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Modeling Hospital Evacuation for Infrastructure Disruptions

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Superstorm Sandy

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Superstorm Sandy highlighted the impacts infrastructure interruptions can have on hospital operations and evacuations.

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Evacuation Decision Challenges

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- High Degree of Uncertainty
- Resource Competition
- High Consequences
- Models can help reason through complexities of evacuations

(www.cbsnews.com)

(www.thewildmagazine.com)

Sandia and Veterans Administration are creating modeling tools to support the hospital evacuation decision process.

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Current Modeling Limitations

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- Don’t address “Should we evacuate?”
- Assume full functionality of infrastructures
  - No impact to power, communications, etc. or dependent hospital operations such as evacuation, elevators, etc.
  - Underestimate resource needs and overestimate rapidity
- Don’t represent staff and organizational adaptations
  - Miss impact of critical human behaviors
  - Underestimate resilience

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Questions to Address

- Given situational awareness, knowledge of infrastructure vulnerabilities, current available resources, and vulnerability of patient population
  - Is evacuation necessary?
  - If so, are current resources adequate to evacuate safely and efficiently?
  - How can resources be best allocated to ensure safe, efficient evacuation?
  - What adaptations can be made in a resource constrained environment?

Case Study: Memorial Hermann Hospital (MHH)

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Environment

- 450 bed adult Level 1 trauma hospital
- Serves 4 million people
- Part of Texas Medical Center, the largest medical center in the world

Photograph from Floodbreak.com

Event

- Hurricane Allison, June 2001
  - Electric power lost with no warning
  - 40 million gallons of water flood basement and electrical switchgear
  - Result: no generator power
  - Of the 575 patients: 106 discharged and 469 evacuated to 29 other facilities either by ambulance or helicopter

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Ventilation Timeline: Nominal Conditions

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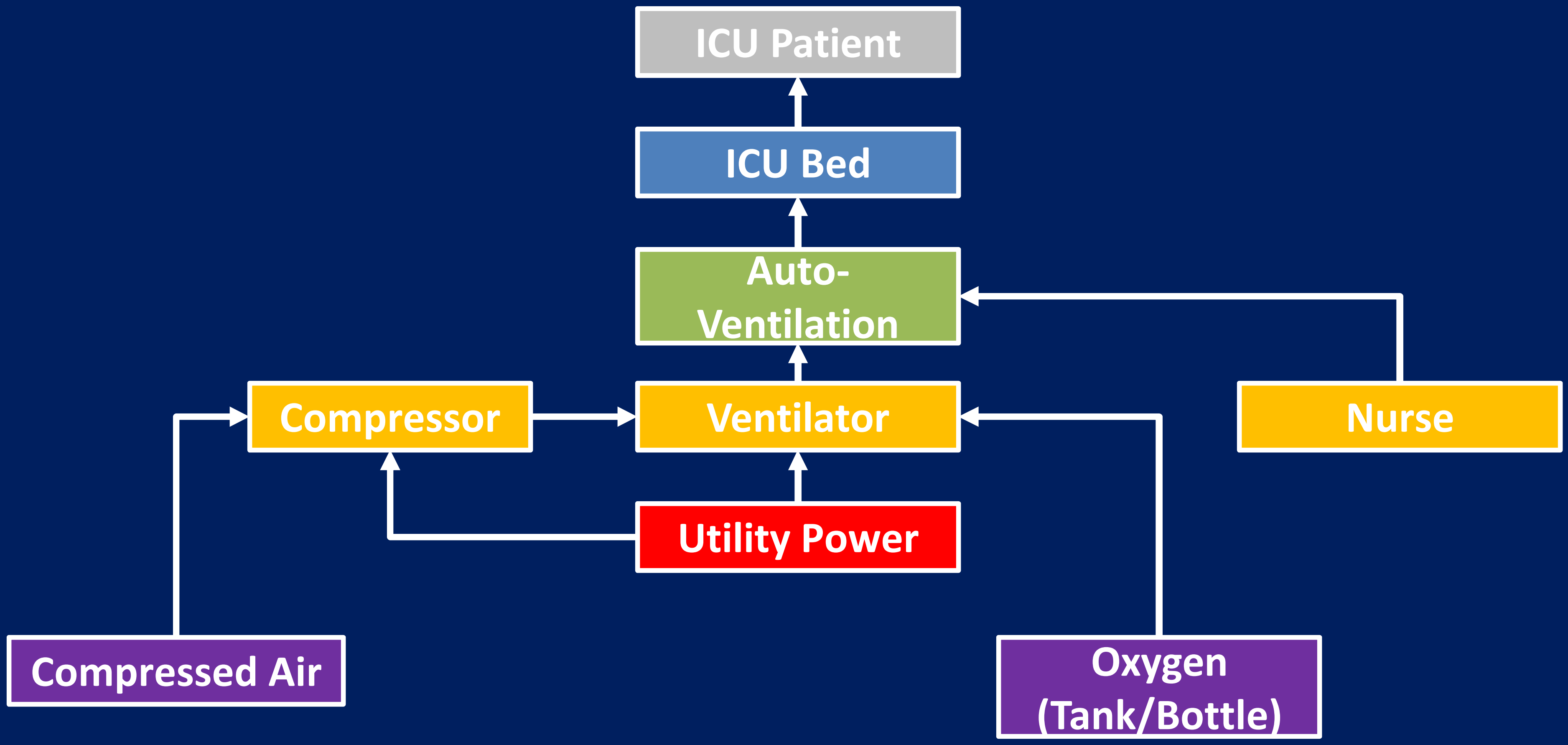

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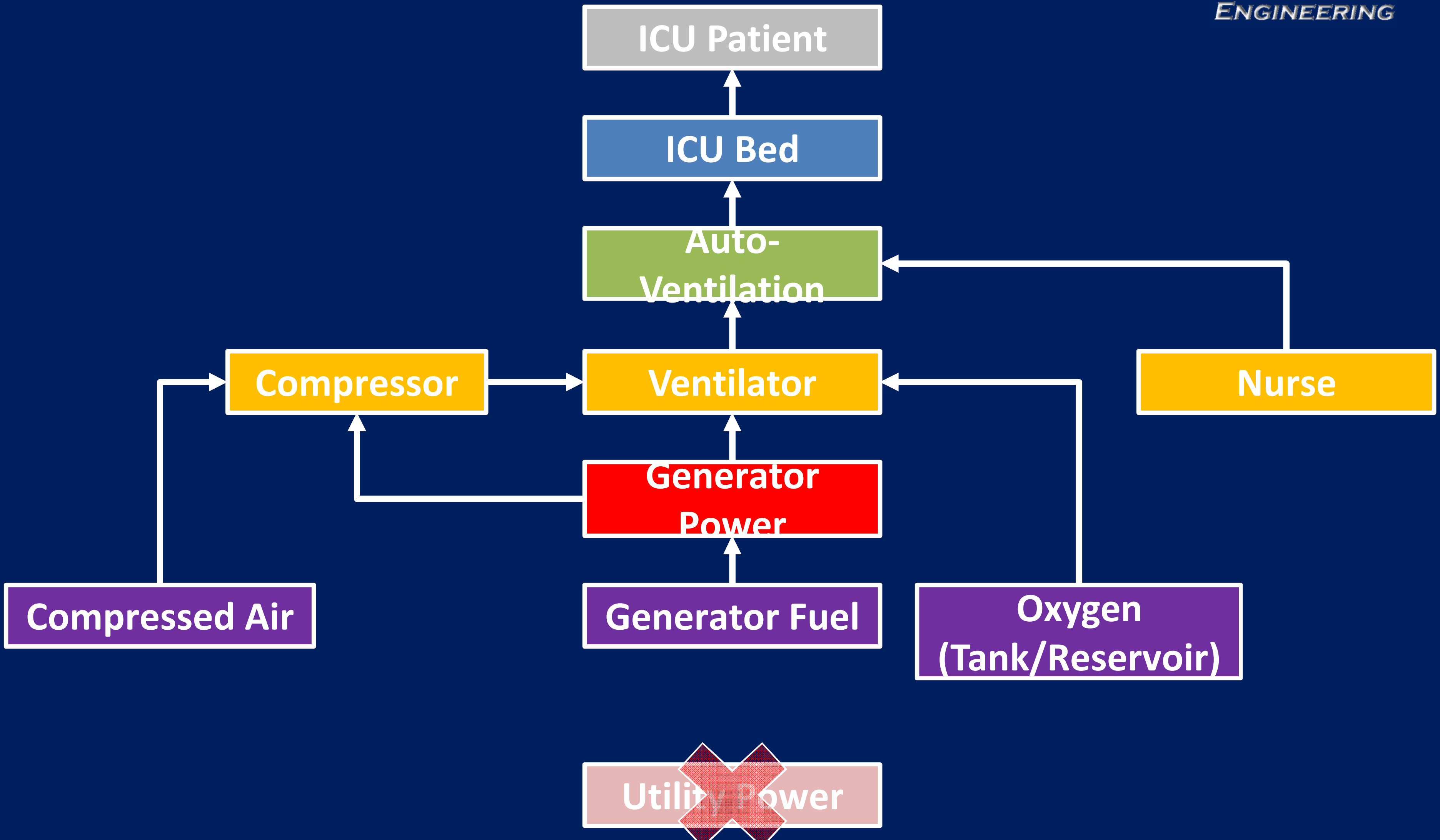
Ventilation Timeline: Initial Power Loss



Generator provides necessary power to continue ventilation

Ventilation Timeline: Loss of Generator

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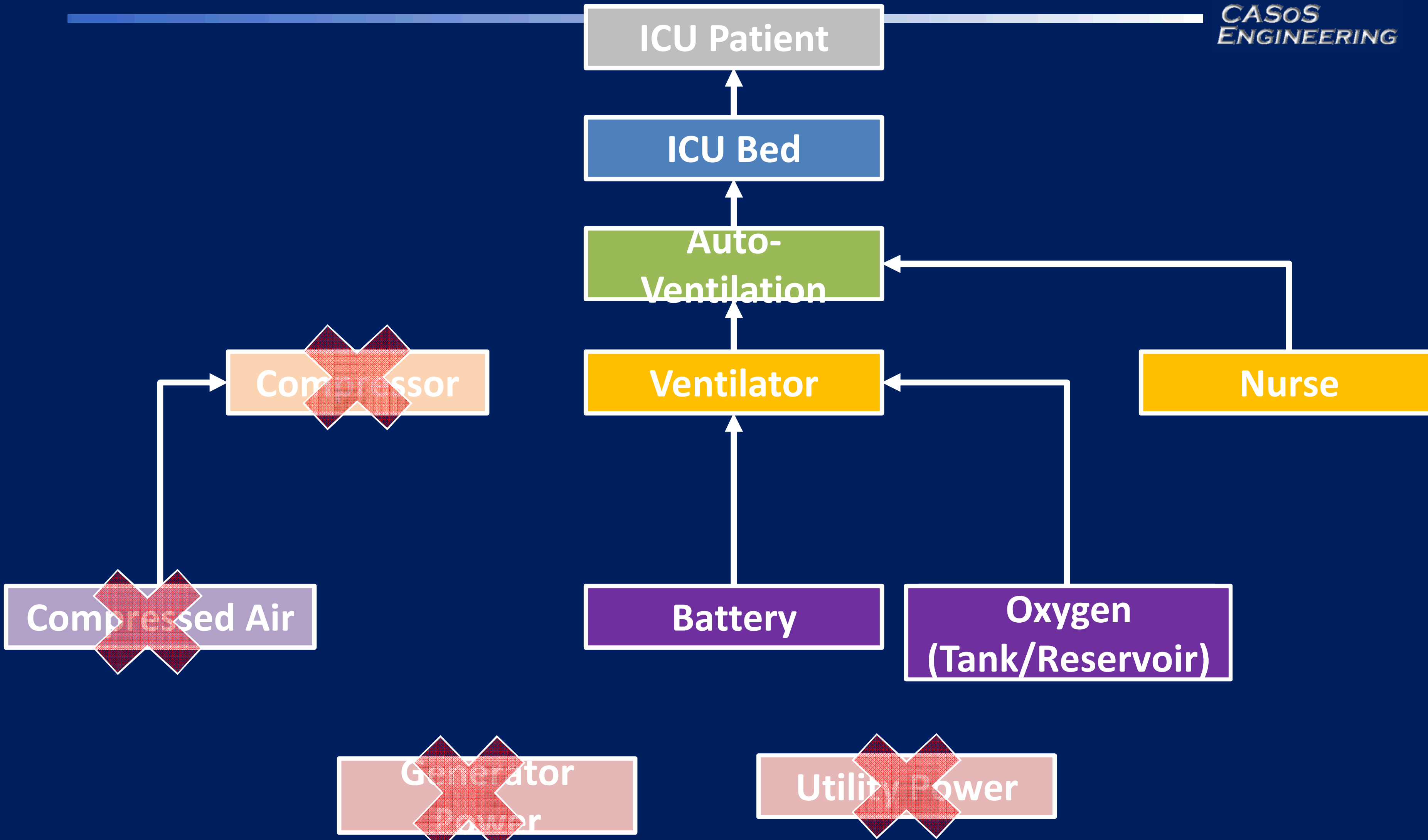

Loss of generator power requires use of bottled oxygen, depleting oxygen supplies more rapidly

Ventilation Timeline: Beyond Battery Capacity

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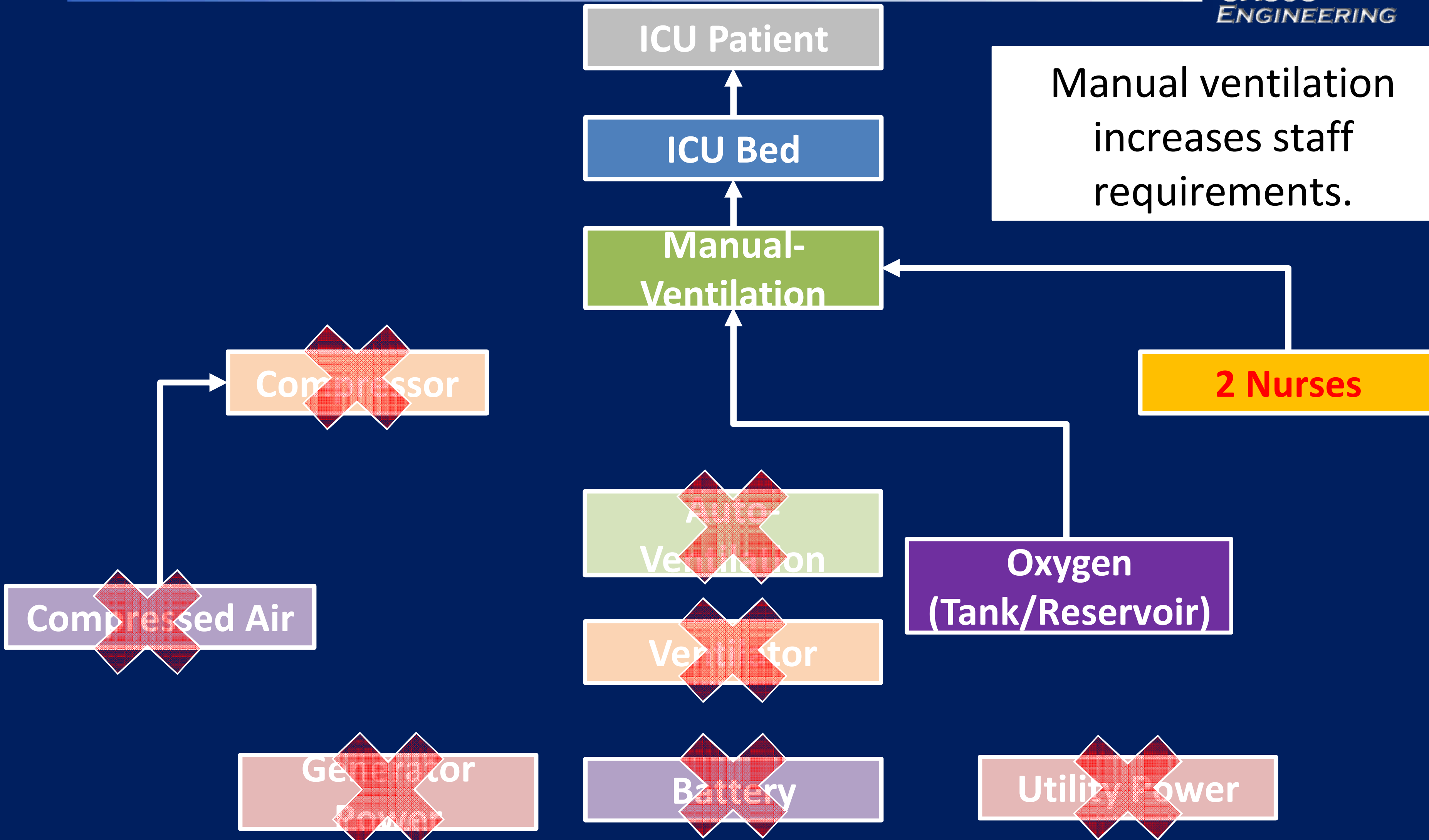

Manual ventilation increases staff requirements.

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Ventilation Timeline: Beyond Oxygen Capacity

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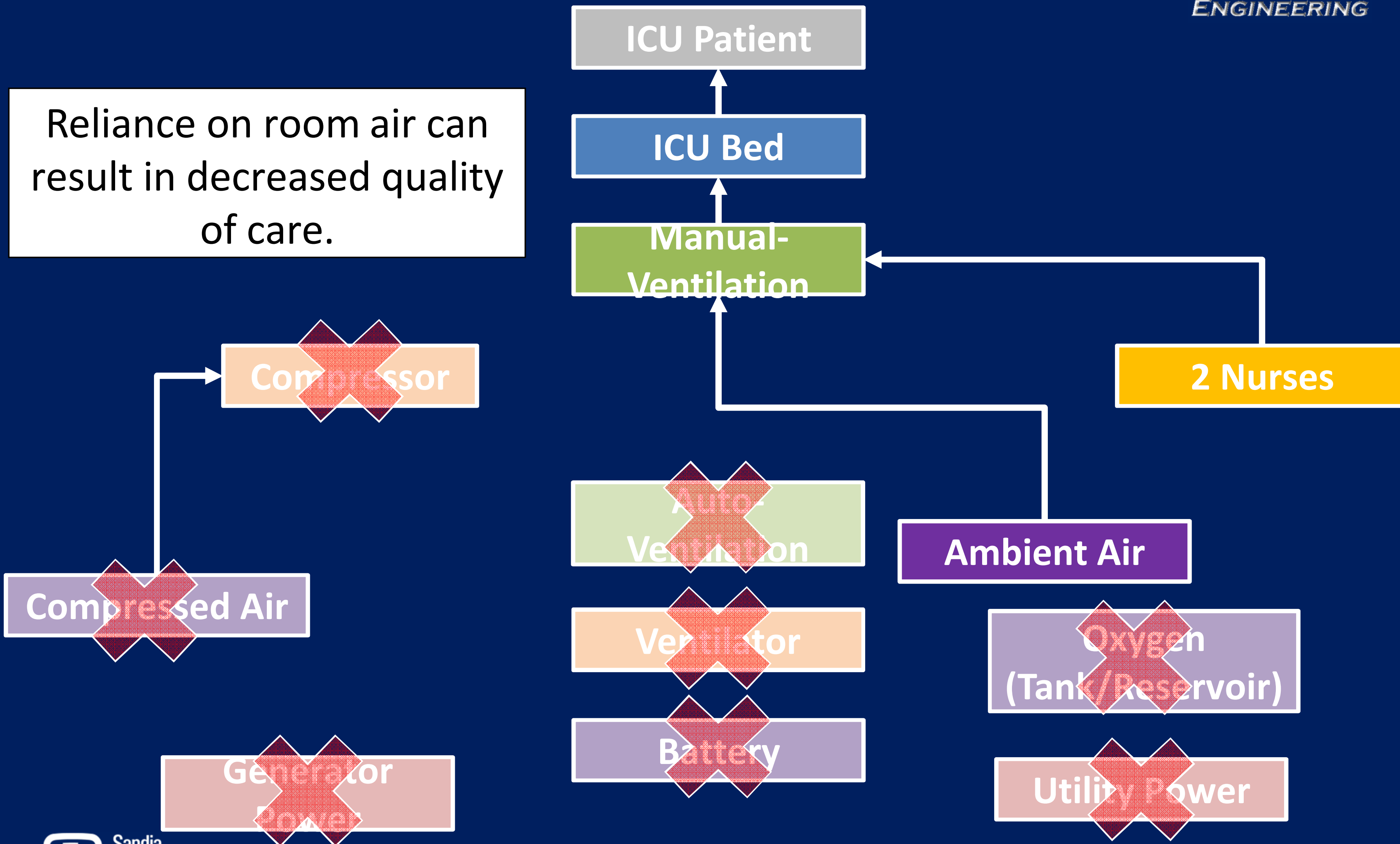
Reliance on room air can result in decreased quality of care.



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Modeling Constructs: Patient Care Hierarchy

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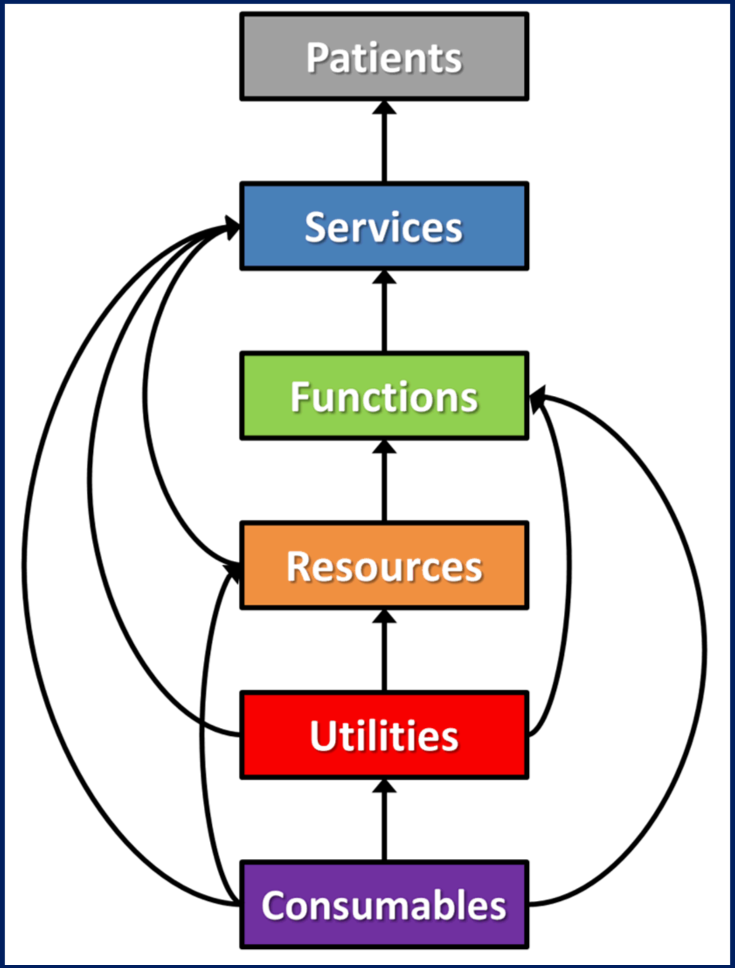

Hierarchy provides conceptual, static view of requirements and dependencies

Modeling Constructs: Notional ICU Example

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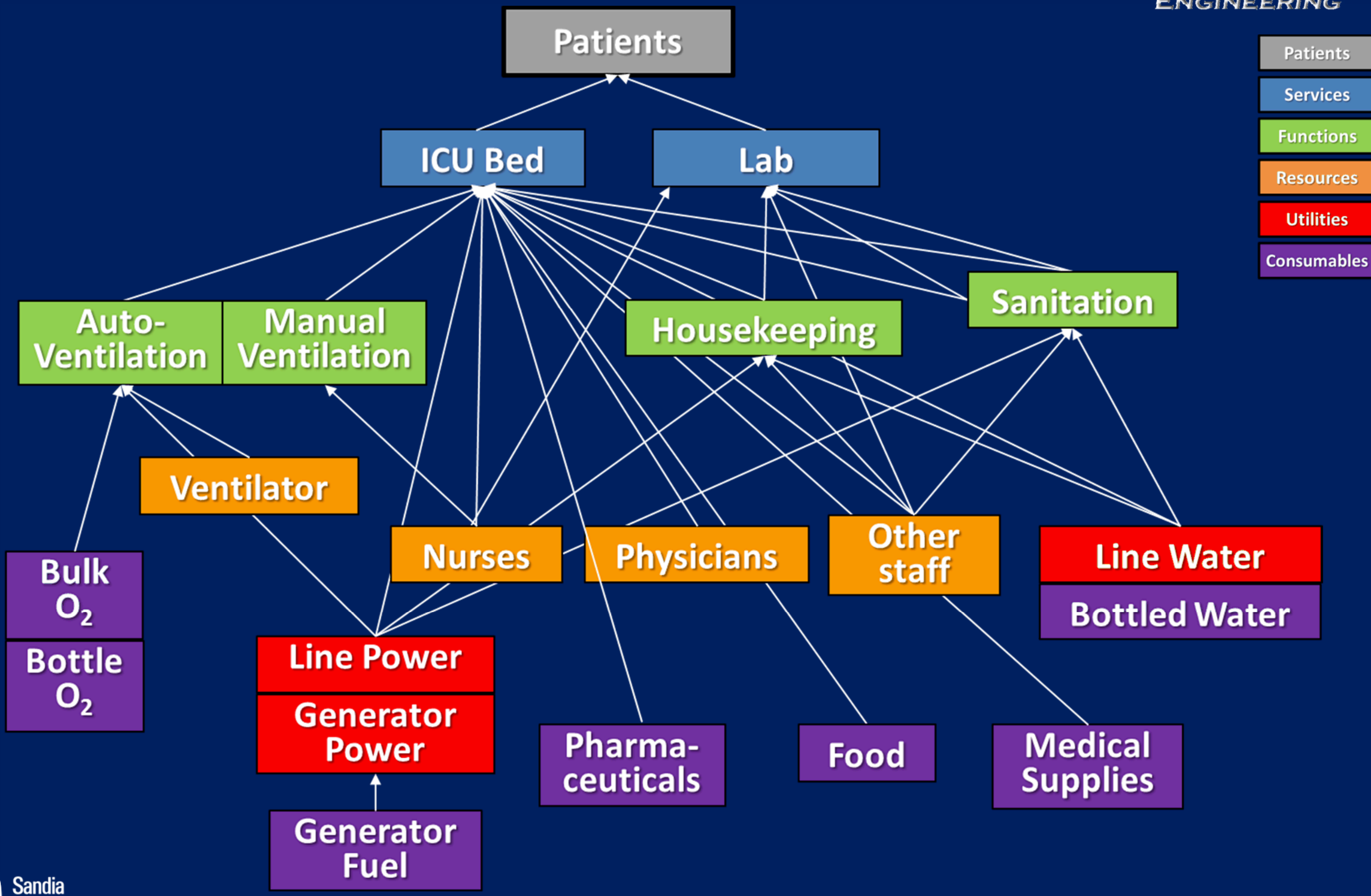

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Modeling Constructs: Constrained Optimization Model

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- Simulate the disruption
  - "What did we lose and for how long?"
  - "What can't we do?"
- Assess requirements
  - "What do patients need vs. what do we have?"
  - "When do we run out?"
- Account for adaptations
  - "How can we compensate?"
- Allocate resources to honor priorities
  - Maximize sustainable care
  - Minimize evacuations
  - Minimize costs

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Sketch of Mathematical Model

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Nonsustainable care | **Evacuations** | **Resource costs**

$$\min \sum_i \sum_t w_i z_i(t) + \sum_i \sum_t \sum_l c_{il} e_{il}(t) + \sum_i \sum_t C_i r_i(t)$$

subject to

$$p_i(t) = p_i(t-1) + a_i(t) - d_i(t) + \sum_{i' \neq i} x_{i'i}(t) - \sum_{i' \neq i} x_{ii'}(t) - \sum_l e_{il}(t)$$

Track patients

$$Y_s(t) = \sum_i \rho_{si} q_i(t) + \sum_i \zeta_{si} \sum_l e_{il}(t) \qquad \text{for all } s, t$$

Track service requirements

$$\sum_{g' \in G_{ns}^f} \left[\frac{v_{g's}(t)}{\beta_{g's}} \right] = Y_s(t) \qquad \text{for all sets } G_{ns}^f, \ \text{for all } s, t$$

Allow substitution

$$r_i(t) < R_i(t)$$

Constrain resources

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Case Study: Memorial Hermann Hospital (MHH)

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Photograph from Floodbreak.com

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Following results recreate and analyze evacuation of the MHH NTICU

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What if administrators chose to shelter in place and not evacuate?

Results: Shelter in Place Decision

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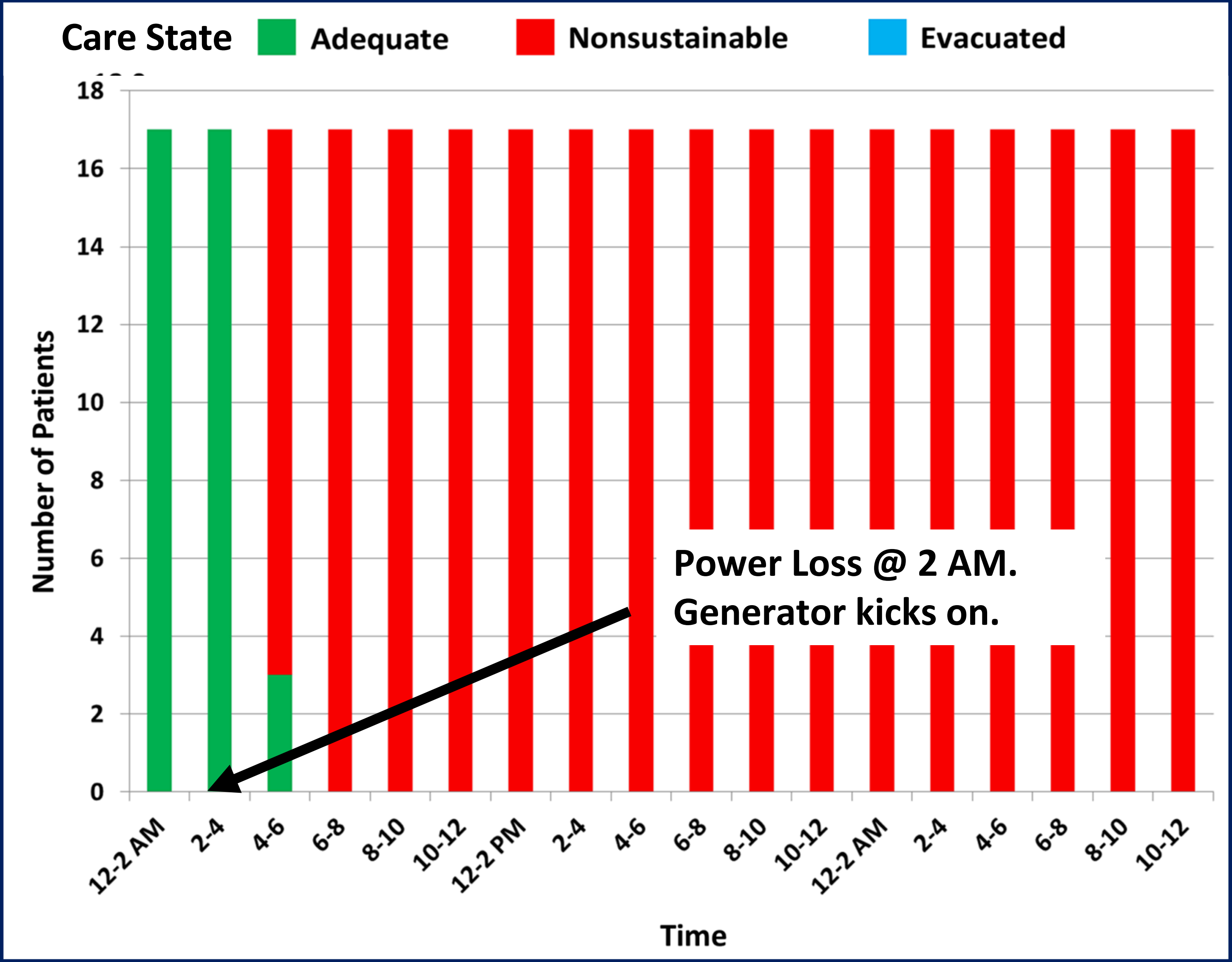

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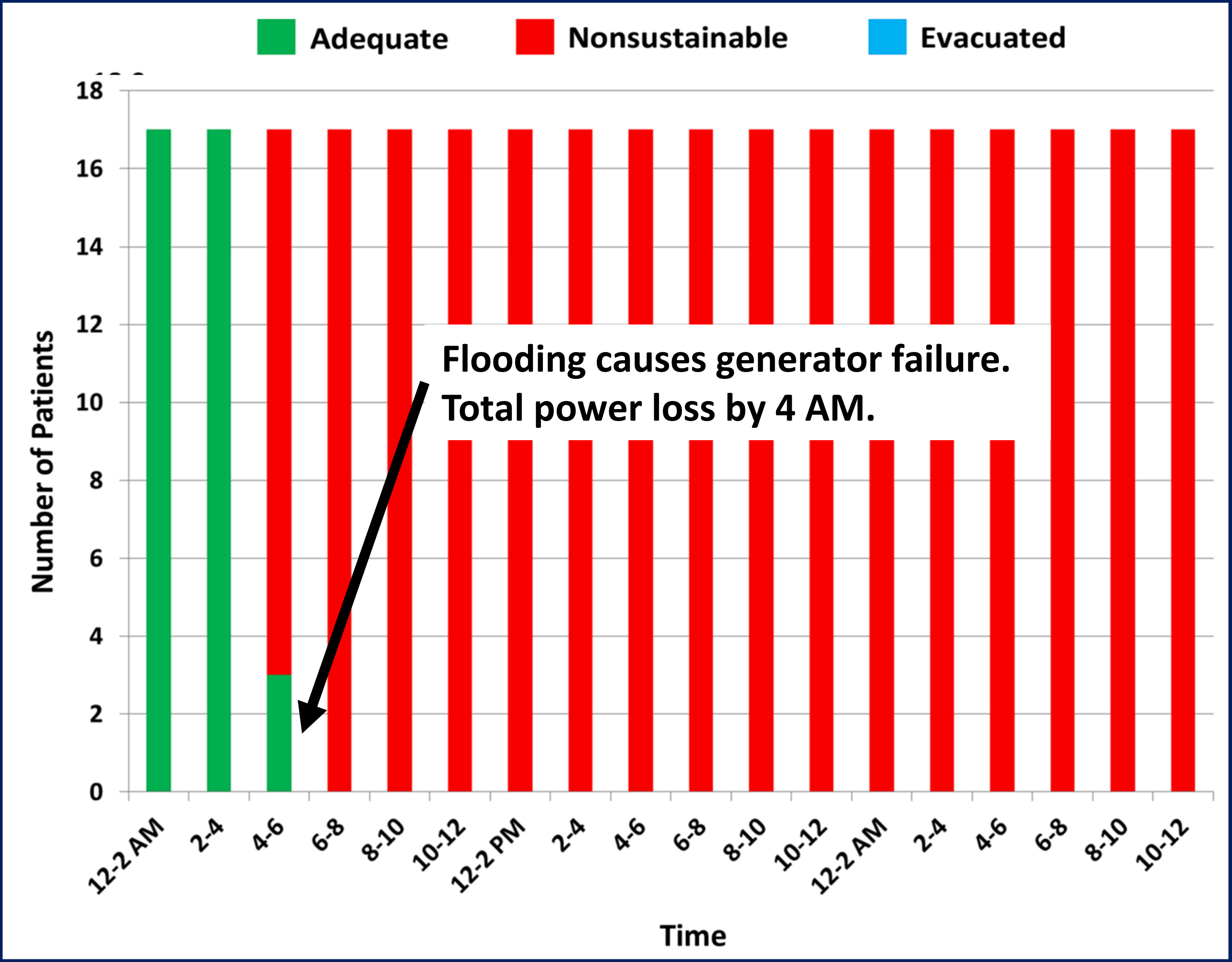
Results: Shelter in Place Decision



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Results: Shelter in Place Decision

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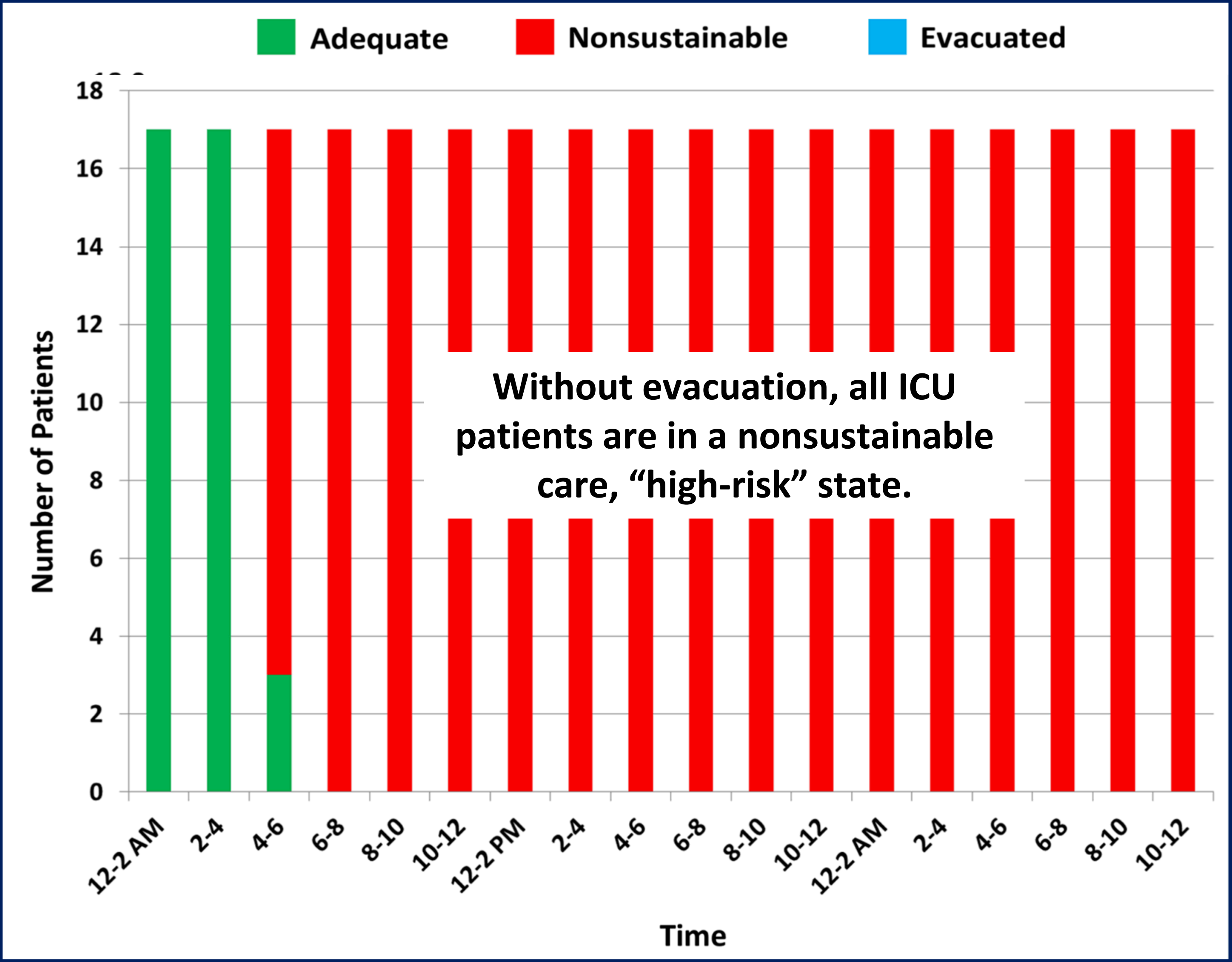

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Evacuation Recreation

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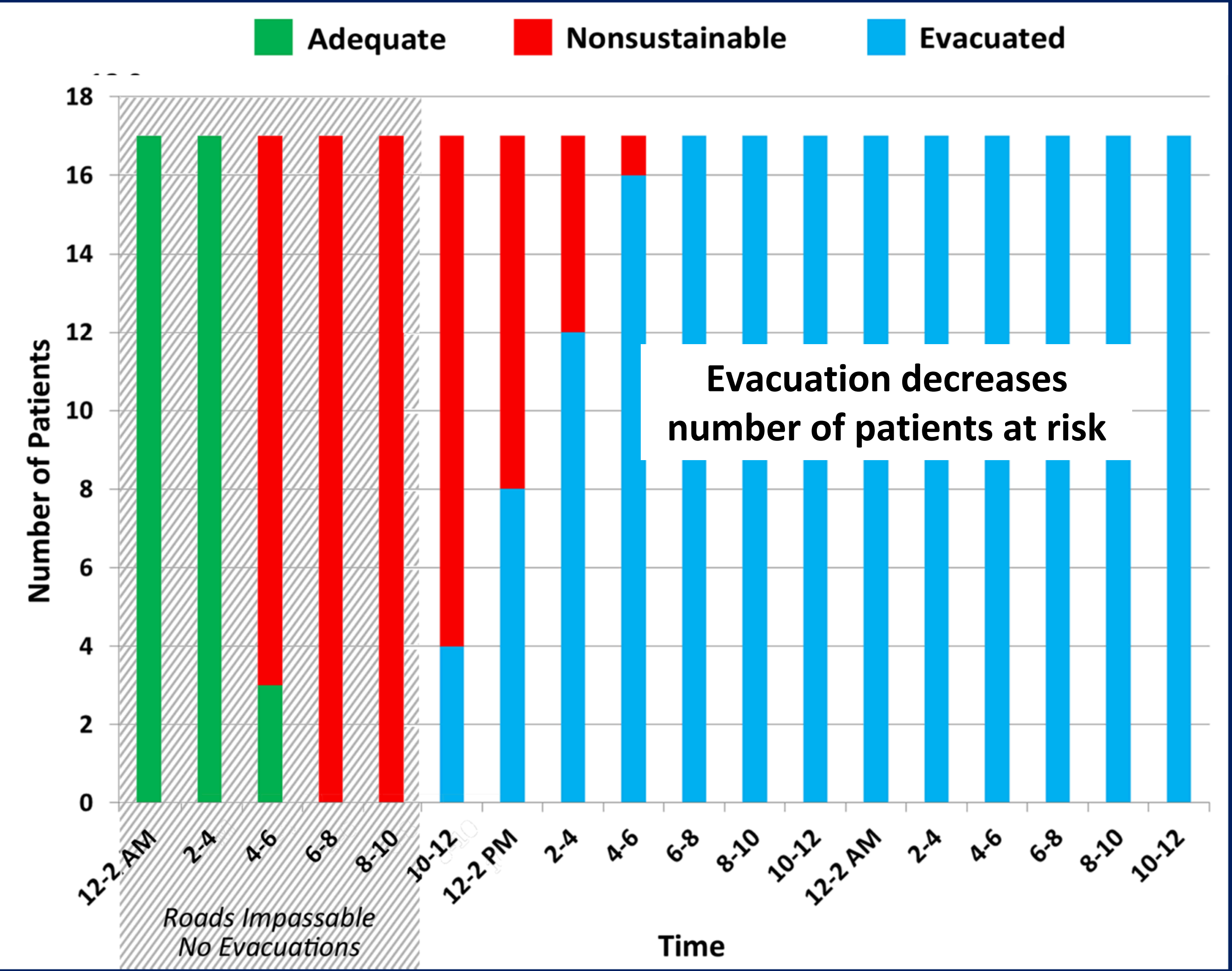
Results: Nominal Evacuation Scenario



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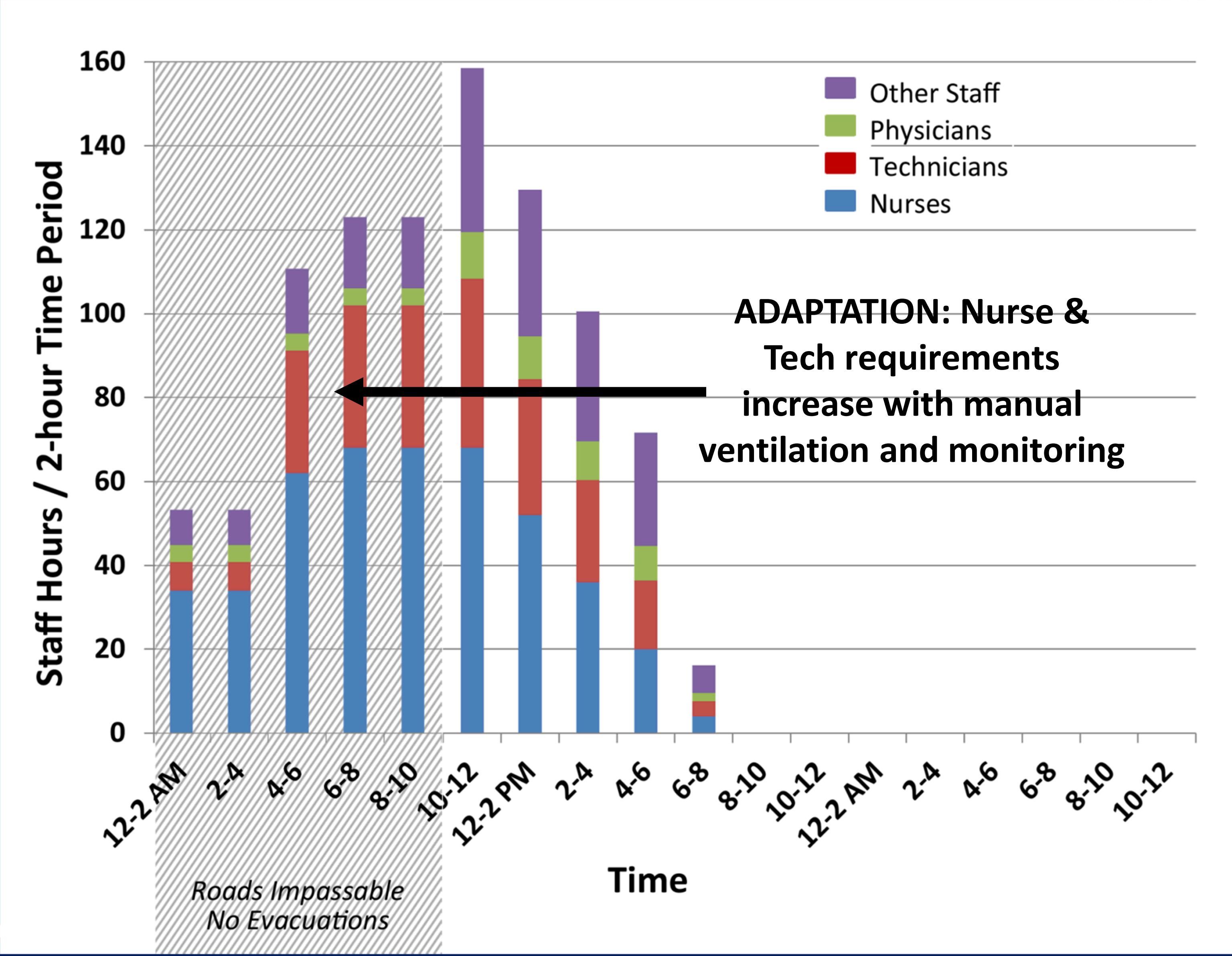
Results: Staff Usage for Evacuation



Results: Staff Usage for Evacuation

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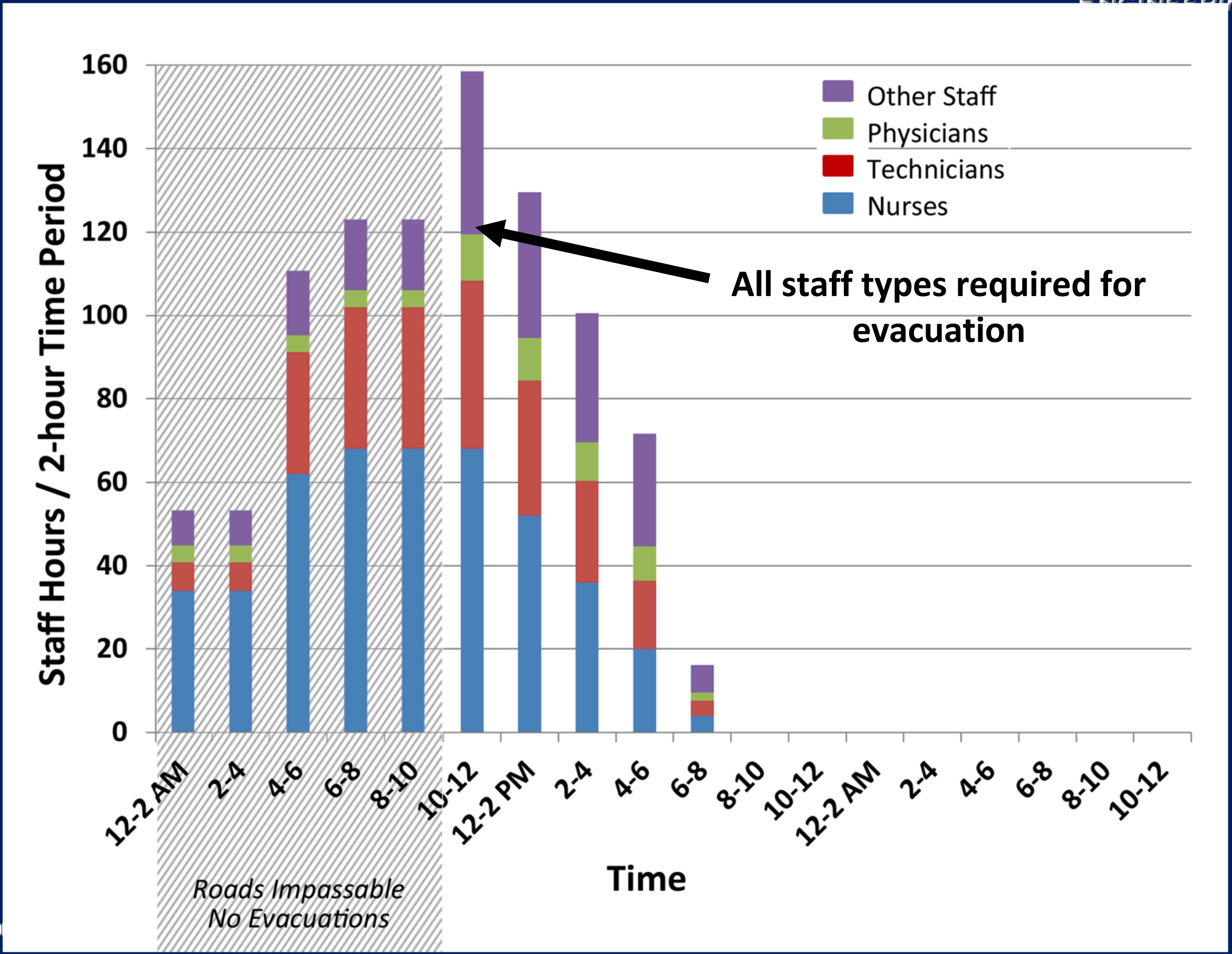

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Results: Staff Usage for Evacuation

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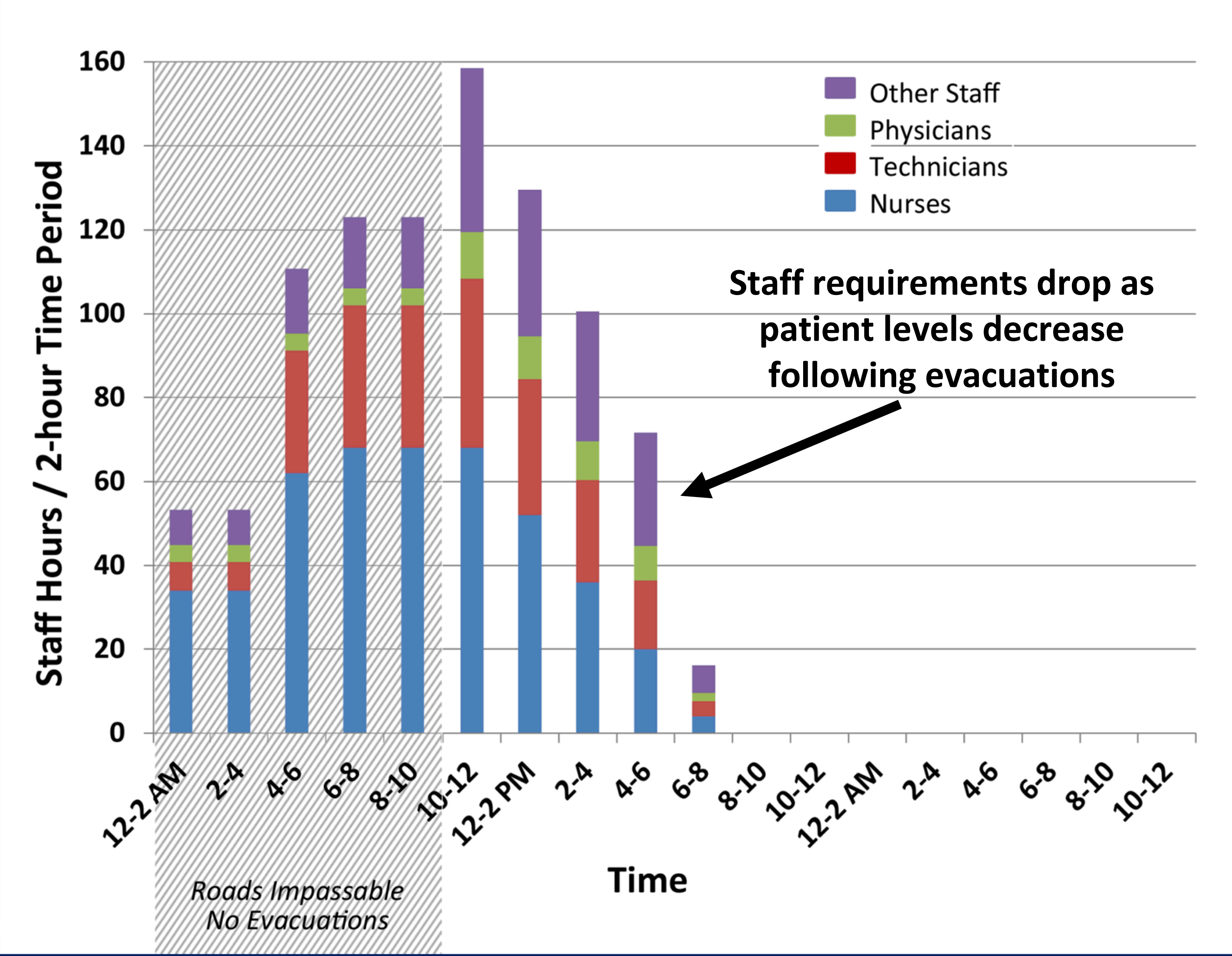

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How could increases/decreases in transportation resources affect the evacuation?

Results: Impact of Transportation Resources

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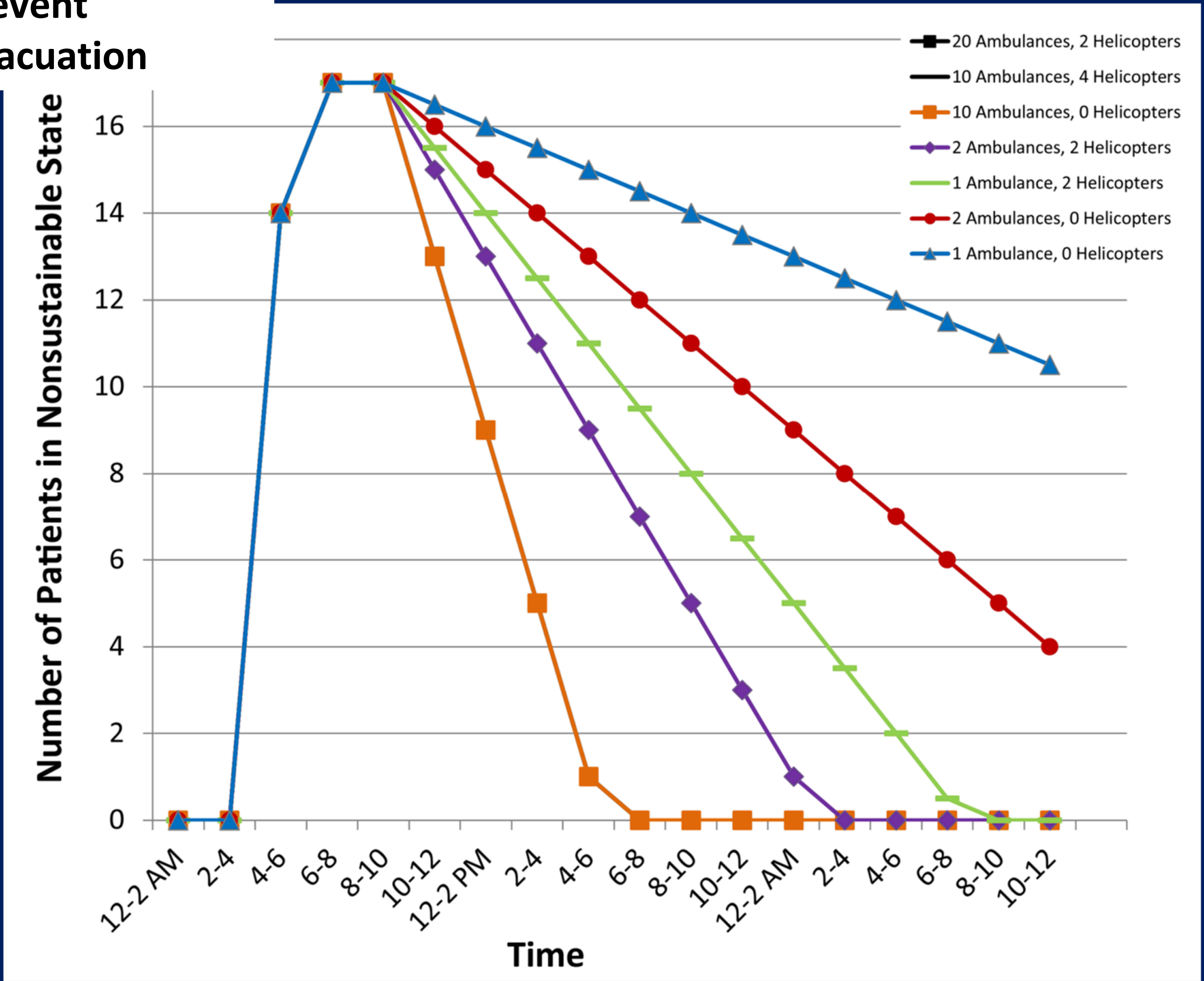
Transportation constraints can slow/prevent complete evacuation



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Results: Impact of Transportation Resources

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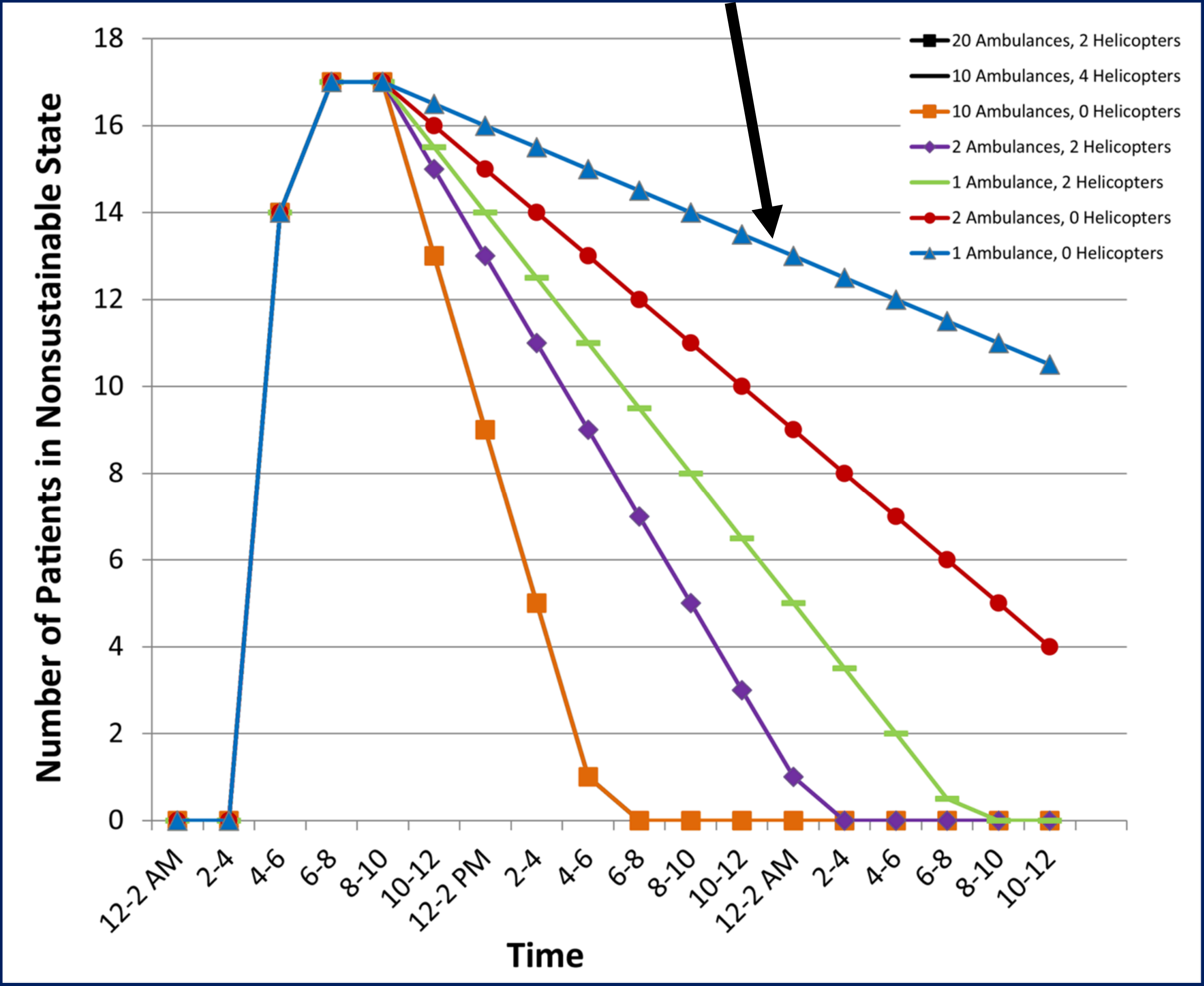
Not enough resources



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Results: Impact of Transportation Resources

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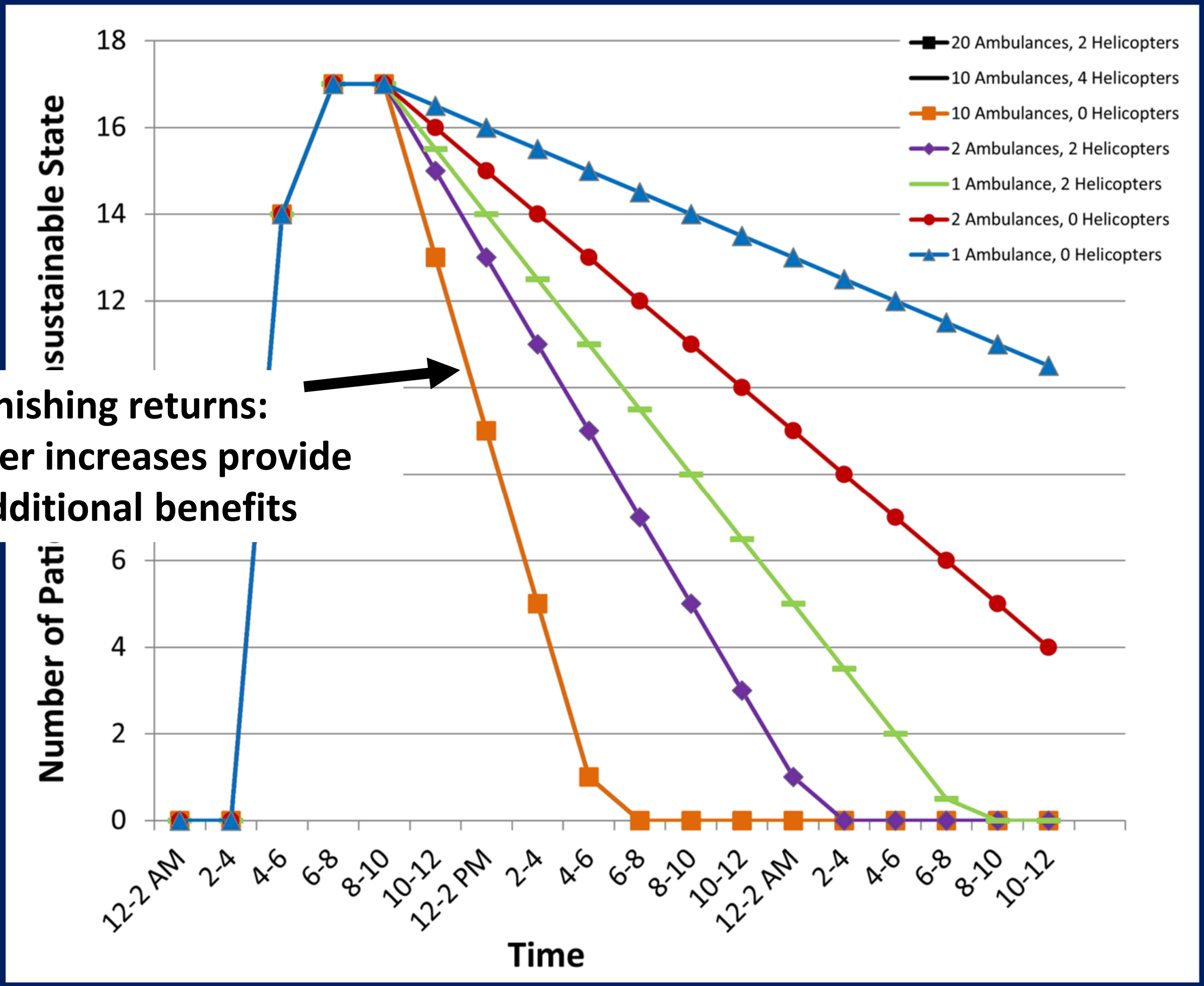

Diminishing returns: further increases provide no additional benefits

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How could increased battery capacities affect the evacuation?

Results: Increase Battery Capacity

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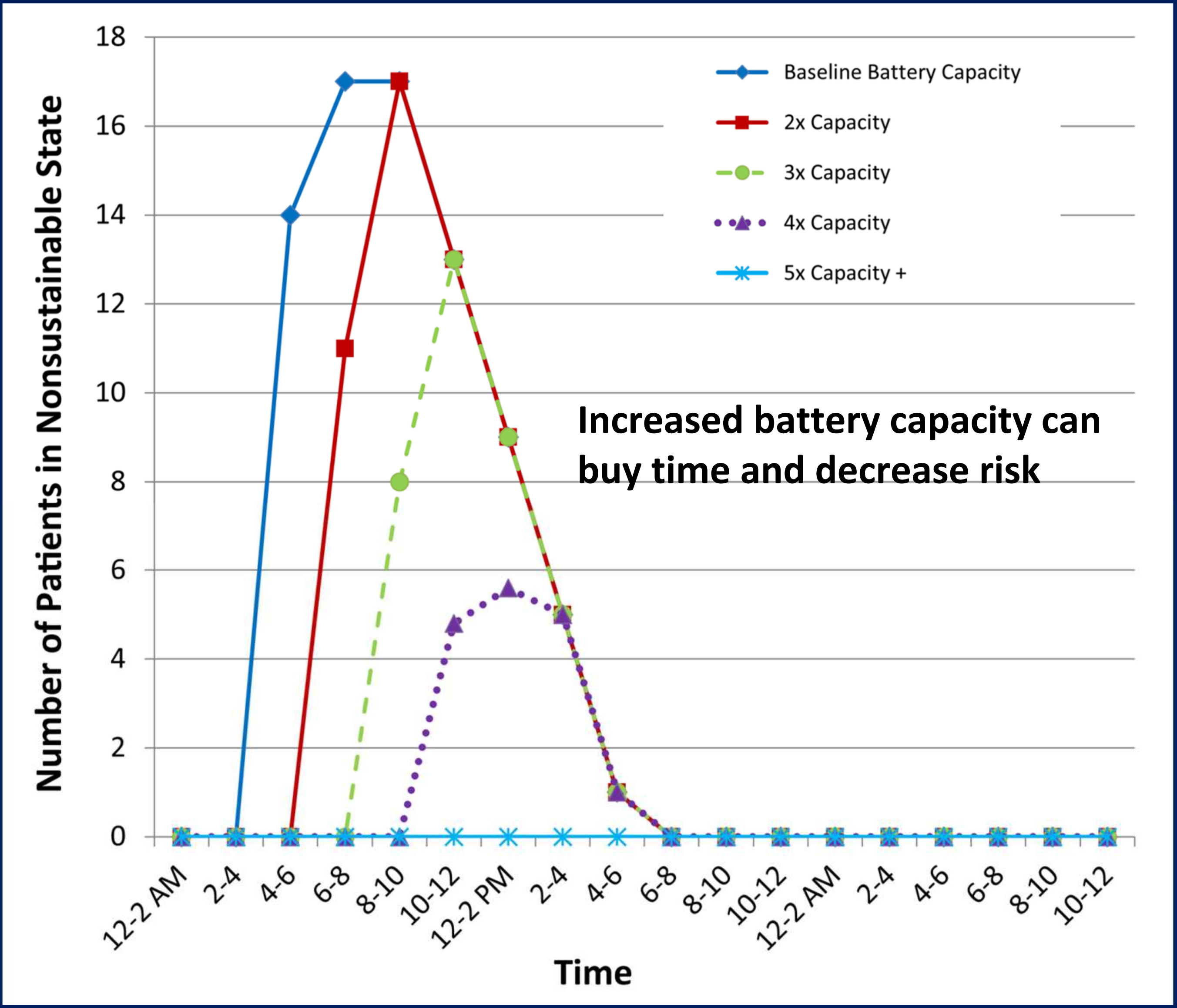

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Results: Increase Battery Capacity

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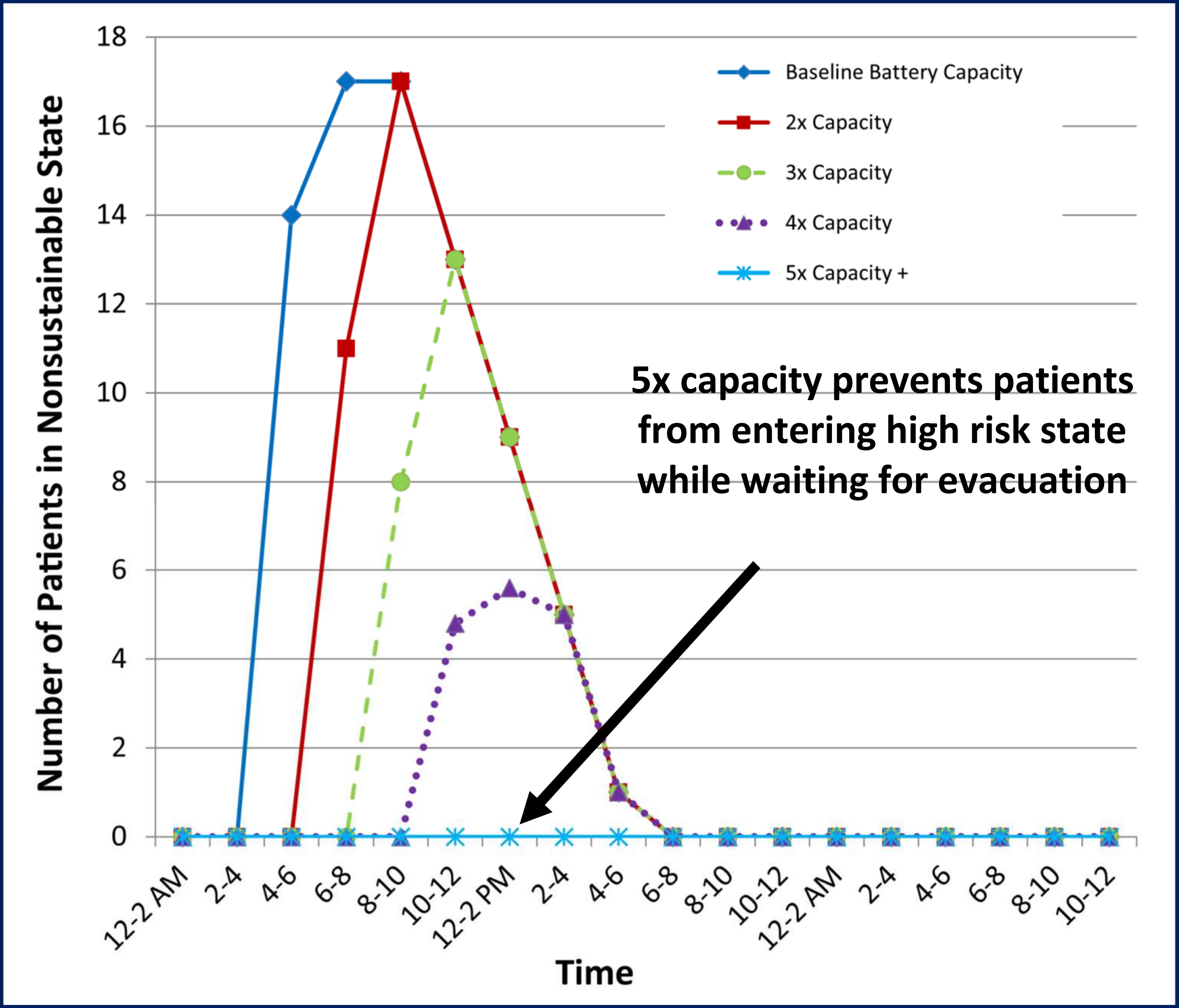

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Current Activities

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- Model extensions
  - Uncertainty
  - Discrete formulation
  - Different kind of shock: introduction of infectious disease patients
- Seeking opportunities to support emergency planning for real facilities

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Additional Information

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- Publications:
  - Model formulation: **Modeling Hospitals' Adaptive Capacity during a Loss of Infrastructure Services**, Vugrin et al. (2015). J of Healthcare Engineering, 6(1): 105-140.
  - Case study: **Modeling Evacuation of a Hospital without Electric Power**, Vugrin et al. (2015). Prehospital and Disaster Medicine

Website: CASOS Engineering

http://www.sandia.gov/CasosEngineering/resilience.html