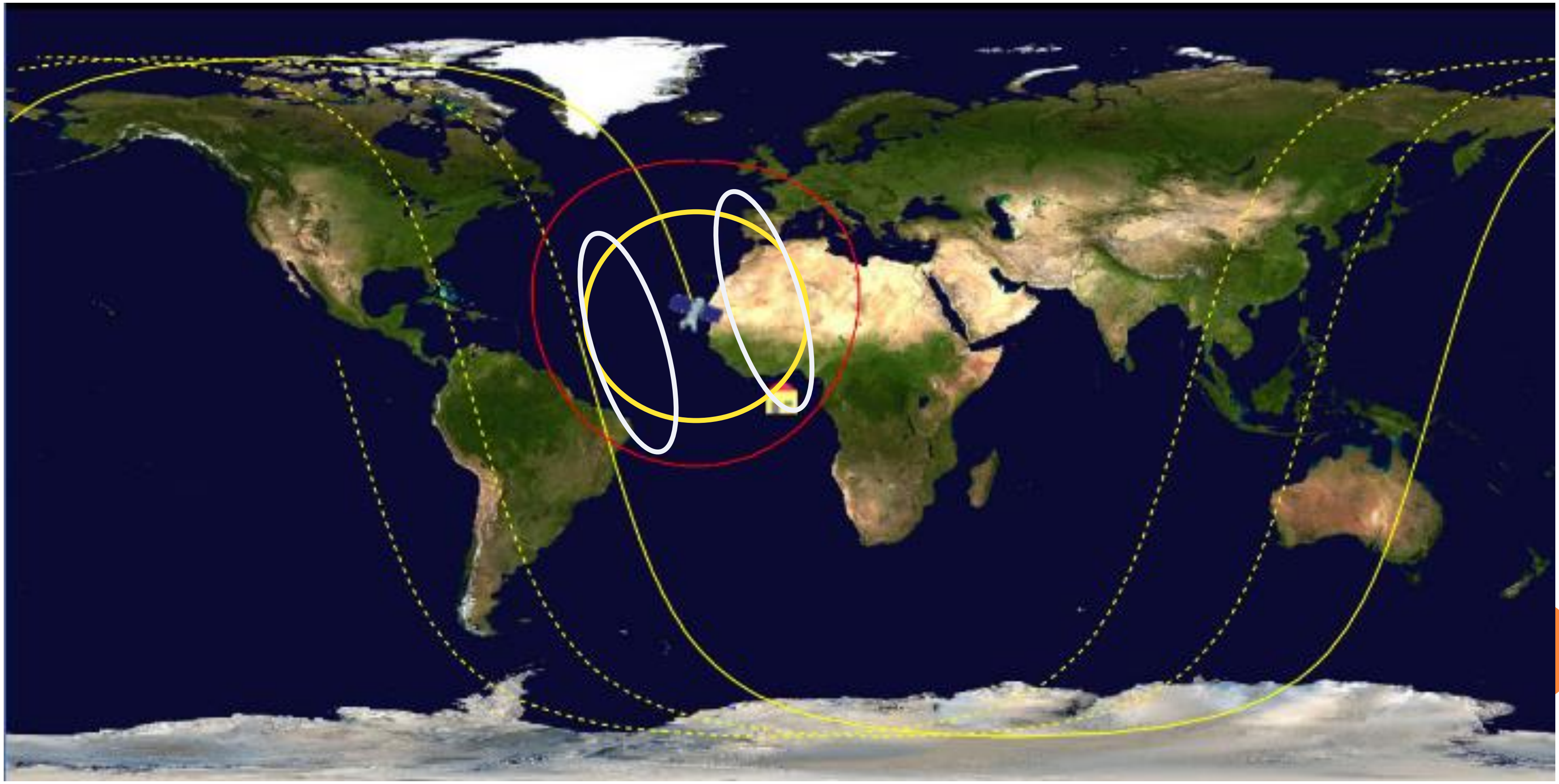
- The last decade has seen major development of Satellite capabilities:
  - Better resolution
  - Larger coverage
  - Commercially available Multi spectral and SAR images
  - Reduction of costs etc.

- Growing reliance on satellite images (where once other options were necessary)

INTRODUCTION (2)

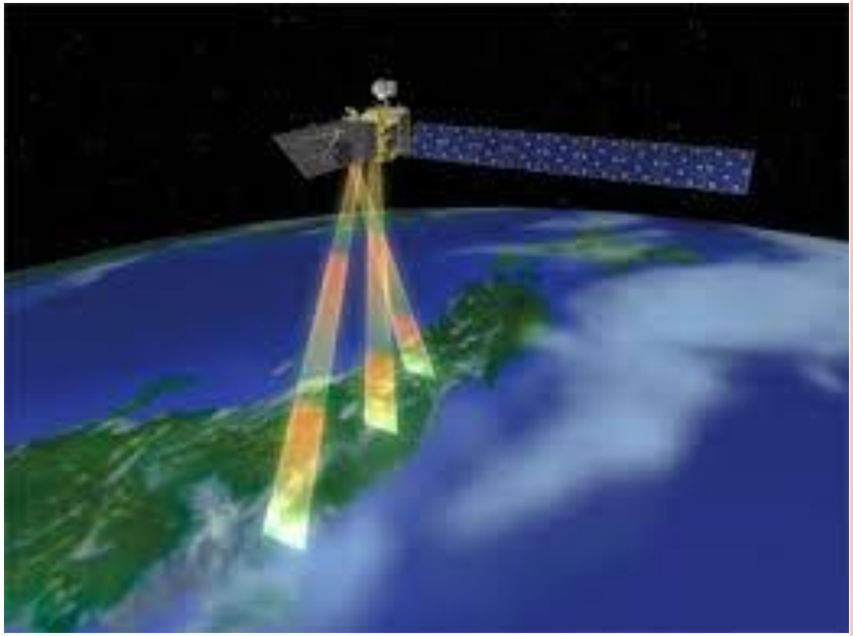
- Sinusoidal ground track
- Sensors
- Imaging trade-off





Objective

- A quantitative comparison of 3-satellite constellation vs. 2-satellite constellation
  - By assessing the imagery abilities of each satellite constellation



Methodology

Requirements

- Identify different satellite image consumers
- Define primary requirements (with relevant consumers)
- Map crucial requirement parameters
- Build requirement DB according to relevant parameters

Constellations

- Create satellite opportunity DB
- Analyze satellite DB vs. requirement DB (allocation problem)
- Provide recommendations

Satellite opportunity DB

Location	Satellite	Time stamp	Resolution	Pass duration
20° latitude	Sat.1 (EO)	Jan. 01 2013 00:12:16	MAX	46s
20° latitude	Sat.2 (SAR)	Jan. 01 2013 03:25:08	Sub 3m	54s
20° latitude	Sat.1 (EO)	Jan. 01 2013 05:07:38	Sub 3m	10s
20° latitude	Sat.1 (EO)	Jan. 01 2013 12:56:20	MAX	72s
20° latitude	Sat.2 (SAR)	Jan. 01 2013 16:32:00	MAX	85s
…	…	…	…	…

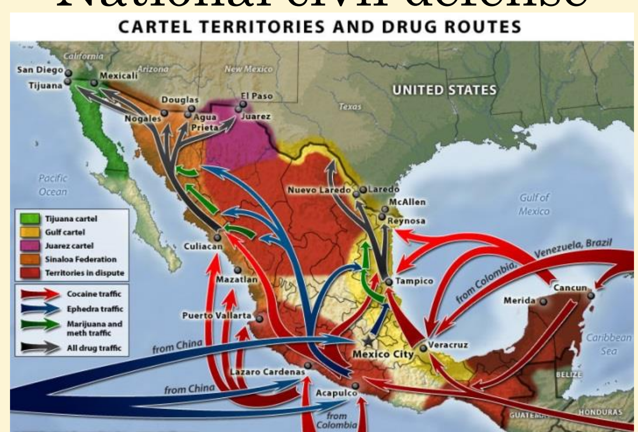
Requirement examples

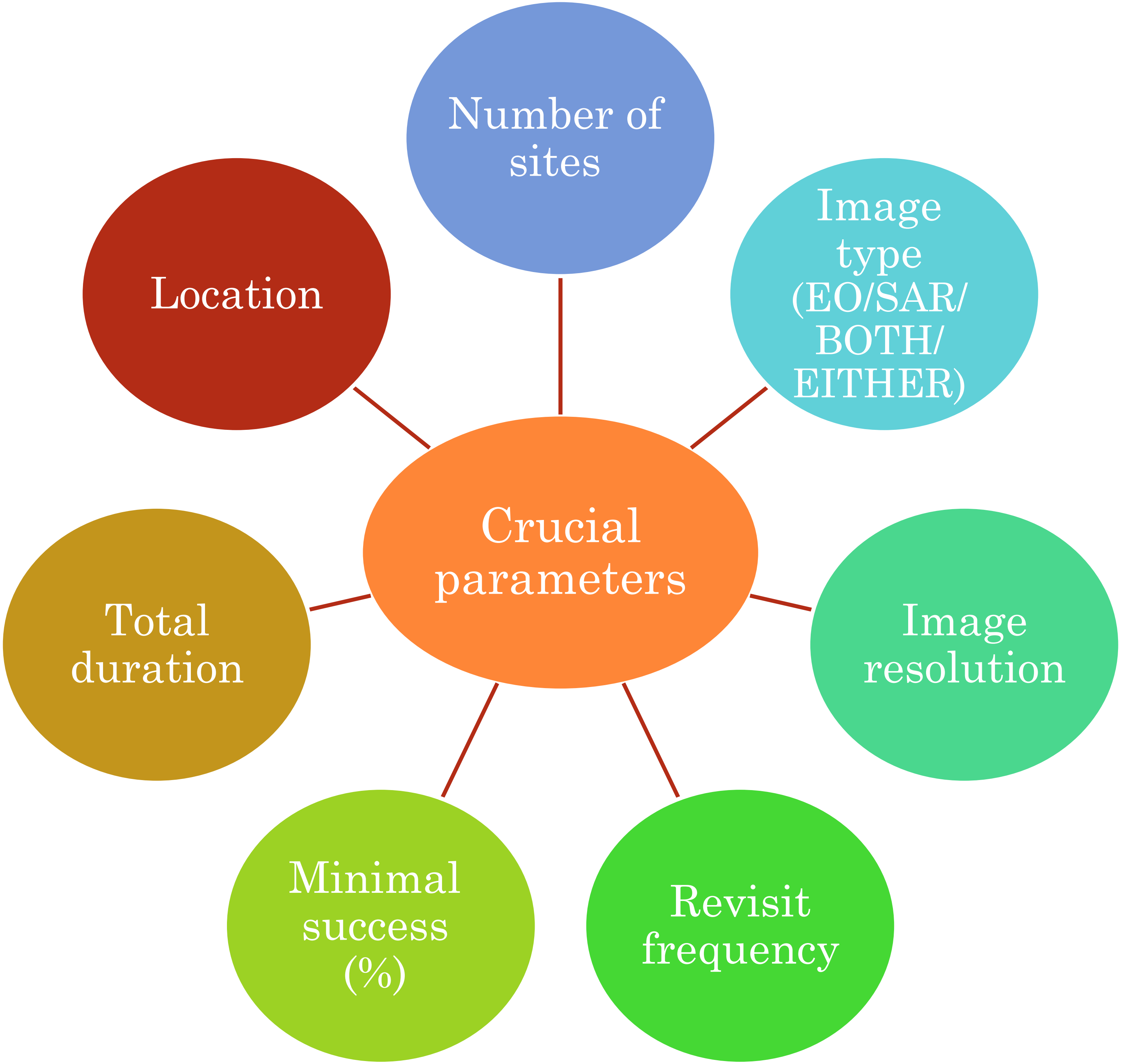
Ecological requirements

Natural disaster recovery

infrastructure mega-projects

National civil defense




Number of sites
Location
Image type (EO/SAR/ BOTH/ EITHER)
Crucial parameters
Total duration
Image resolution
Minimal success (%)
Revisit frequency

Requirement parameters examples

Requirement	Avalanche detection	Drug trafficking	Animal Migration
Number of sites	1	3	130
Image type	EITHER	EO	EO
Image resolution	max	max	Sub 3 m
Revisit frequency	Daily	Hourly or at least 4 times a day	Weekly
Longest period without image	34 h	4.3 h	10 d
Minimal success	80%	100%	75%
Total duration	6 m	3 d	Year round
Location	Specific (Nepal)	Semi -Specific (Border)	Non -Specific

Approach

- Quantitative measure required → Probability of meeting the requirement → Based on solving an allocation problem

Naïve approach → greedy algorithm

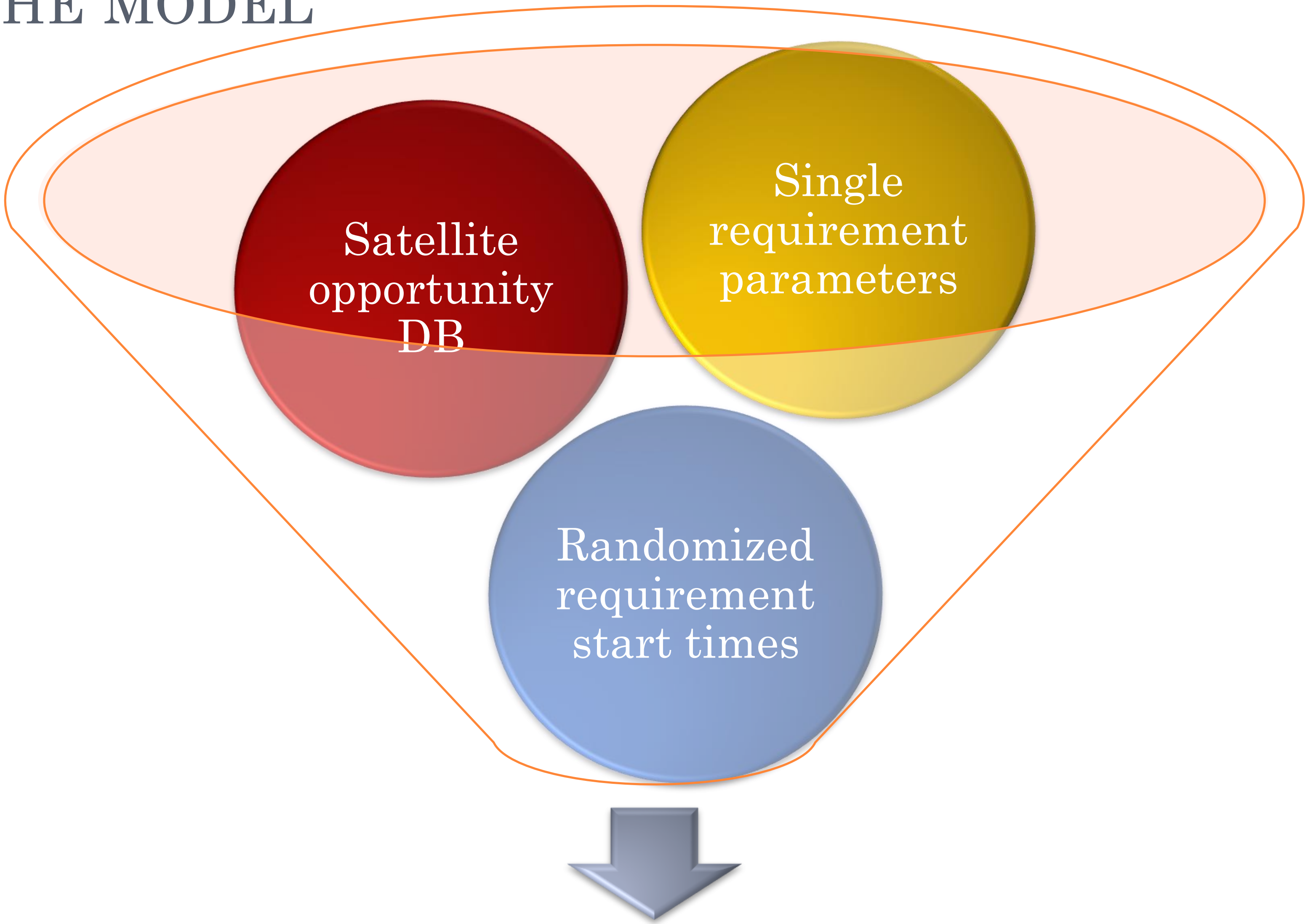
- Fails with mixed image requirement
- Inefficient
- Does not allow estimation of total load

Optimization model

- Binary programming → optimally allocate each opportunity
- Only works for small-medium problem
- Allows load estimation

*Neither method allows for direct load analysis

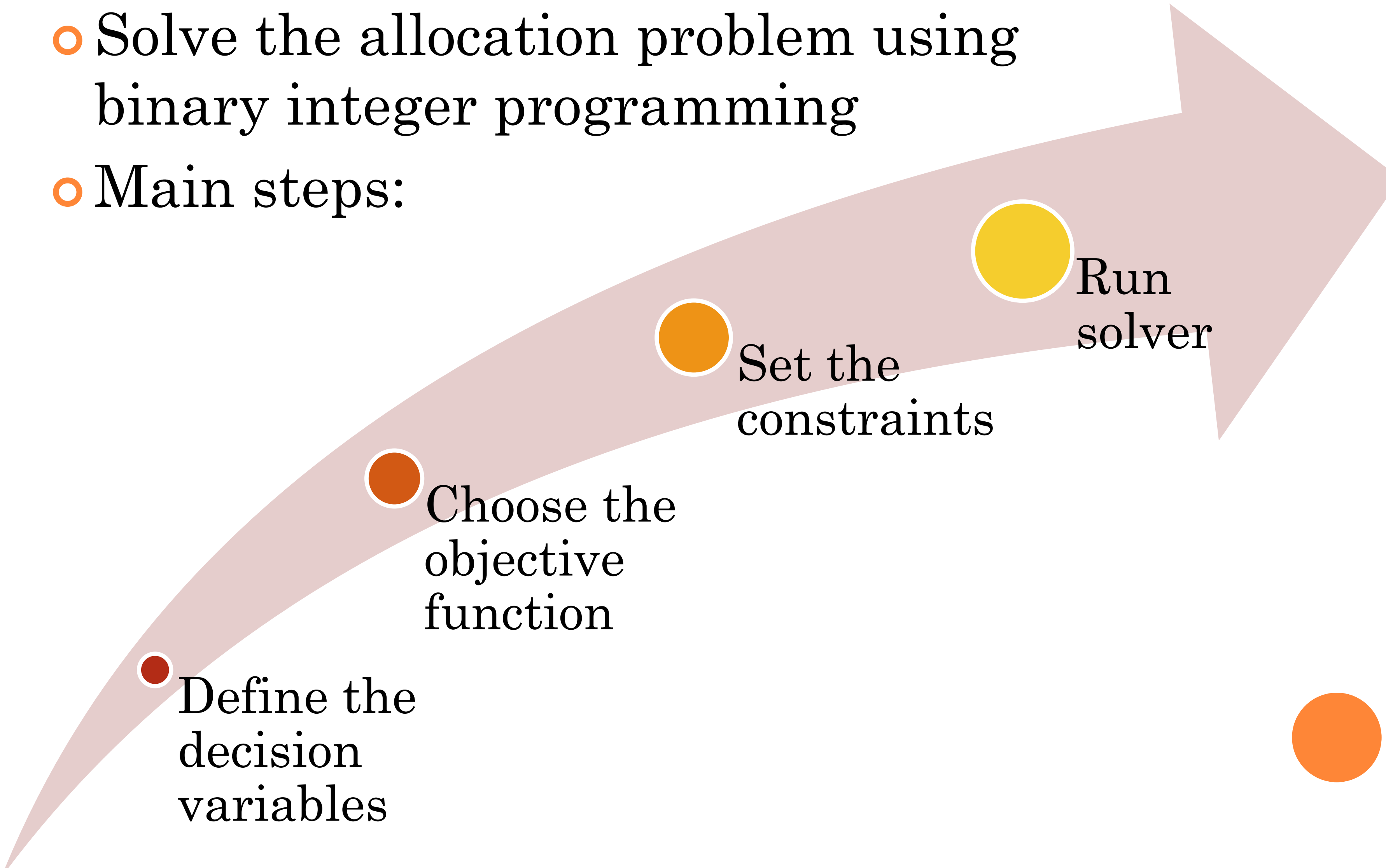
The model



The probability of meeting the requirement with each constellation

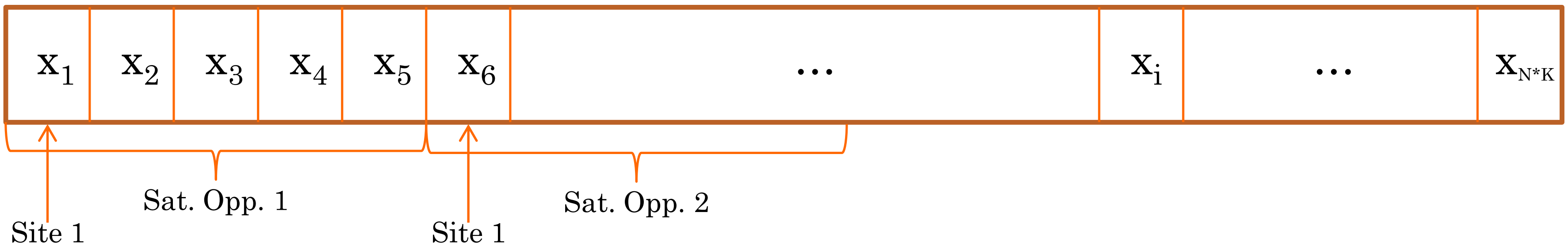
Problem statement

- Solve the allocation problem using binary integer programming
- Main steps:



Mathematical formulation – decision variables

- "Allocation opportunity" as the decision variable



- Where:
- K - number of sites in the requirement
- N - number of relevant satellite passes
- $\{x_1 \ldots x_{N \cdot K}\}$ - The decision variables vector
  - x_i represents the allocation of pass $floor(i/N)$ to site $mod(i, K)$

Mathematical formulation – objective function

- Is there a need for an objective function?
- Our objective → Minimize the total sum of allocated images
  - allows to calculate the load per requirement, hence estimate the total requirement capacity

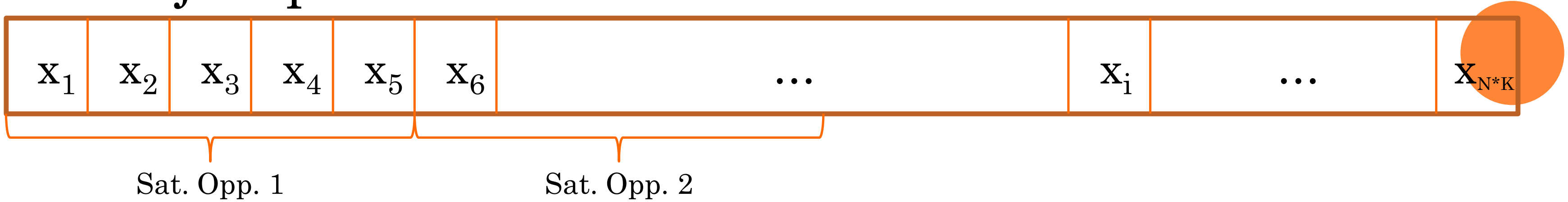
$$\min(f) = \min\left(\sum_{1}^{N \cdot K} x_i\right)$$

MATHEMATICAL FORMULATION – CONSTRAINTS (1)

- Potential images constraint:
  - Each satellite pass allows for a given # of potential images per area

$$\forall j \in (1, N), \qquad \sum_{l=(j-1)\cdot K+1}^{j\cdot K} x_l \le n_j$$

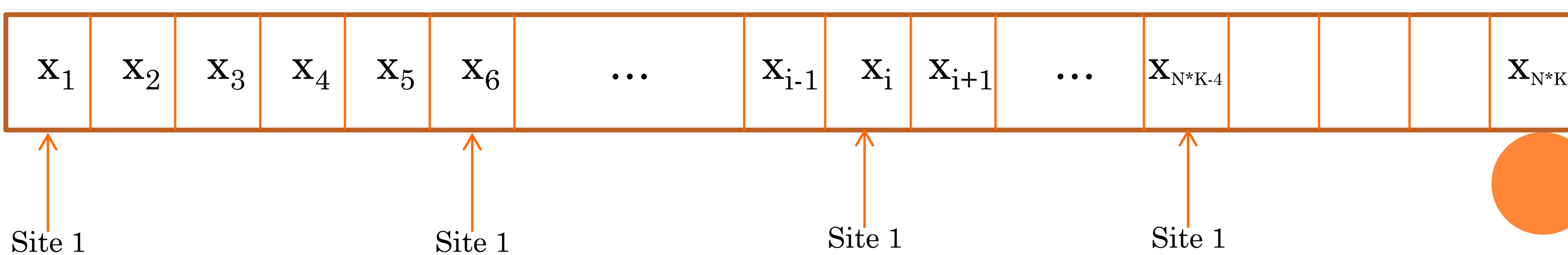
- Where:
- n_j - the total number of images for a given area in the j-th pass



Mathematical formulation – constraints (2)

- Minimal necessary allocations constraint:
  - For each site in the requirement there is a minimal necessary allocation of at least p images

$$\forall k \in (1, K), \qquad \sum_{r=1}^{N} x_{(r-1)\cdot K+k} \geq p$$



Mathematical formulation – constraints (3)

- Minimal necessary allocations constraint 2:
  - Each site may also contain separate SAR and EO allocation

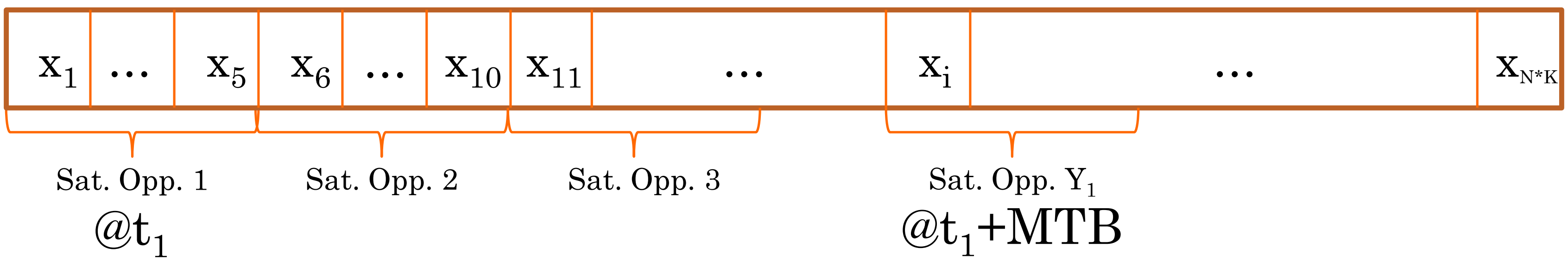
$$\forall k \in (1, K), \forall s \in N_{SAR}, \quad \sum_{s} x_{(s-1)\cdot K+k} \geq p_{SAR}$$

$$\forall k \in (1, K), \forall q \in N_{EO}, \quad \sum_{q} x_{(q-1)\cdot K+k} \geq p_{EO}$$

- Where:
- p_{SAR}- the min # of SAR images; p_{EO}- the min # of EO images;
- N_{SAR}- the total SAR capacity in the relevant time period;
- N_{EO}- the total EO capacity in the relevant time period.

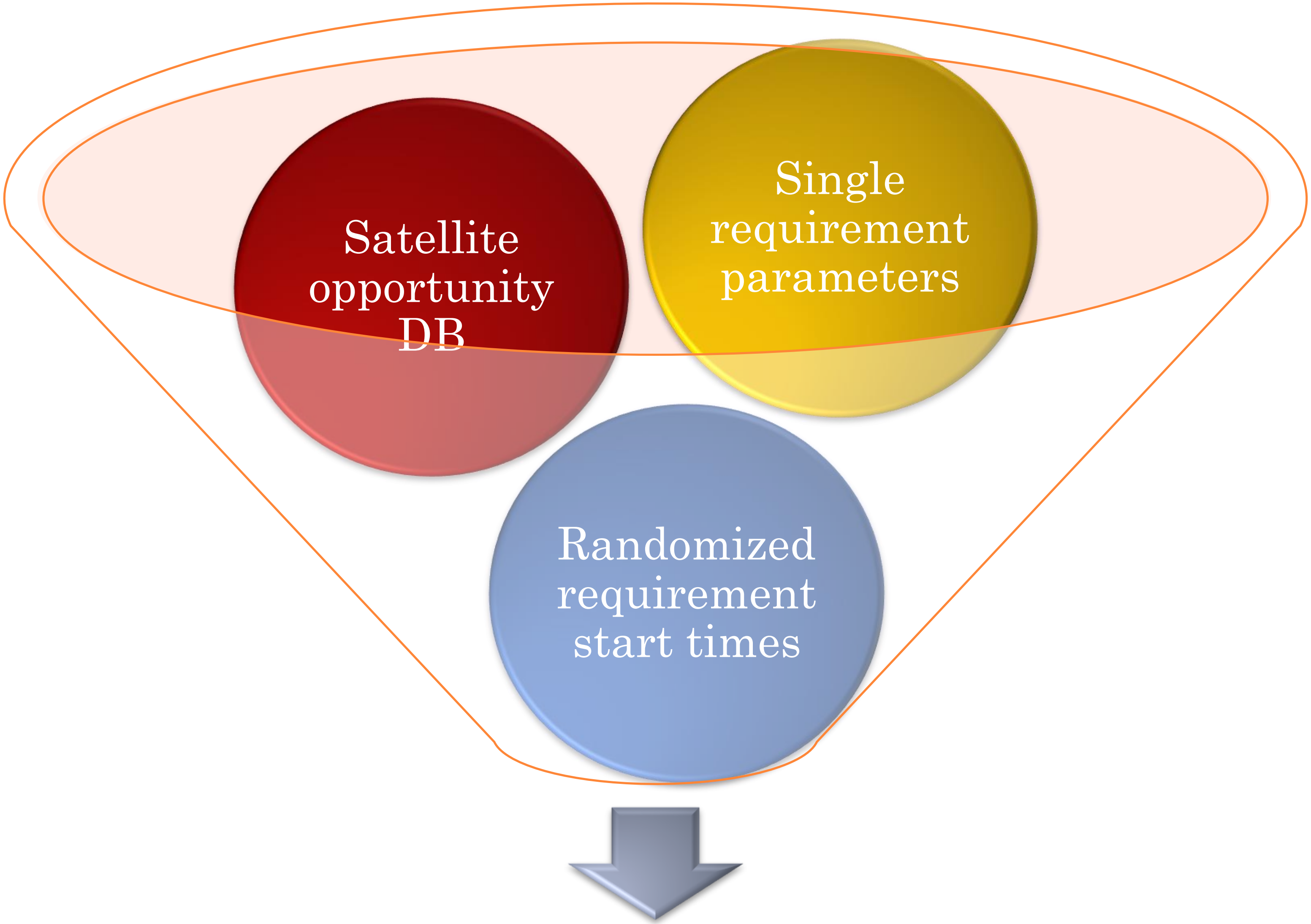
Mathematical formulation – constraints (4)

- Maximum time between allocations constraint:
  - For each requirement there is a maximal time allowed between two allocations



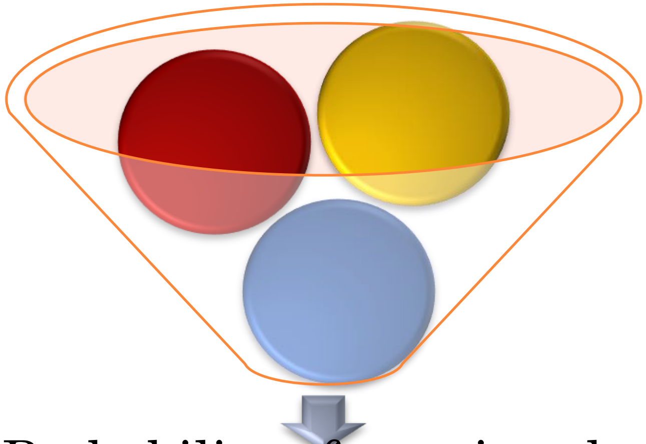
$$\forall n \in N, \qquad \forall k \in K, \qquad \sum_{t=0}^{Y_n - 1} x_{(n+t)\cdot K + k} \geq 1$$

- Where:
- Y_n- the number of passes within the maximal time period from the n-th pass



The probability of meeting the requirement with each constellation

Solving the problem



Start time	Constraint 1	Constraint 2	Constraint 3	Constraint 4	Conclusion
Jan 01 2013 02:03:56	✓	✓	✓	✓	✓
May 18 2013 12:02:03	✓	✓	✓	✗	✗
March 30 2013 16:17:15	✓	✓	✗	✓	✗
December 05 2013 01:18:36	✓	✓	✓	✓	✓
May 06 2013 18:03:15	✓	✓	✓	✓	✓
…					
Final conclusion					**60%**

Full results for a single requirement

Latitude	2-satellite constellation	3-satellite constellation
20°	90%	100%
30°	90%	100%
40°	60%	80%
50°	20%	70%
60°	0%	0%

Few days with insufficient passes cause failure due to max time constraint

Multiple days with insufficient passes cause failure due to max time constraint

Limited # of max res passes do not allow for total # of req images

Summary & Conclusions

- Our analysis points to a substantial increase in satellite relevance due to technological improvement
- Addition of third satellite improves capabilities but only slightly
- Full analysis contains:
  - Method for combining results from different requirement
  - Detailed load estimation
  - Addition of important qualitative factors
  - Budgetary limitations

Thank you for your attention!