THE DRONE SYSTEM II: AVAILABILITY PERFORMANCE ANALYSIS AND MODELING

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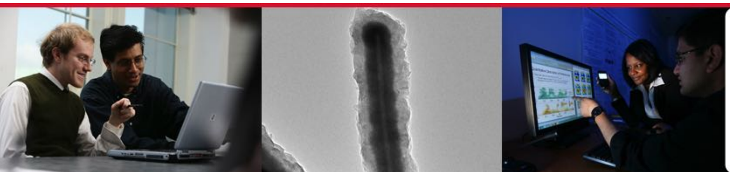
AGENDA

- Purposes and Approach
- Background
- Deterministic Model
- Analytical Stochastic Model
- Trade-off Analysis
- Conclusions and Next Steps
- Backup Slides

PURPOSES AND APPROACH



META-PURPOSE

- This is the second in a series of papers that will provide examples of how to use a Model-Based Systems Engineering (MBSE) approach to implementing the processes outlined in the INCOSE *Systems Engineering Handbook* and ISO/IEC/IEEE 15288:2015.
- The first paper in the series series provided a Drone System example of how to implement the following systems engineering technical processes:
  - Stakeholder Needs and Requirements Definition
  - System Requirements Definition
  - Architecture Definition

  and provided simple examples of some of the key outputs associated with these processes (presented in an earlier poster session).
- This paper focuses on providing a Drone System example of how to implement the following processes, methods, and analysis areas:
  - (Technical) System Analysis Process
  - (Technical Management) Decision Management Process
  - Modeling and Simulation Methods
  - Reliability, Availability, and Maintainability Analysis
  - Cost Effectiveness Analysis
- It also illustrates some key pedagogical points:
  - Relationships between analysis, system architecture decisions, and modeling and simulation
  - Relationships between analytical models and Monte Carlo simulation

PURPOSES

- Drone System Purpose: The "Drone System" shall provide continuous surveillance and/or delivery service over a given area.

- Analysis Purpose: Determine the most cost-effective design (i.e., minimum number and type of drones and charging stations) required to satisfy the system's "availability" (i.e., percent time that Ndr drones are "on station") requirement.

ANALYSIS APPROACH

- Identify and document (from DSI):
  - User and System Requirements
  - Reference System Architecture (& Design)
  - Concept of Operations
  - Relevant Measures of Effectiveness and KPPs
    - Ao, MTBMs, MDTs
  - Relevant Design and Environmental Factors
    - Nd, Nchg, Nctl, Tofd, MTBMd, MDTd
- Identify and document
  - Reference Design
  - Design Options
  - Simplifying Assumptions
- Develop Ao model
  - Deterministic Model
  - Analytical Stochastic Model
- Identify Design Options
- Perform Design Trade-off Analysis

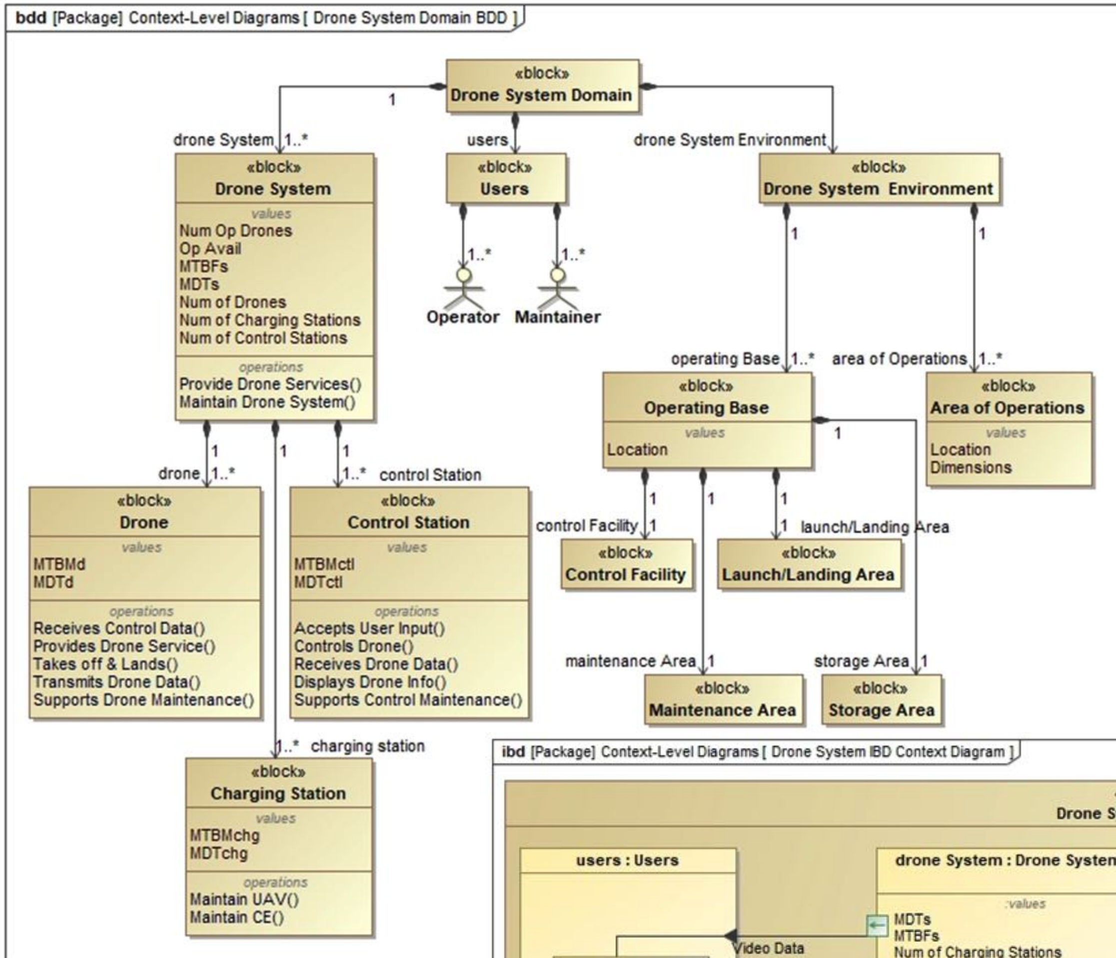
BACKGROUND


The
Institute for
Systems
Research
THE A. JAMES CLARK SCHOOL of ENGINEERING
UNIVERSITY OF MARYLAND

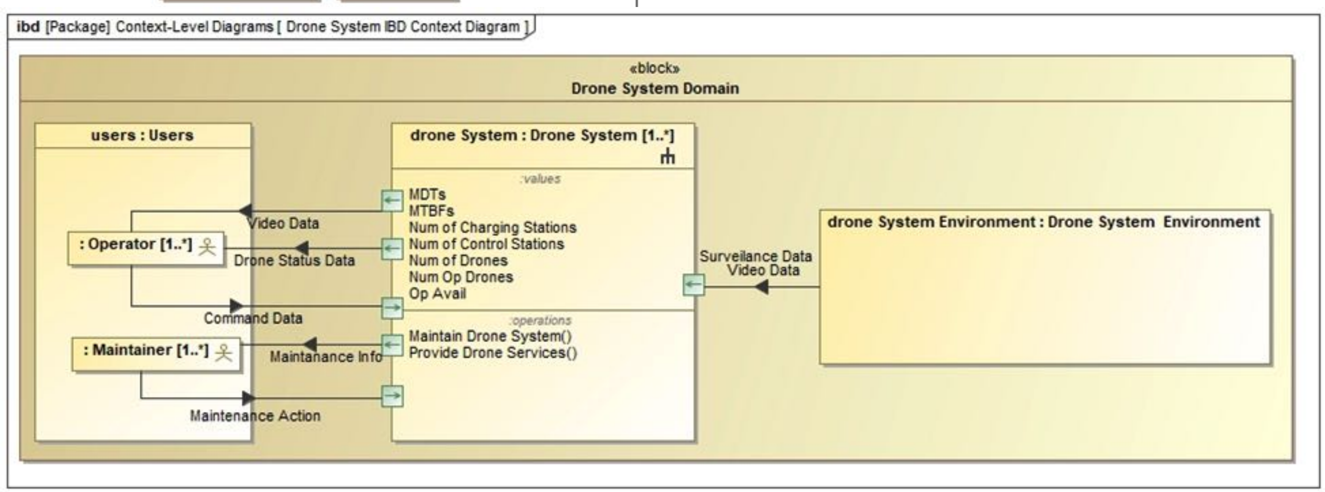
ACKNOWLEDGMENT

- I would like to thank **NoMagic** for the Academic License for Cameo Systems Modeler that enabled the development of the artifacts provided in my Drone System I (DSI) paper and in the next few slides.

DRONE SYSTEM ARCHITECTURE



- SysML BDDs and IBDs compactly provide:
  - System context
  - System structure
  - Key metrics and factors
  - Key functional requirements
  - System interfaces
- From Drone System I



DRONE SYSTEM OPERATIONAL CONCEPT (1)

- The Operational Concept may be succinctly captured in Use Case Narratives and Activity Diagrams (from DSI):

Use Case ID & Name: UC 1 – Provide drone services

Trigger: A drone is called into service.

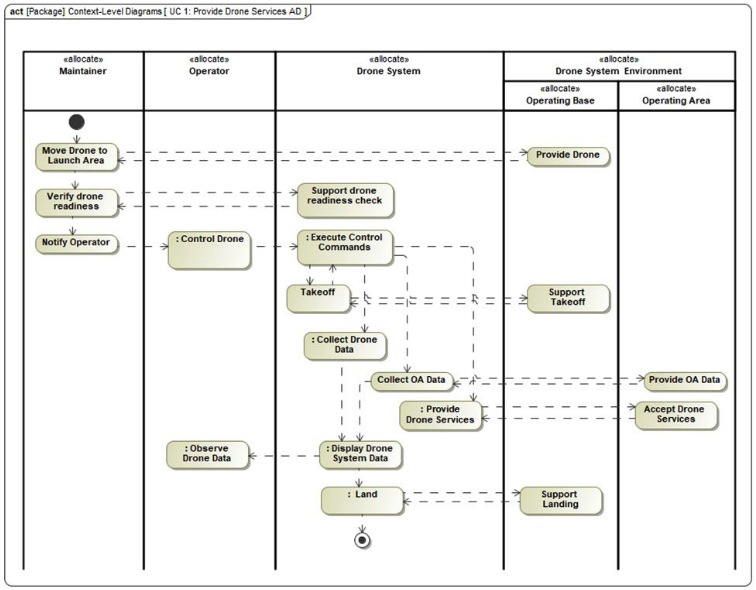
Main Success Scenario:

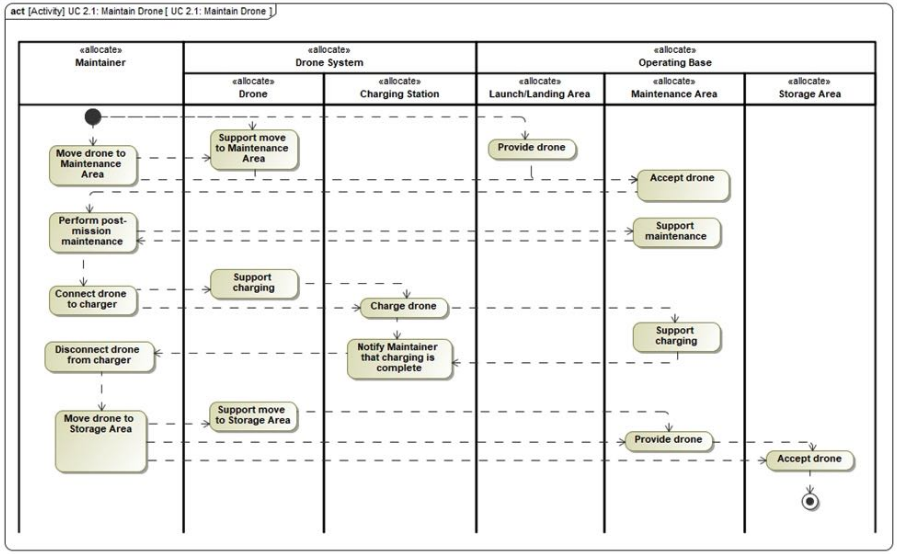
1. The drone maintainer moves the drone from the storage area to the launch area, verifies that it is flight ready, and notifies operator.
2. The drone operator controls the flight of the drone.
3. The drone executes its mission (deliver package or perform surveillance).
4. The drone operator returns the drone to the launch/landing area.
5. End

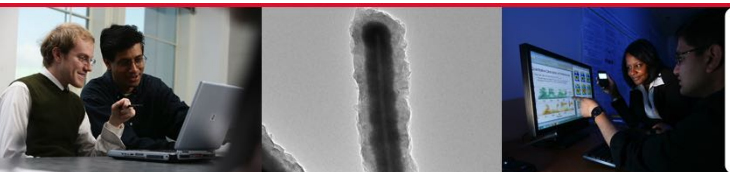
Use Case ID & Name: UC 2.1 – Maintain the Drone

Trigger: A drone has returned to base (landed).

1. The drone maintainer moves the drone to the maintenance area.
2. The drone maintainer performs any required maintenance on the drone.
3. The drone maintainer connects the drone to the recharging station.
4. The charging station recharges the drone.
5. The drone maintainer moves the drone the storage area.
6. End

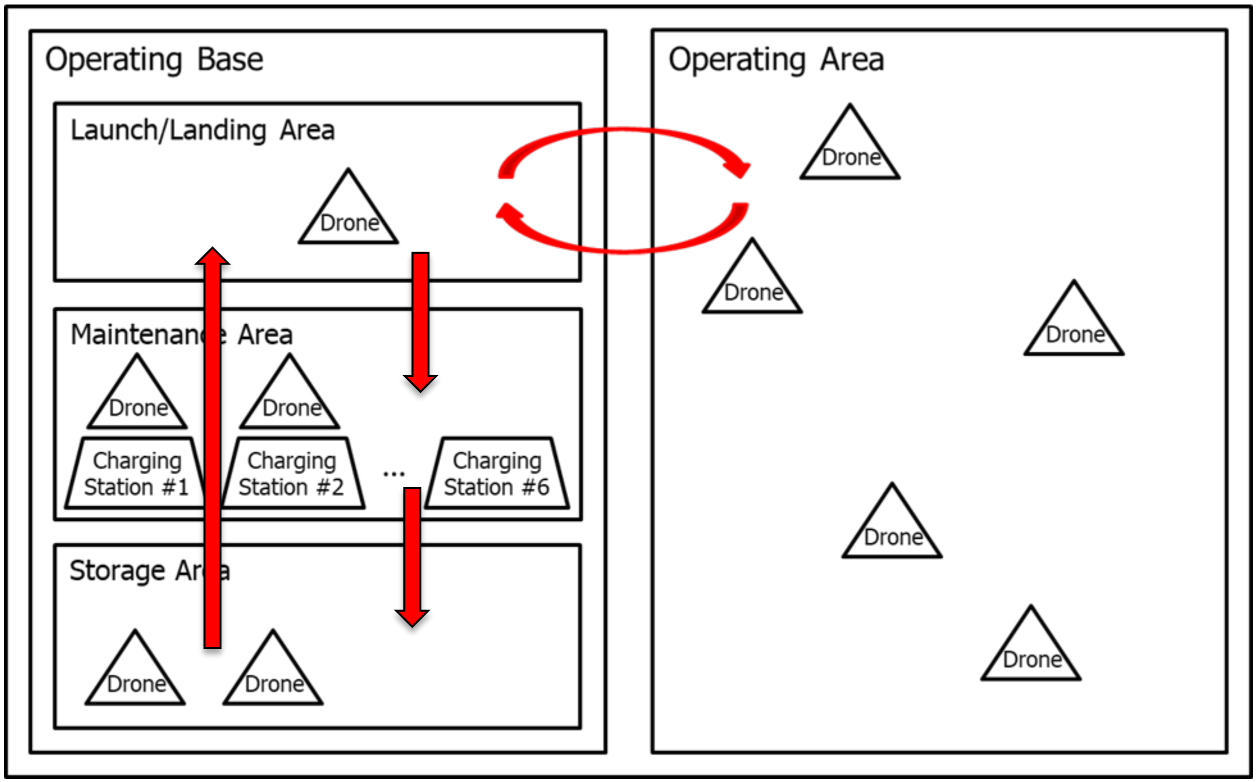






DRONE SYSTEM OPERATIONAL CONCEPT (1)

- And illustrated schematically as follows:



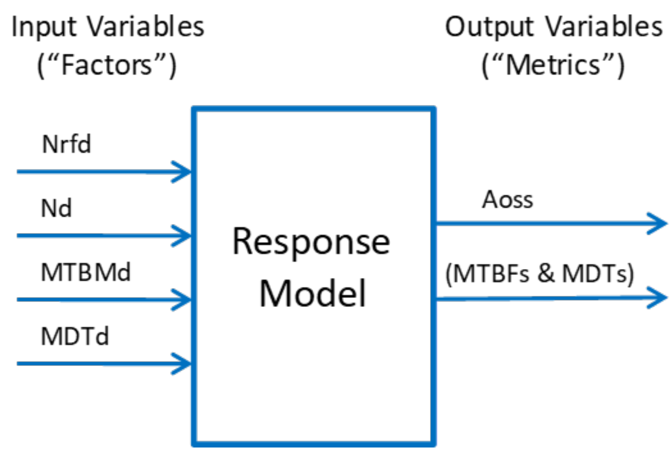
REFERENCE DESIGN

- Based on the requirements identified in the User Needs and Requirements section (which requires 5 drones flying at all times) and the system architecture provided on Slide 9, the following reference design is proposed:
  - Nd = 10 drones.
  - Nchg = 6 charging stations.
  - Nctl = 5 control stations.
  - Mean MTBMd = 90 min.
  - MDTd = 90 min.

DEFINITIONS & SIMPLIFYING ASSUMPTIONS

- **System Failure:** having fewer than Nrfd drones in the air
- **Metrics:**
  - **Ao:** System availability = MTBFs/(MTBFs+MDTs)
  - **MTBFs:** Mean time between system failure (fewer than Nrfd drones operating)
  - **MDTs:** Mean system down time
- **Design Parameters (Factors):**
  - **Nrfd:** Required number of simultaneously flying drones
    - Nrfd = 5 d for our system
  - **Nd** = number of drones in the system
    - Nd = 10 d for reference architecture
  - **Nchg:** Number of charging stations
  - **MTBMd:** Mean time between drone maintenance (aka the average flight time).
    - MTBMd = 90 min for reference case
    - Simplifying assumption: TBMd is exponential
    - This is analogous to a component "failure."
  - **MDTd:** Mean time to move drone to and from storage and to perform recharging/maintenance
    - MDTd = 90 min for reference case
    - Simplifying assumptions:
      - Recharging time dominates MDTd
      - DTd is exponential

- **Response Model Diagram:**



DETERMINISTIC MODEL

SIMPLE DETERMINISTIC MODEL/ANALYSIS

- Use a timeline analysis
- Example for MTBMd = 90 min, & MDTd = 90 min
  - For Nd = 5 d,
    - optimal solution is to run all five drones for 90 min, return and repair for 90 min
    - => Ao = 90 min/(90 min + 90 min) = 0.5
  - For Nd = 10,
    - optimal solution is to run five drones for 90 min, return and repair for 90 min; while these are down, run the other 5 drones
    - => Ao = 360 min/(360 min + 0 min) = 1.0
  - => Need **5 charging stations**.

Drone #	Time Slot											
	30	60	90	120	150	180	210	240	270	300	330	360
1	1	1	1	0	0	0	1	1	1	0	0	0
2	1	1	1	0	0	0	1	1	1	0	0	0
3	1	1	1	0	0	0	1	1	1	0	0	0
4	1	1	1	0	0	0	1	1	1	0	0	0
5	1	1	1	0	0	0	1	1	1	0	0	0
6	0	0	0	1	1	1	0	0	0	1	1	1
7	0	0	0	1	1	1	0	0	0	1	1	1
8	0	0	0	1	1	1	0	0	0	1	1	1
9	0	0	0	1	1	1	0	0	0	1	1	1
10	0	0	0	1	1	1	0	0	0	1	1	1
Drone Total	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**

ANALYTICAL STOCHASTIC MODEL

ANALYTICAL STOCHASTIC MODEL/ANALYSIS

- In our problem, Nrfd of Nd drones need to be operating; when one goes down, it needs to be recharged (and the number of charging stations is limited to Nchg).
- This problem is analogous to determining the **availability** (or mean time between system failure) of a “**k-out-of-N**” “**cold standby**” system with **Nr repair crews** (a classic RAM problem).
- A “Markov Chain” model yields the results provided on the following slide (Kuo & Zuo, 2003).

K-OUT-OF-N, COLD STANDBY, NR REPAIR CREWS AVAILABILITY MODEL

- **Availability:**

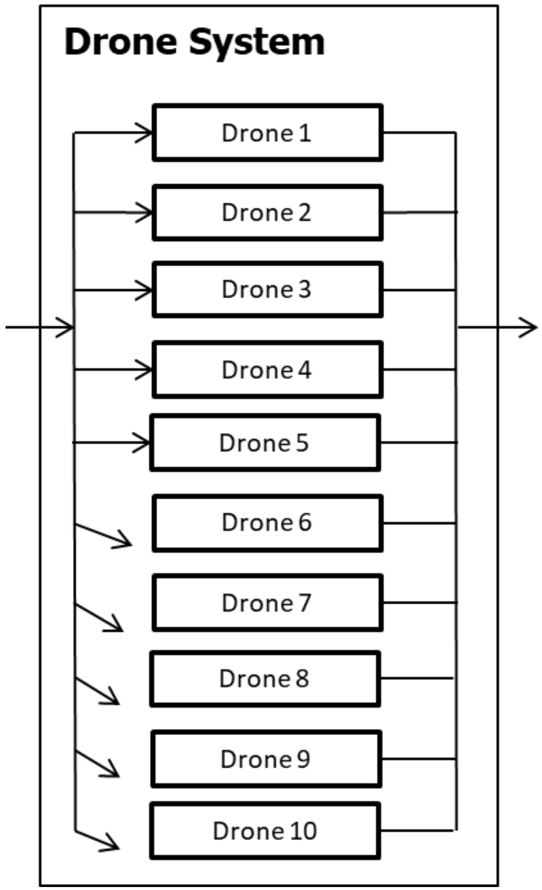
$$Aoss = \frac{UpTime}{UpTime + DownTime} = \frac{Operational\ Time}{Operational\ Time + DownTime} = \frac{MTBFs}{MTBFs\ + MDTs}$$

- **Mean Time Between System Failure:**

$$MTBFs(k\ of\ N; CS; Nrc\ RCs) = \frac{1}{\mathrm{k}\,\lambda} \sum_{i=0}^{N-k} \frac{k!\ (N-k)!}{\mathrm{i}!\ (N-i)!}\ (r)^{N-k-i}$$

- **Mean System Down Time:**

$$MDTs(k\ of\ N; CS; Nrc\ RCs) = \frac{\mathrm{MDTd}}{\mathrm{N - k + 1}}$$



EXCEL INSTANTIATION

- The model was implemented as follows in Excel (example for reference design):

Inputs (Factors)	
k =	5
N =	10
MTBMd =	90
MDTd =	90
MTBMd/k =	18
r = MTBMd/MDTd =	1
k! =	120
(N-k)! =	120

Calculations			
i	i!	(N-i)!	Σ Term
0	1	3628800	3.968E-03
1	1	362880	3.968E-02
2	2	40320	1.786E-01
3	6	5040	4.762E-01
4	24	720	8.333E-01
5	120	120	1.000E+00
		Sum =	2.53

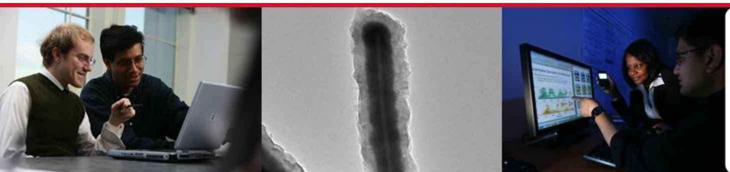
Outputs (Metrics)	
MTBFs =	45.6
MDTs =	15.0
Aoss =	0.752

- Legend:
  - Green = factor value (input)
  - Yellow = intermediate calculation
  - Blue = metric value (output)

- Note that the model permits one to change:
  - Number of drones
  - Number of repair crews (chargers)
  - Drone flight fime (or MTBMd)
  - Drone maintenance (recharge) time.
- The stochastic model for the reference design results in:
  - Aosssm = 0.75
  - vs. Aossdm = 1.0

  for the deterministic model.

TRADE-OFF ANALYSIS



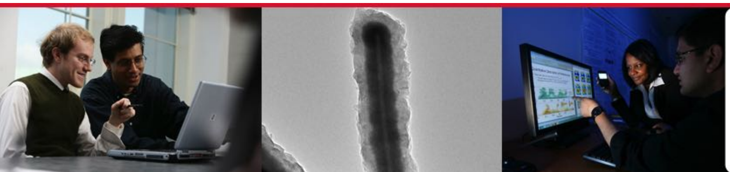
TRADE-OFF ANALYSIS DESIGN OPTIONS

- Trade-off Analysis Scope:
  - Full trade space: Vary Nd, Nch, MTBMd, MDTd (& over larger range of values)
  - **Illustrative trade space:** Vary **Nd** & **MDTd** (for brevity)
    - Assume reference values of Nch = 5, MTBMd = 90 min
- Results:
  - Design Options that meet the requirement:
    - DO3: **Nd = 15, MDTd = 90**
    - DO5: **Nd = 12, MDTd = 60**
  - **Different from deterministic solution** (Nd=10, MDTd =90)

Trade Space

Design Option	Nd	MDTd (min)	MTBFs	MDTs	Aoss
1	10	90	45.6	15	0.752
2	12	90	75	11.3	0.87
3	15	90	184.8	8.2	0.958
4	10	60	74.8	10	0.882
5	12	60	168.2	7.5	0.957
6	15	60	728.3	5.5	0.993

CONCLUSIONS AND NEXT STEPS



CONCLUSIONS

- Deterministic models generally provide misleading (optimistic) results.
- The analytical stochastic model indicates that there are two (lower cost) options that meet the Aoss requirement:
  - Nd = 15, MDTd = 90 min
  - Nd = 12, MDTd = 60 min

- Study shortfalls:
  - Unrealistic distributions are used for down times and drone flight times.
  - Trade-space analysis is incomplete.
  - Without a system cost model, one cannot determine which design option is actually “lowest cost.”
  - The trade-off between cost and Aoss has not been addressed.

- Study provides simple instructional example of:
  - How to tie trade-off analysis to architecture and requirements
  - How to structure and approach the initial stages of a trade-off analysis (and the use of simplifying assumptions)
  - Some shortfalls of incomplete analysis

NEXT STEPS

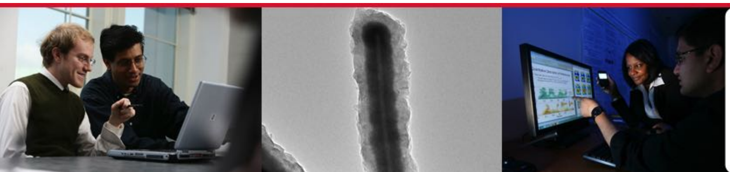
- Develop an executable analytical stochastic model within SysML.
- Perform a “full-scale” cost-effectiveness trade-off analysis using a Multi-Attribute (objective) Value Function (MAVF) Model.
  - Perform an Aoss trade-off analysis over entire design space (Nd, Nch, MTBMd, MDTd).
  - Develop a cost model.
  - Develop MAVF model using Aoss and Cost as the “metrics.”
- Develop Monte Carlo (MC) simulation that permits more realistic distributions for MTBMd and MDTd.
  - Determine impact of more realistic distributions on the Aoss results.
- Perform sensitivity study on “optimal solution.”
- Discuss these refinements within the context of a “Spiral Approach” to systems analysis, modeling, and simulation process(es).

- I intend to address these steps in my next one or two papers next year (assuming an interest in the topic).

BACKUP SLIDES

SIMPLIFYING ASSUMPTIONS

- The principal system performance requirement is “Nrfd drones shall be flying at all times” (in our case, 5 drones). (Nrfd is the required number of flying drones.)
- A “System Failure” is defined as having fewer than Nrfd drones flying.
- The “Mean System Down Time” (MDTs) is defined as the mean time that it takes the system to return to Nrfd flying drones.
- The system (and its users) will operate 24/7.
- The (steady state) operational availability of the system (Aoss) is defined as the probability that Nrfd drones are flying (at any given moment).
- The mean time between failure (MTBF) for the drone, charging station, and control station elements are significantly greater than the mission duration and as such may be ignored.
- For availability modeling purposes, a drone completing its required time on station will be considered an “effective critical failure” (for that drone) since it will require an immediate maintenance action (post-flight preventative maintenance and charging). As such, the principal “reliability” metric of interest is the mean time between maintenance for the drone (MTBMd).
- The mean down time for a drone (MDTd) is the sum of the times associated with moving the drone to and from the launch area and performing pre-flight checkout and drone maintenance.



NEEDS AND REQUIREMENTS

- From DSI:
  - Customer/User Statement of Need (SON): “A drone system is needed that is capable of providing reliable and timely drone delivery or surveillance capability to a given area.”
  - Mission profile/assumptions (implicit **user requirements**):
    - The expected demand will be five missions per hour (and must be met).
    - Each mission will require a devoted drone.
    - The area of operations will have a radius of 10 mi.
    - The operating base will be in the center of the area of operations.
    - Delivery packages will weigh up to 5 lbs.
    - Drones will be maintained and refueled/recharged after each flight.
  - Derived **system requirements**:
    - A drone shall have a fully loaded time of flight of at least one hour.
    - The drone shall be capable of performing surveillance missions.
    - The drone shall be capable of performing package delivery missions.
    - The drone shall be capable of carrying packages of up to 5 lbs.
    - The drone system shall have an operational availability of Ao = 0.95.

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