Mass and Volume Optimization of Space Flight Medical Kits

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14 May 2014
Outline

• Introduction & Background
  • Integrated Medical Model (IMM)
  • Optimization problem definition

• Approach
  • Knapsack problem
  • Dynamic programming

• Results

• Conclusion
What is “IMM”? 

- Software-based decision support tool 
- Uses Monte Carlo simulation to forecast medical outcomes for a mission and crew
Defining the Problem

Optimize the allocation of medical resources for a given mass, volume, and/or level of acceptable risk.

Which resources to include in medical kit / medical system such that...

crew health is maximized while meeting some mass and/or volume constraint?

or

we minimize mass and/or volume while meeting some acceptable level of risk?
Defining the Problem

Let $T$ be a set of $n$ medical treatments $\langle t_1, t_2, t_3, \ldots, t_{n-1} t_n \rangle$

Treatment $t_i$ has mass $m_i$, volume $v_i$, and some benefit $b_i$

Objective: Maximize crew health while meeting some mass constraint $M$ and/or volume constraint $V$

What is the subset $K \subseteq \langle t_1, t_2, t_3, \ldots, t_{n-1} t_n \rangle$ such that we:

Maximize $\sum_{i \in K} b_i$

Subject to $\sum_{i \in K} v_i \leq V$ and $\sum_{i \in K} m_i \leq M$
Defining the Problem

Let $T$ be a set of $n$ medical treatments $\langle t_1, t_2, t_3, \ldots, t_{n-1} t_n \rangle$

Treatment $t_i$ has mass $m_i$, volume $v_i$, and some benefit $b_i$

Objective: Minimize mass and volume subject to some acceptable level of risk $R$. Let $B$ be the required total benefit of the kit to achieve $R$.

What is the subset $K \subseteq \langle t_1, t_2, t_3, \ldots, t_{n-1} t_n \rangle$ such that we:

Minimize $\sum_{i \in K} v_i$ and $\sum_{i \in K} m_i$

Subject to $\sum_{i \in K} b_i \geq B$
Approach

Classic combinatorial optimization problem: Knapsack Problem

- Brute force: $2^n$ run time
- Dynamic programming: $n \times M \times V$ run time
  - Problem has optimal substructure
  - Use recursive function to build solution from solutions to sub-problems
Approach

- Use IMM outputs to:
  - Define $T$ – our set of treatments
  - Assign benefit values $b_i$ to elements of $T$
Let $T = \langle t_1, t_2, t_3, \ldots, t_{n-1} t_n \rangle$ be the minimum set of resources for some $k$ IMM trials so that all medical events are fully treated within any single trial.
Objective: Maximize crew health subject to mass and volume constraints.

- Assigning benefit value $b_i$ for treatment $t_i$
  - Maximize crew health index (CHI)*
    - $b_i$ is a function of the frequency $t_i$ is used during mission and the impact to CHI if the medical conditions requiring $t_i$ go untreated
  - Minimize probability of evacuation (pEVAC)
    - $b_i$ is a function of the frequency that medical conditions requiring $t_i$ result in an evacuation

*CHI is a function of quality time lost
Approach

Objective: Minimize kit mass and volume subject to a risk threshold.

Assigning benefit value $b_i$ for treatment $t_i$

- Maximize crew health index (CHI)
  - $b_i$ is a function of the mean contribution $t_i$ makes to CHI over $k$ IMM simulations

\[ \sum_{i \in T} b_i = B_{tot} \]

Find subset $Q \subseteq \{t_1, t_2, t_3, ..., t_{n-1}, t_n\}$ s.t. we:

Maximize $\sum_{i \in Q} \nu_i$ and $\sum_{i \in Q} m_i$ subject to $\sum_{i \in Q} b_i \leq B_{tot} - B$

Let $K = T \setminus Q$
Results – 4 crew, 14 day mission

Optimization Priority: Minimize pEVAC
Results – 4 crew, 14 day mission

Optimization Priority: Maximize CHI
Results – 2 crew, 24 day mission

Optimization Priority: Maximize CHI
Results – 2 crew, 24 day mission

Optimization Priority:
Minimize pEVAC
Conclusion

- Outcomes from mass/volume-constrained medical kits generated by the new approach more closely approach the best-case unlimited-resource scenario than previous implementations (Minard et al)
- Features of optimization algorithm include:
  - Group resources into ‘treatments’
  - Ability to tailor resource benefit measures \( b_i \) according to optimization objectives and priorities
- Algorithm provides an efficient means to objectively allocate medical resources for spaceflight missions using the Integrated Medical Model

Questions?

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