Masterclasses
Session 3: System Modelling

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1st DISCOVERER Master classes

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Overview

- Systems

- Models

- System Modelling Example

- VLEO System Design

Simple (!) Space System Design
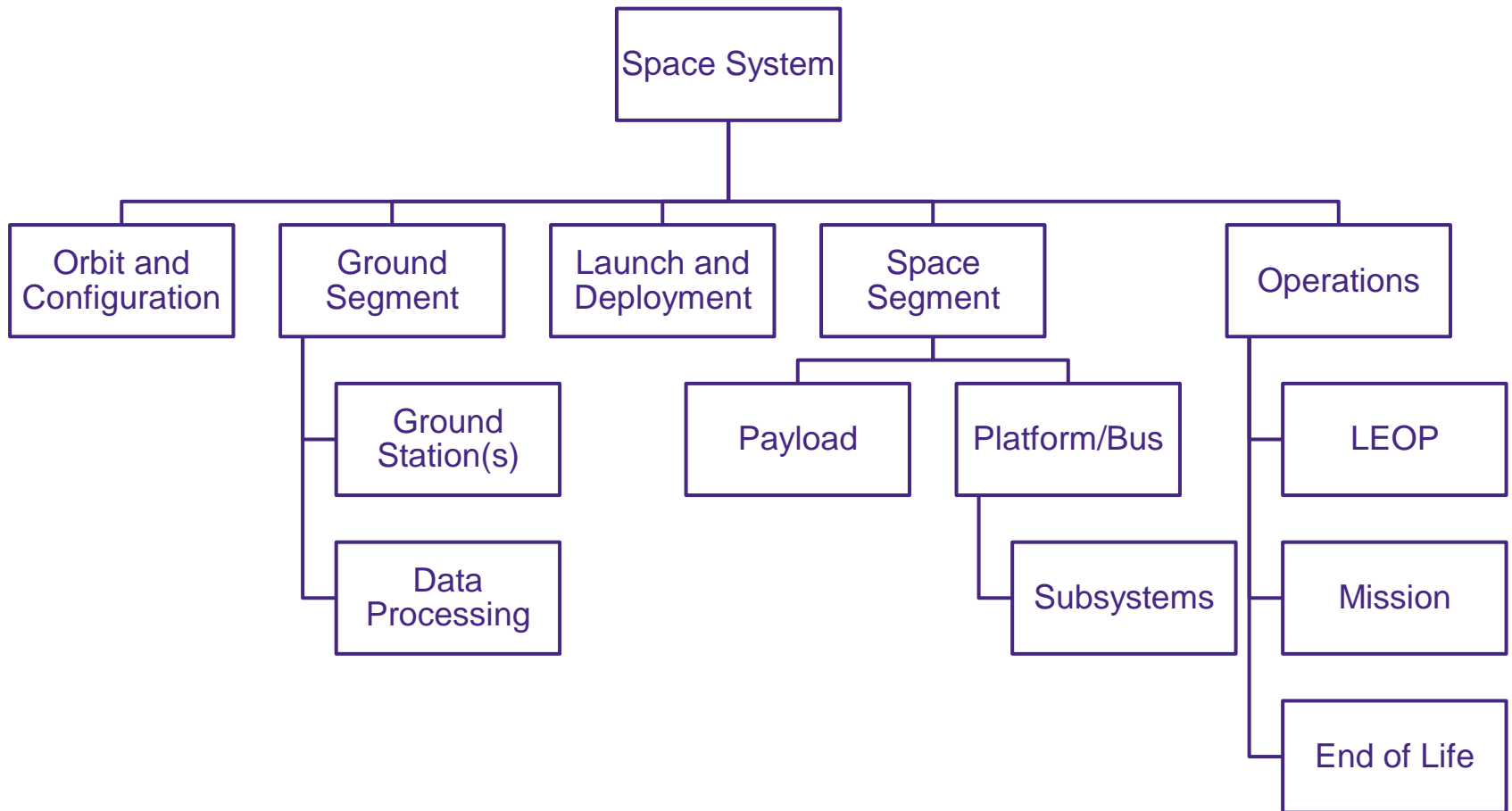
# Complex System Design
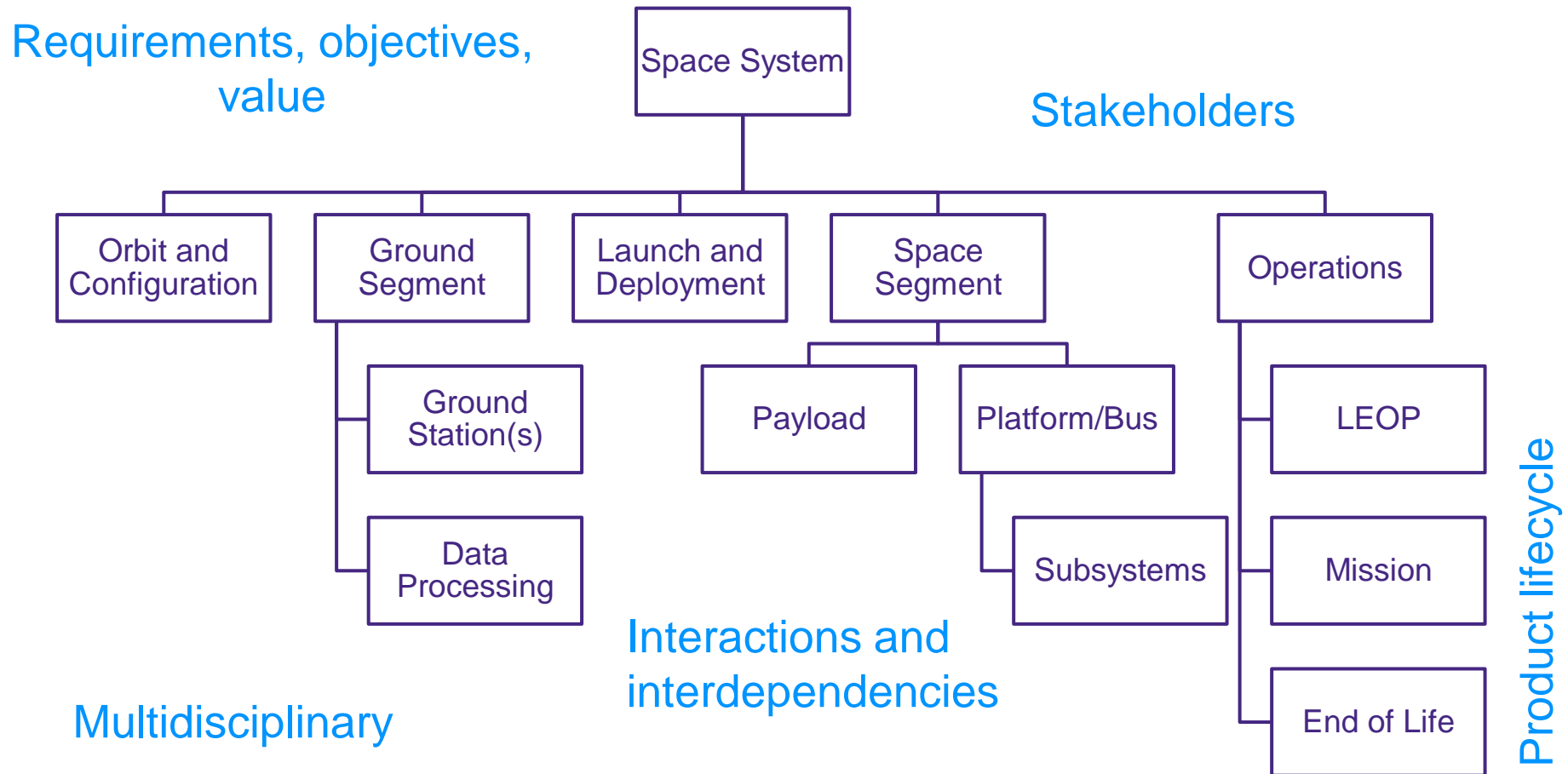
What is a System?

- *"a construct or collection of different elements that together produce results not obtainable by the elements alone."*

    – NASA Systems Engineering Handbook (NASA/SP-2007-6105)

- *"Generally, I do not like calling things 'systems,' as everything is a system, including your dog."*

    – Elon Musk, IAC 2017

- We can represent systems as a network of interconnected subsystems, components, or models

System Network Diagram (DSM/N2/N²)

Nodes indicate model interface inputs and outputs
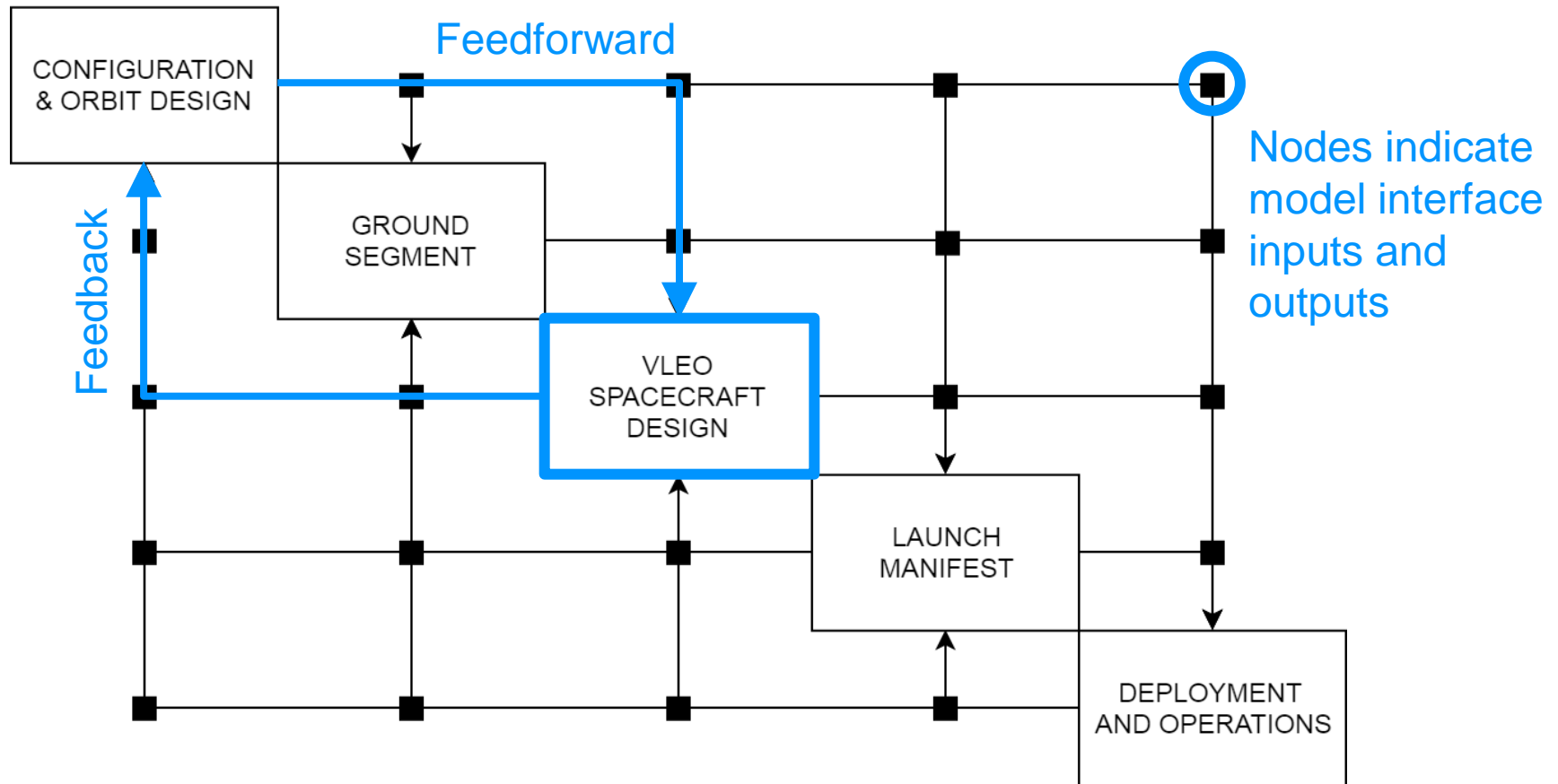
Subsystem Dependencies and Interactions

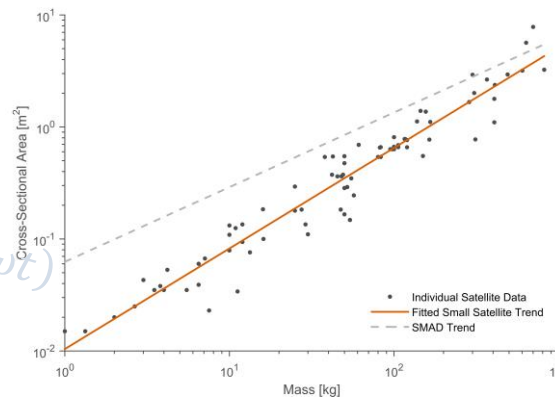|	Payload	TT&C	Power	Comms	Structure	ADCS	Propulsion	Thermal	OBDH
Payload	•		X			X			X
TT&C	X	•				X			X
Power	X	X	•			X		X	X
Comms	X			•		X			X
Structure	X	X	X	X	•		X	X	
ADCS	X	X	X		X	•	X		
Propulsion	X		X		X		•		
Thermal	X	X	X		X	X	X	•	
OBDH	X	X	X	X					•

Dependency

Interaction

What is a Model?

- A simplified version or abstraction of an object or system of interest

- Graphical, mathematical, physical, or other logical representation

- Built from fundamental elements or relationships

$$x(t) = x_0(t)\cos(\omega t) + v_0$$

$$v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right)$$

$$F = ma \qquad E = mc^2 \qquad \frac{dS}{dt} \geq 0 \qquad \sin(\omega t)$$

Combustion efficiency	0.9
Ru	8314
Atmospheric Pressure (Pa)	1.01E+05
Thrust (N)	200
Chamber Pressure (Pa)	5.00E+06
O/F	1
gamma	1.274
Tc (K)	1322
MW	18.79
Cf	1.5226
C*	1095.164774
Tc actual	1189.8
At (m^2)	2.63E-05
Dt (m)	0.0058
mdot sys	0.1138
mdot fuel	0.0569
mdot oxidiser	0.0569
Pc check	4743416.49
Thrust check	189.7366596
C* check	1154.405033
Ct check	1.52E+00

System Design Methodology

Traditional
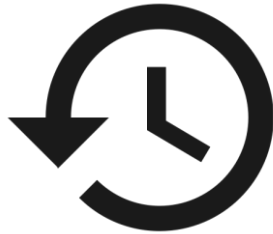
Document-centric

- Text, diagrams, etc

- Discrete and disjointed documents

- Snapshot

- Design loops

Contemporary

Model-based

- Integrated system model

- Single point of truth
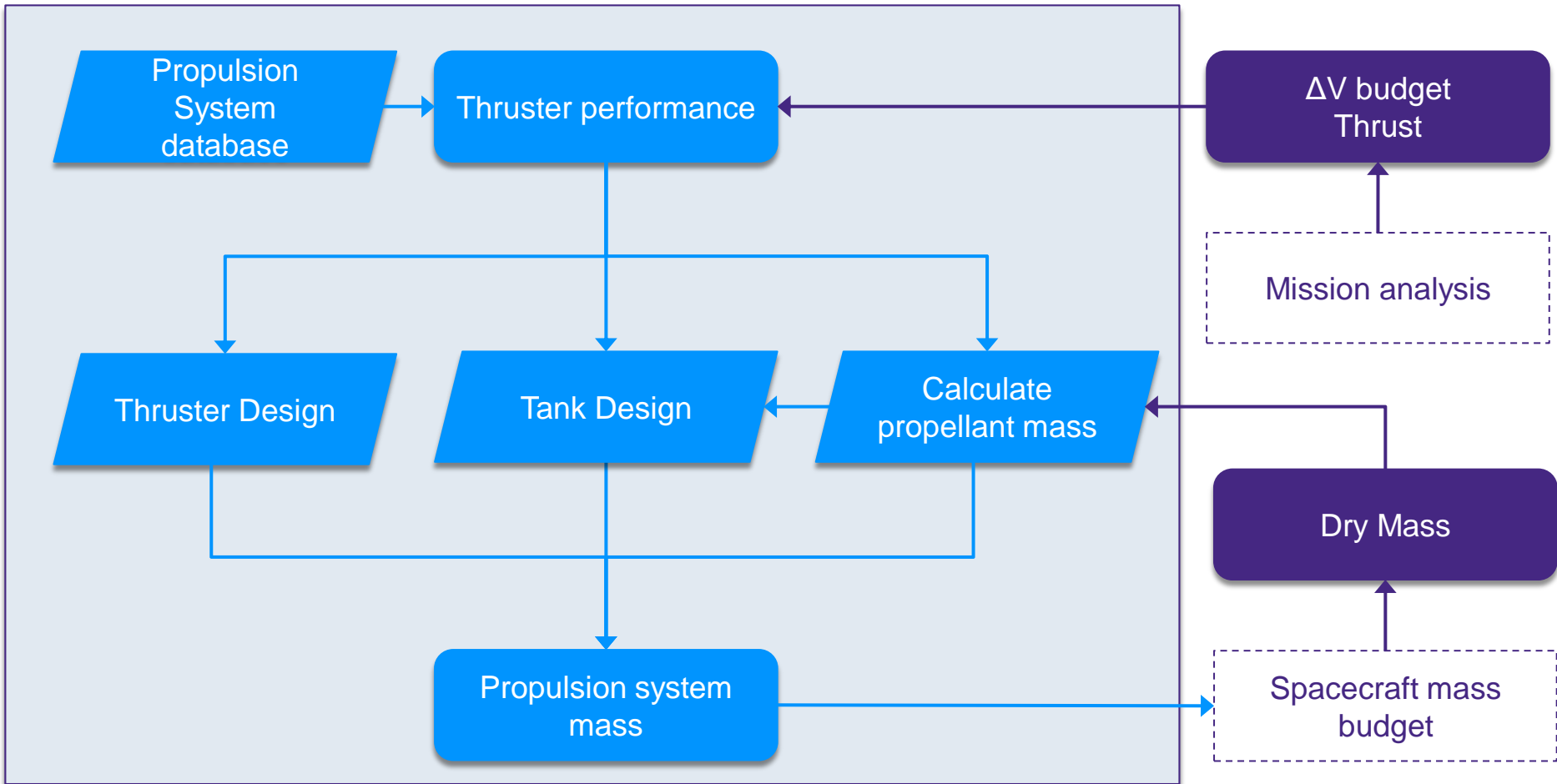
- "Real-time" dynamic updates

- Optimisation

A Simple System Modelling Example
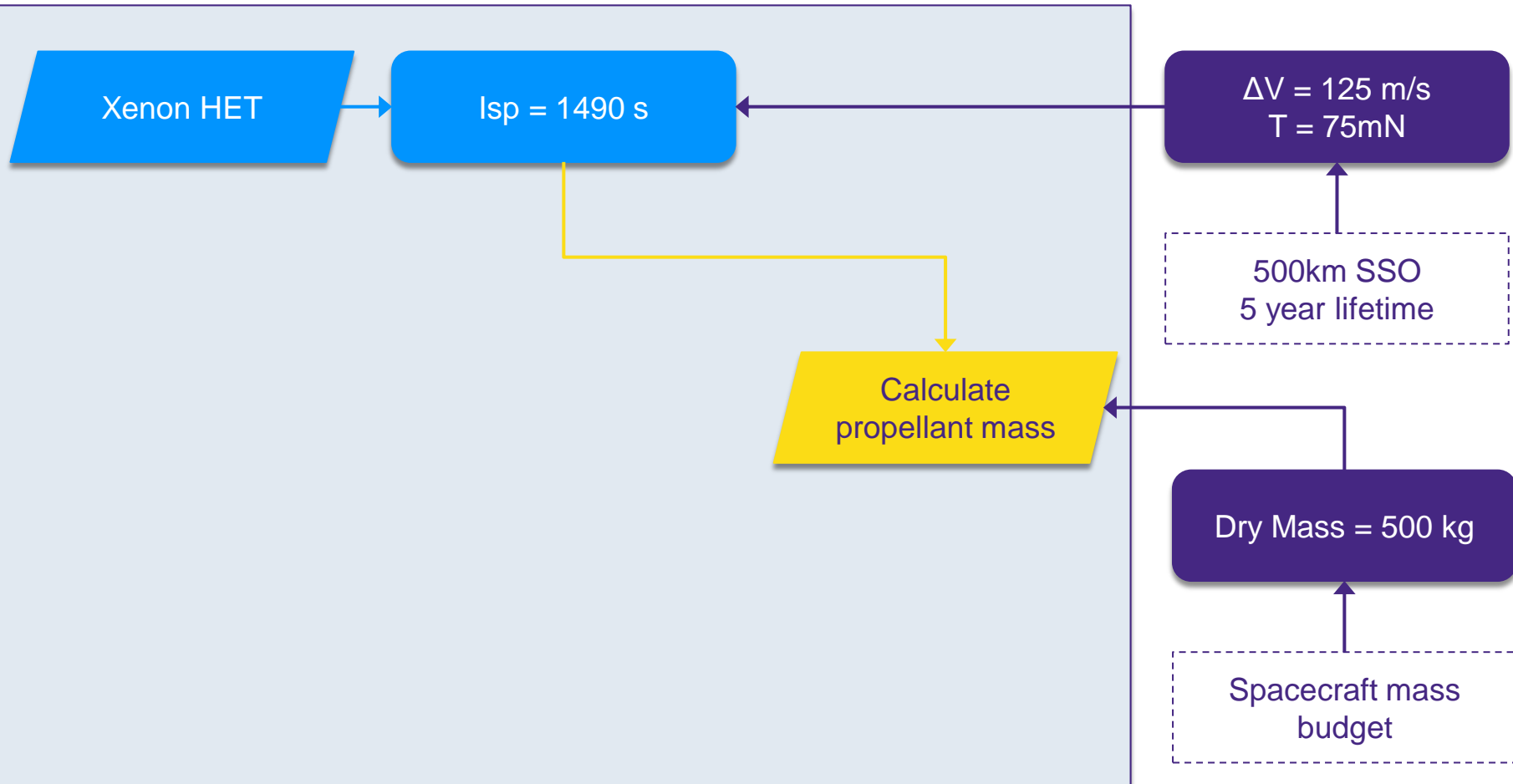
Propulsion Subsystem Mass

Subsystem Model
Propulsion System Model

Subsystem Model
Propulsion System Model

Subsystem Model
Propellant Mass

- Using the Ideal rocket equation

$$\Delta V = I_{sp} g_0 \log \frac{m_0}{m_1}$$

Wet (initial) mass

Dry (final) mass

- Where: $m_0 = m_1 + m_p$

- Expression for required propellant mass
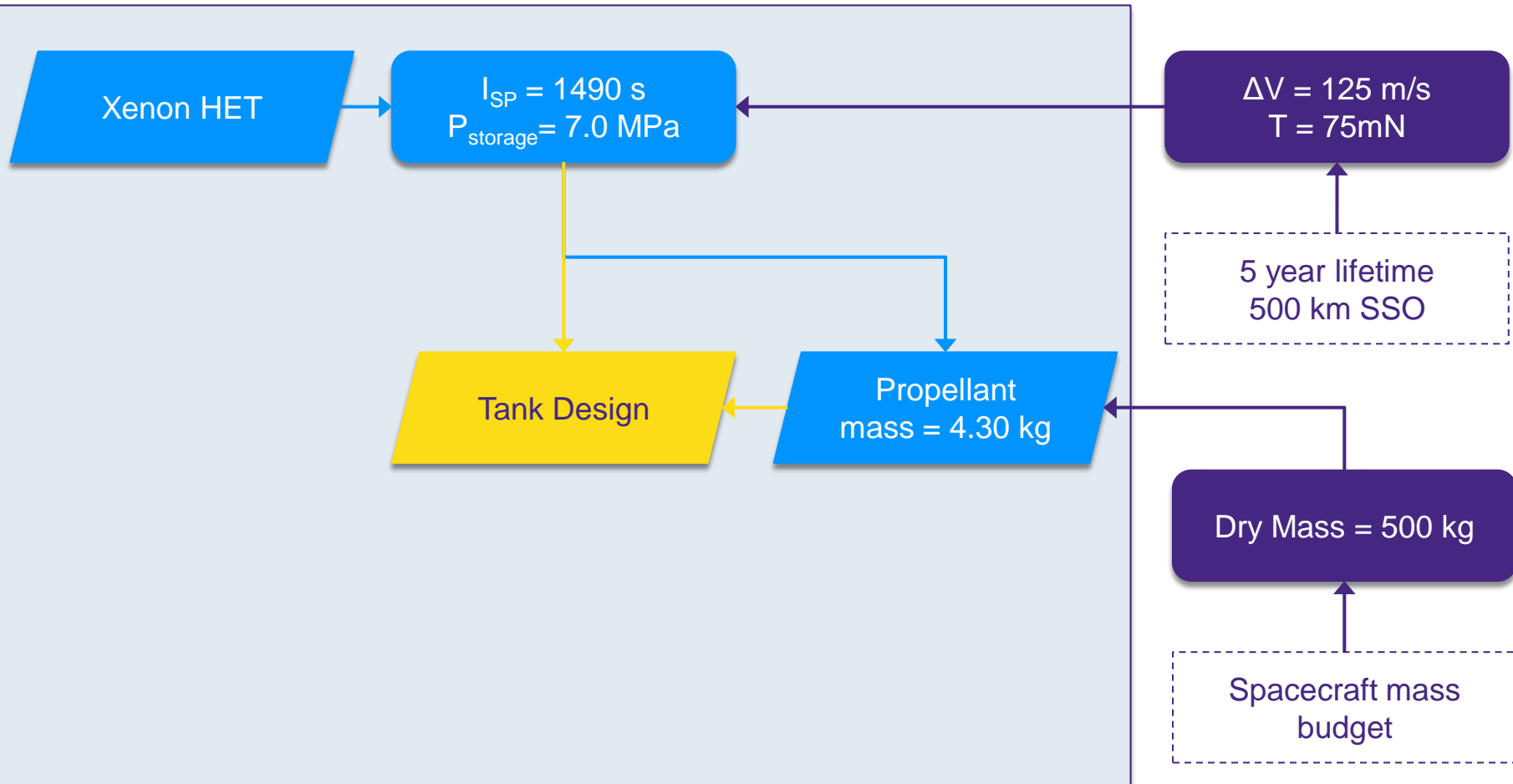
$$m_p = m_1 (e^{\Delta V / I_{sp} g_0} - 1)$$

$$m_p = 500 (e^{125/1490*9.81} - 1)$$

$$m_p = 4.30 \text{ kg}$$

Subsystem Model
Propulsion System Model

Xenon HET

I_{SP} = 1490 s
$P_{storage}$ = 7.0 MPa

ΔV = 125 m/s
T = 75mN

5 year lifetime
500 km SSO

Tank Design

Propellant
mass = 4.30 kg

Dry Mass = 500 kg

Spacecraft mass budget

Subsystem Model
Empty Tank Mass

- V_{tank} varies based on propellant type (gaseous, liquid, self-pressurising)

- Tank volume for Xe propellant in blowdown can be calculated using ideal gas equation

$$V_{tank} = \frac{m_p R T}{P_{max} M_p}$$

Propellant molar mass
Xe = 131.3 g mol^{-1}

$$V_{tank} = \frac{4.3 * 8.31 * 293.15}{7 \times 10^6 * 131.3 \times 10^{-3}} = 0.0114 \text{ m}^3$$

Subsystem Model
Empty Tank Mass

- Assuming spherical tank mass (for simplicity)
- Find wall thickness t_{wall} required to contain the volume of propellant at maximum pressure

$$r_{tank} = \sqrt[3]{\frac{V_{tank}}{\frac{4}{3}\pi}} = 0.14\text{m}$$

Factor of safety (eg 3)

$$t_{wall} = FoS \cdot \frac{P_{max}r_{tank}}{2\sigma_{yield}} = 1.19 \text{ mm}$$

Material properties eg Titanium:

σ_{yield} = 1230MPa
ρ = 4460 kg m^{-3}

$$m_{tank} = \frac{4}{3}\pi\left[(r_{tank} + t_{wall})^3 - r_{tank}^3\right]\rho_{tank}$$

$$m_{tank} = \frac{4}{3}\pi\left[(0.14 + 1.19 \times 10^{-3})^3 - 0.14^3\right] * 4460 = 1.32 \text{ kg}$$

Subsystem Model
Propulsion System Model

Xenon HET

I_{SP} = 1490 s
$P_{storage}$= 7.0 MPa

ΔV = 125 m/s
T = 75mN

5 year lifetime
500 km SSO

Thruster Design

Tank
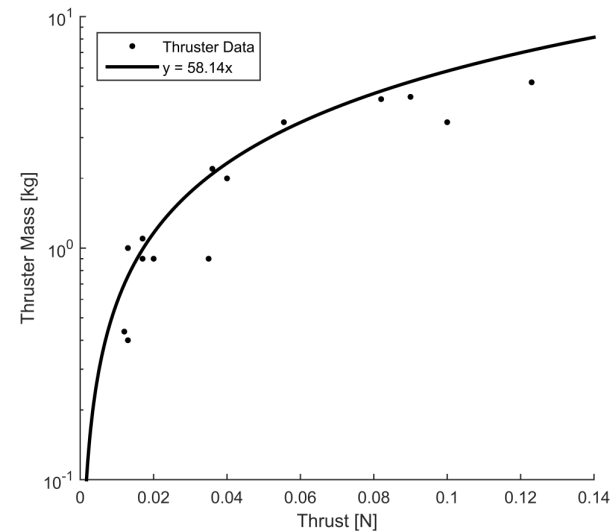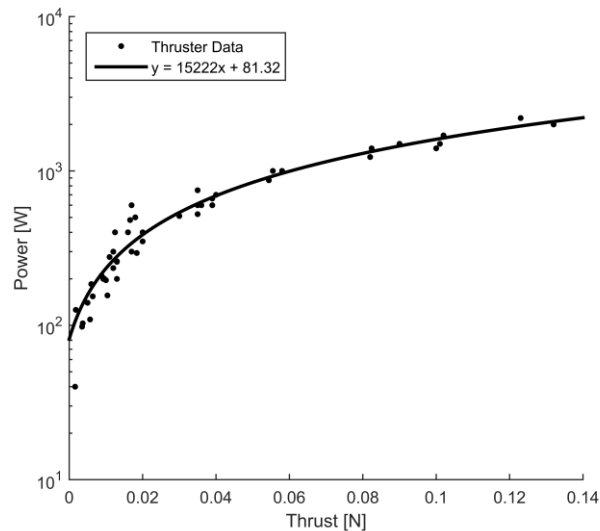mass = 1.32 kg

Propellant
mass = 4.30 kg

Dry Mass = 500 kg

Spacecraft mass budget
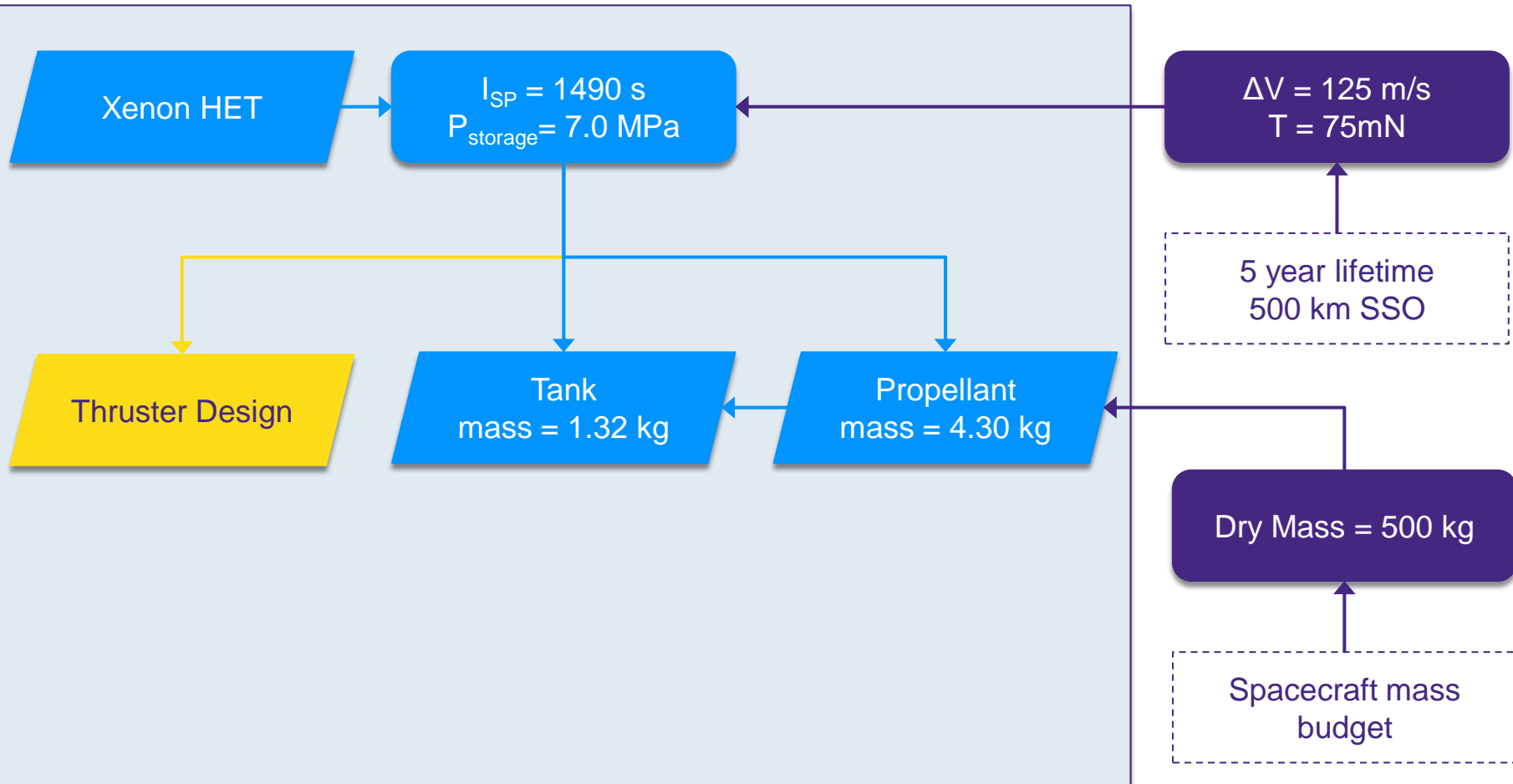
Subsystem Model
Thruster Design

- Absence of known thruster model

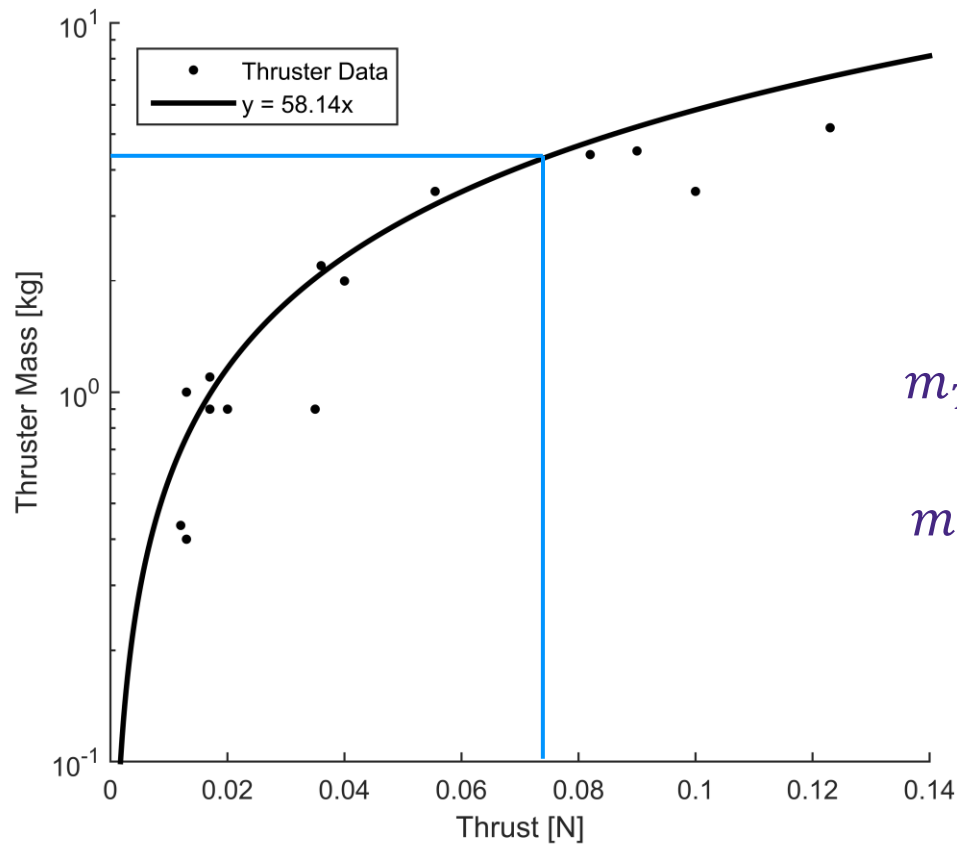- Identify relationships between thrust, mass, power, ISP, pressure etc

From published and publically available data on Hall Effect Thrusters (<2.5kW)

Subsystem Model
Thruster Design

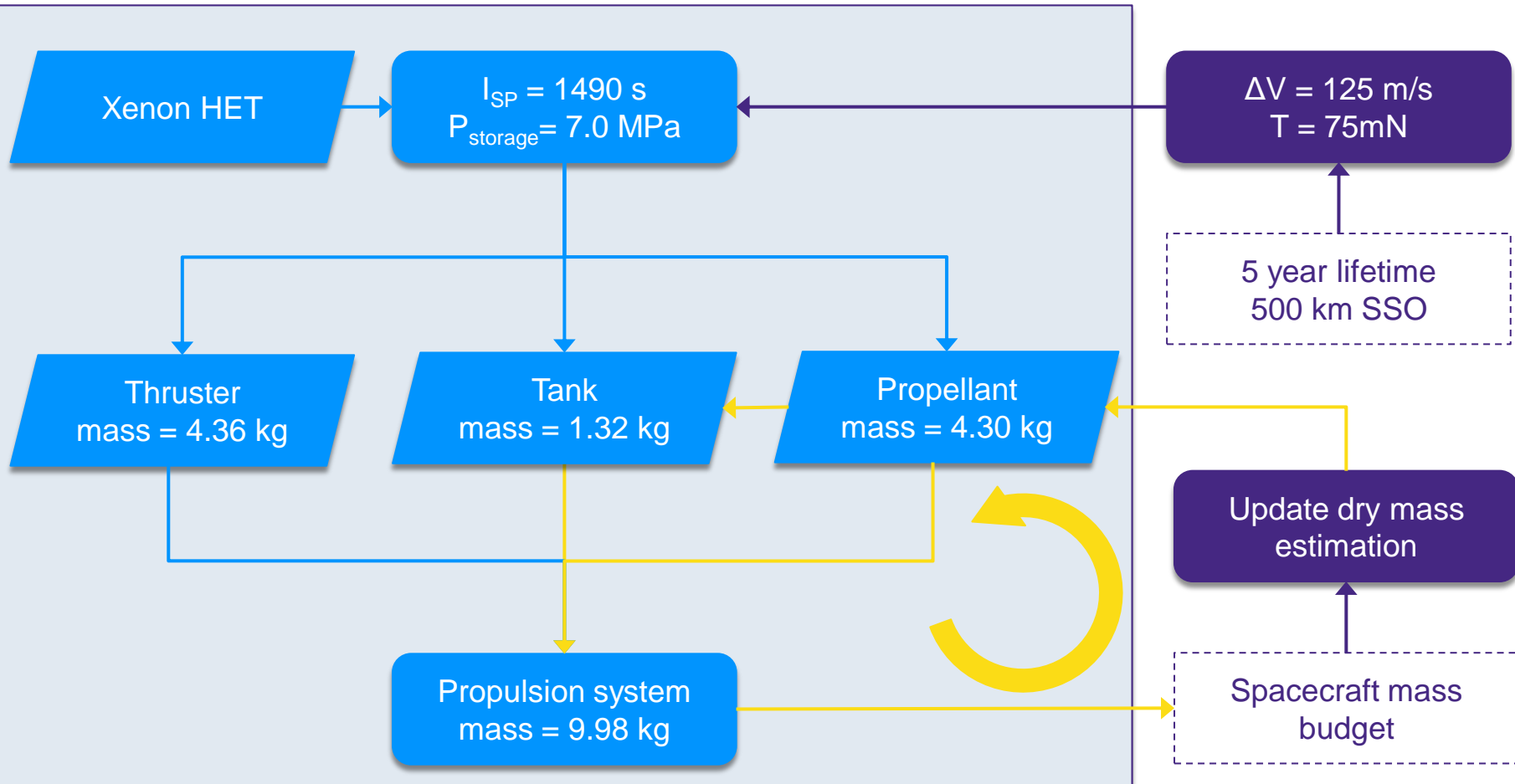$$m_T = 58.14\,T$$

$$m_T = 58.14 * 0.075 = 4.36 \text{ kg}$$

Subsystem Model
Propulsion System Model
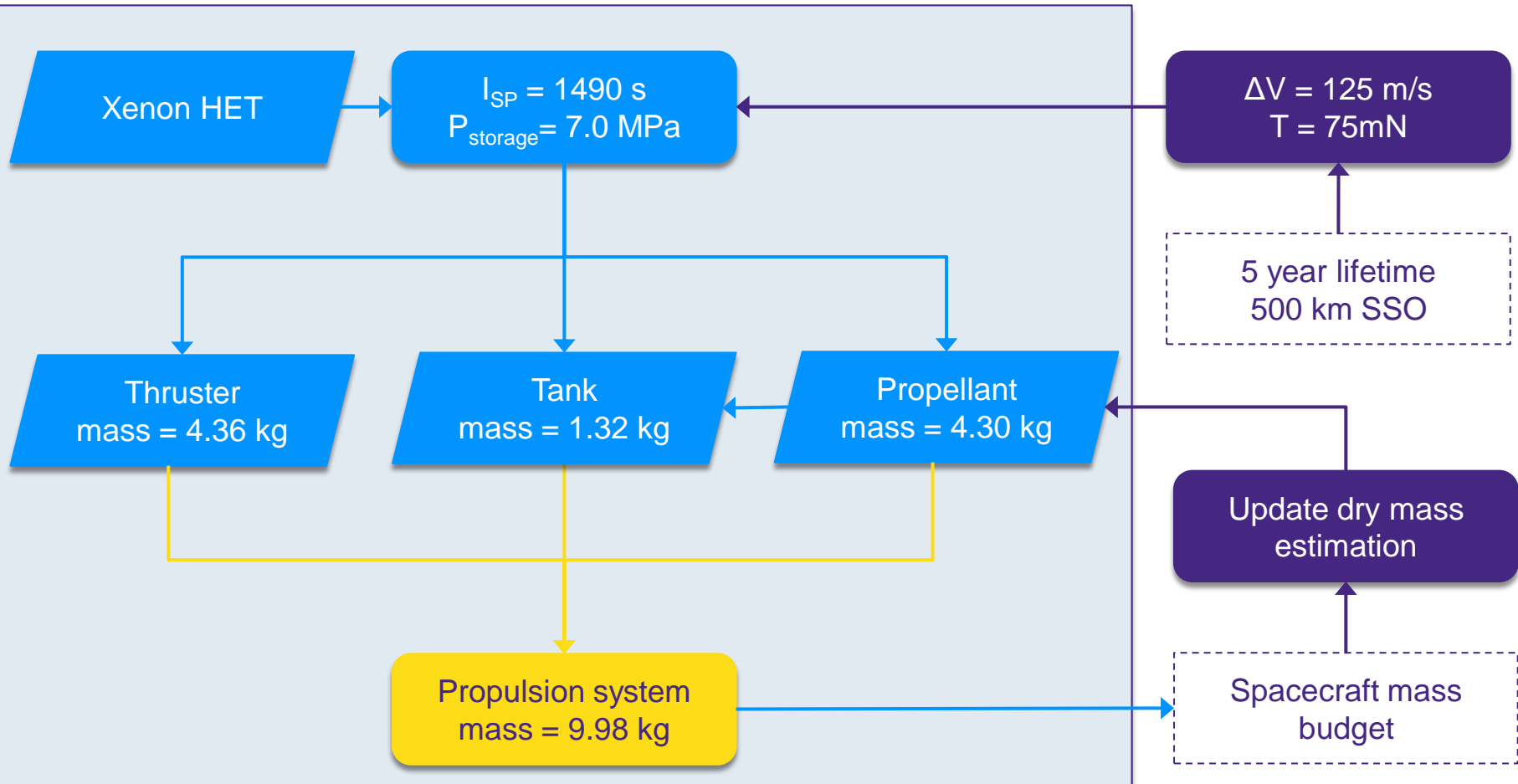
Subsystem Model
Propulsion System Model

Margins

- Mass

    - 20% system level mass margin on "nominal dry mass" including:

    - ≥ 5% for "Off-The-Shelf" items

    - ≥ 10% for "Off-The-Shelf" item requiring minor modifications

    - ≥ 20% for new designed/developed items or items requiring major modifications or re-design

- 2% propellant residual

- Delta-V

    - 5% for detailed analysis of manoeuvres

    - 100% for analytical or general analysis of manoeuvres

    - 100% for attitude control and angular momentum management

"Tailored ECSS Engineering Standards for In-Orbit Demonstration CubeSat Projects" 2016
"Margin Philosophy for Science Assessment Studies" 2012
ESA/ESTEC

VLEO System Design
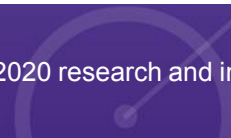
VLEO System Design

VLEO System Design

Traditional Design
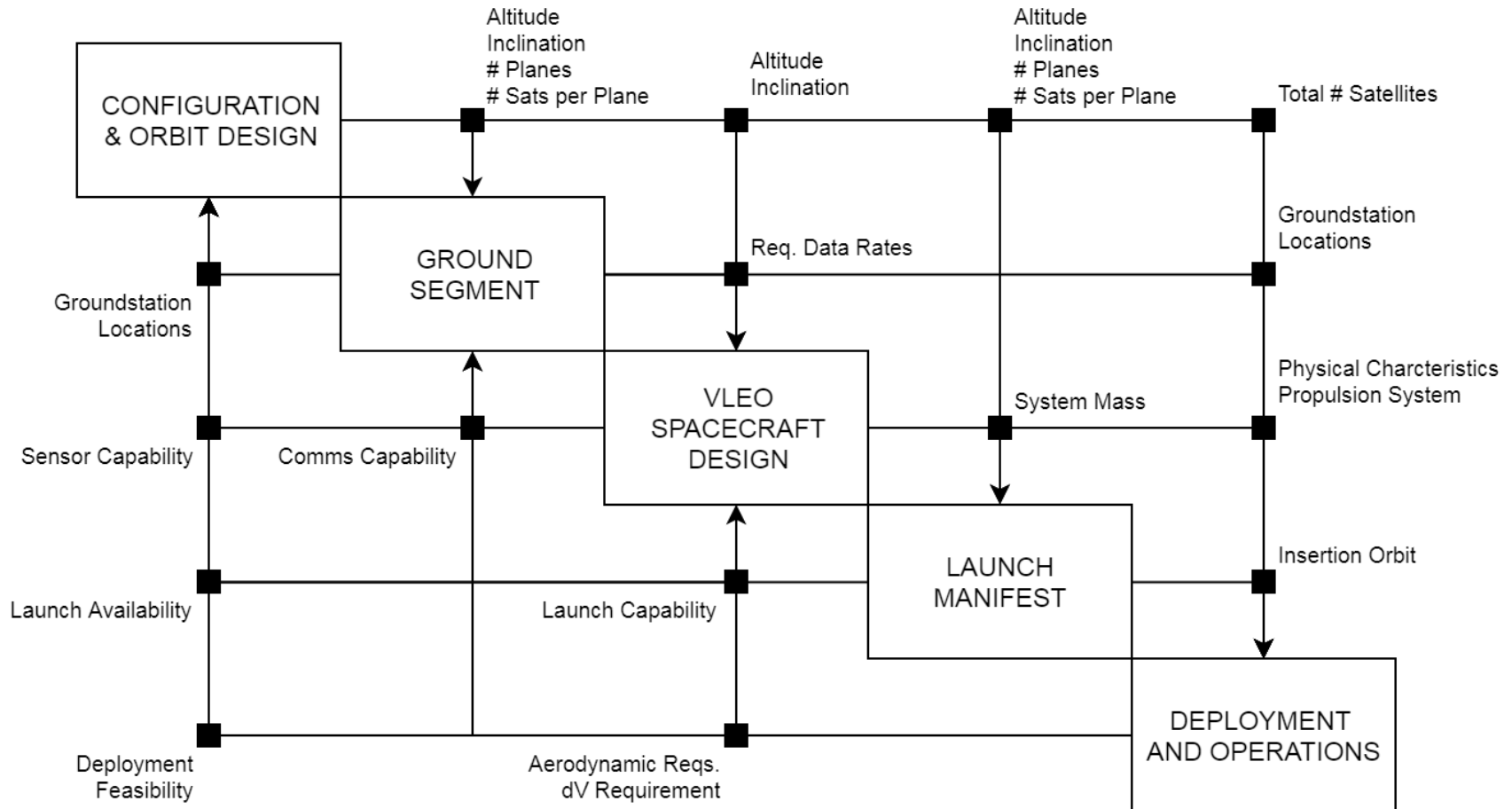
Objectives:
1. Lower Cost
2. Lower Mass
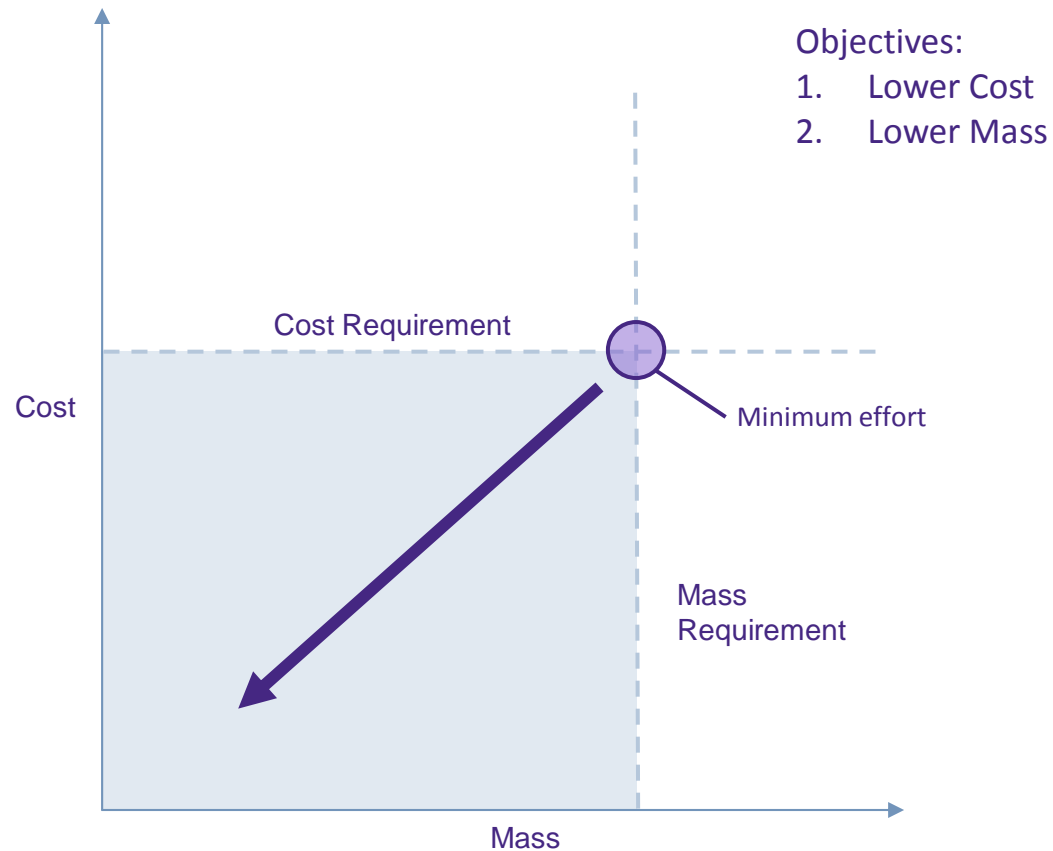
Good Potential Designs

Objectives:
1. Lower Cost
2. Lower Mass

Cost

Mass

Pareto Front: "best designs"

(Can't improve one objective without reducing another)
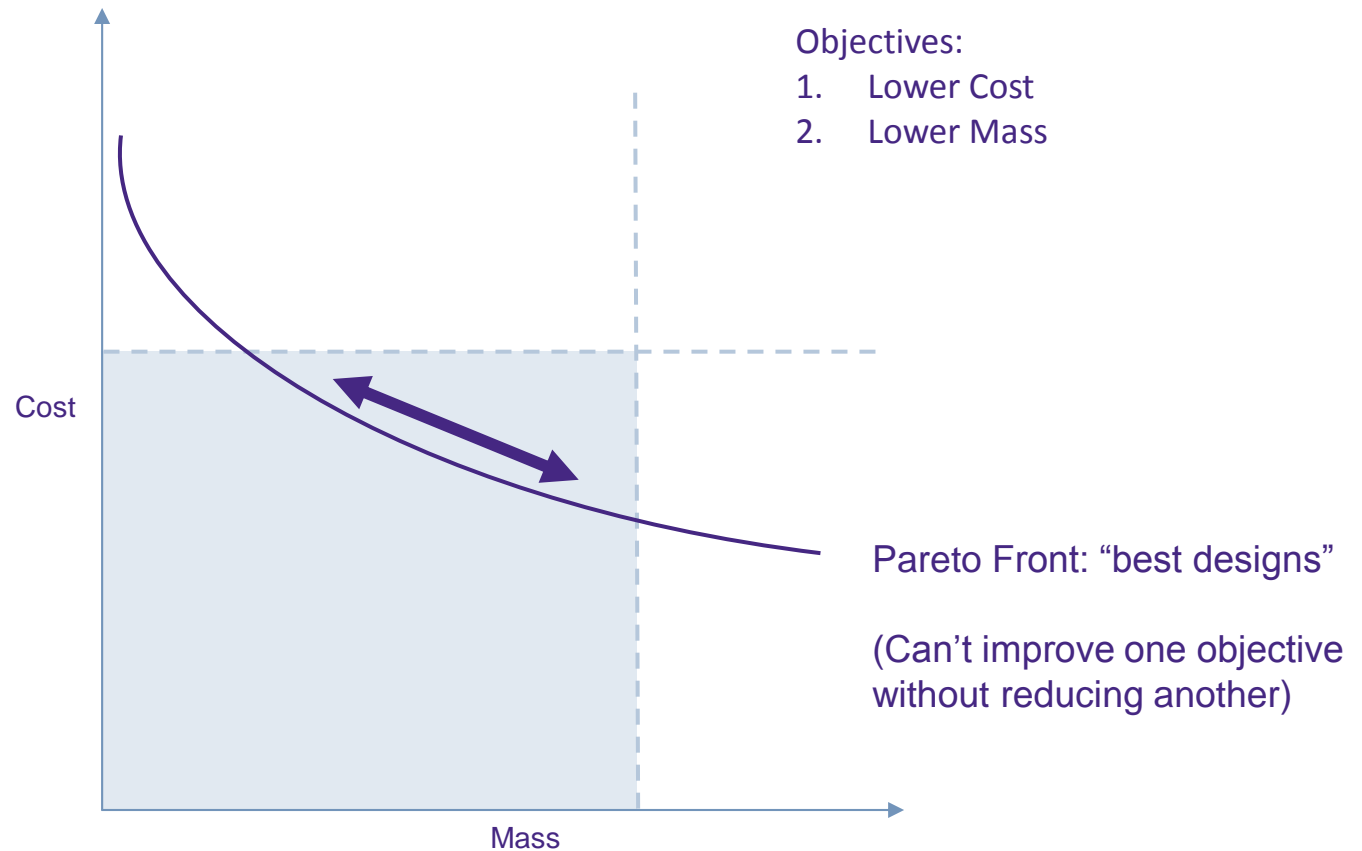
How do you tradeoff multiple objectives?

Introducing Value

Value defined using economics

Translating engineering parameters and market needs to a single metric

$ Value

Cost

Mass

Satisfying Design
(Requirements
Non-negotiable)

Best Design
(Requirements
Negotiable)
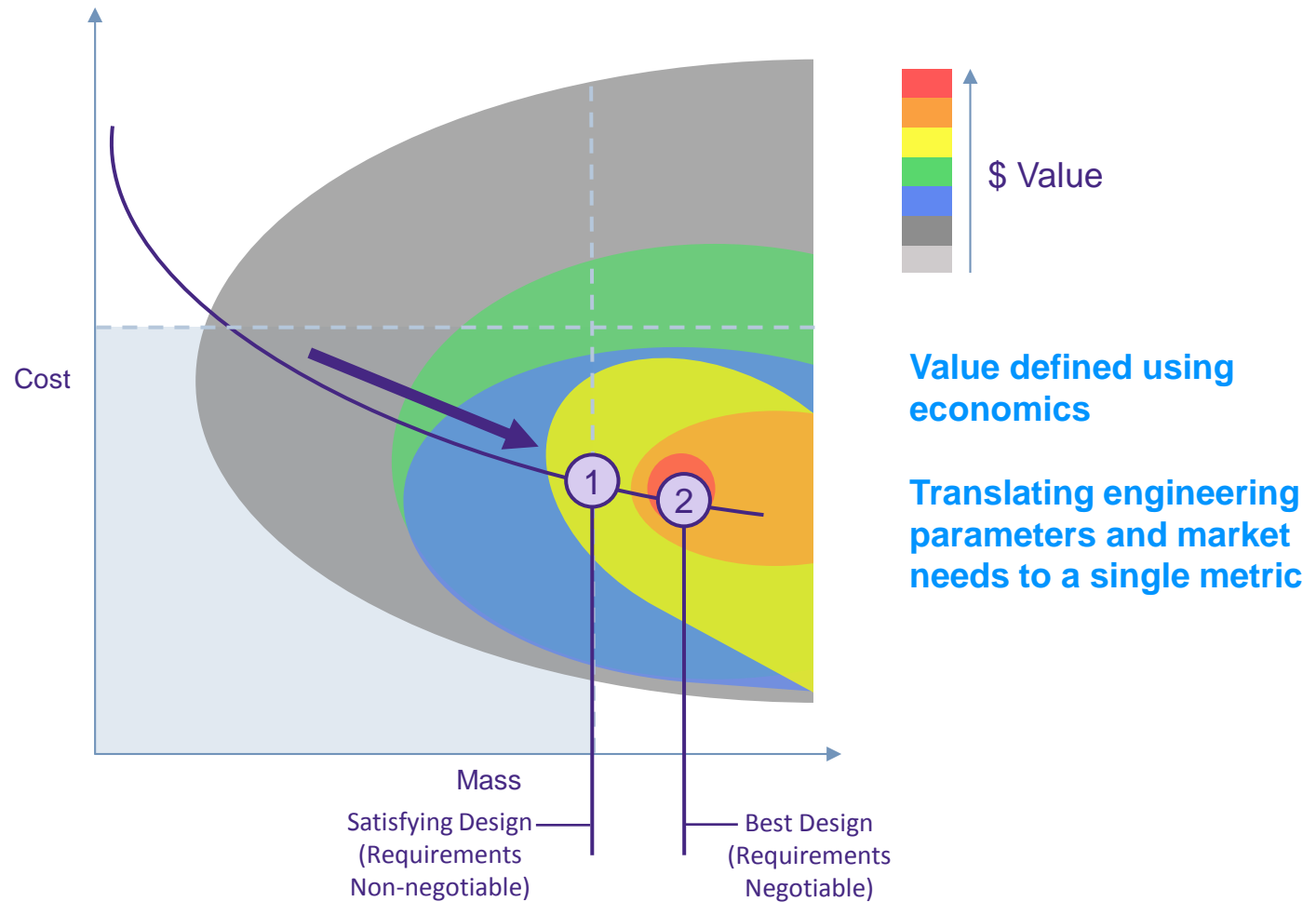
VLEO System Concepts

- Integration of market analysis and business models to system design

- How do we measure the "goodness" of any design?

- Can we apply Value to this?

  - Whose value?

  - Can we build a good value model?

  - What information is required?

  - What models are required?

  - What level of detail is required?

- What would this look like?

VLEO Design Framework
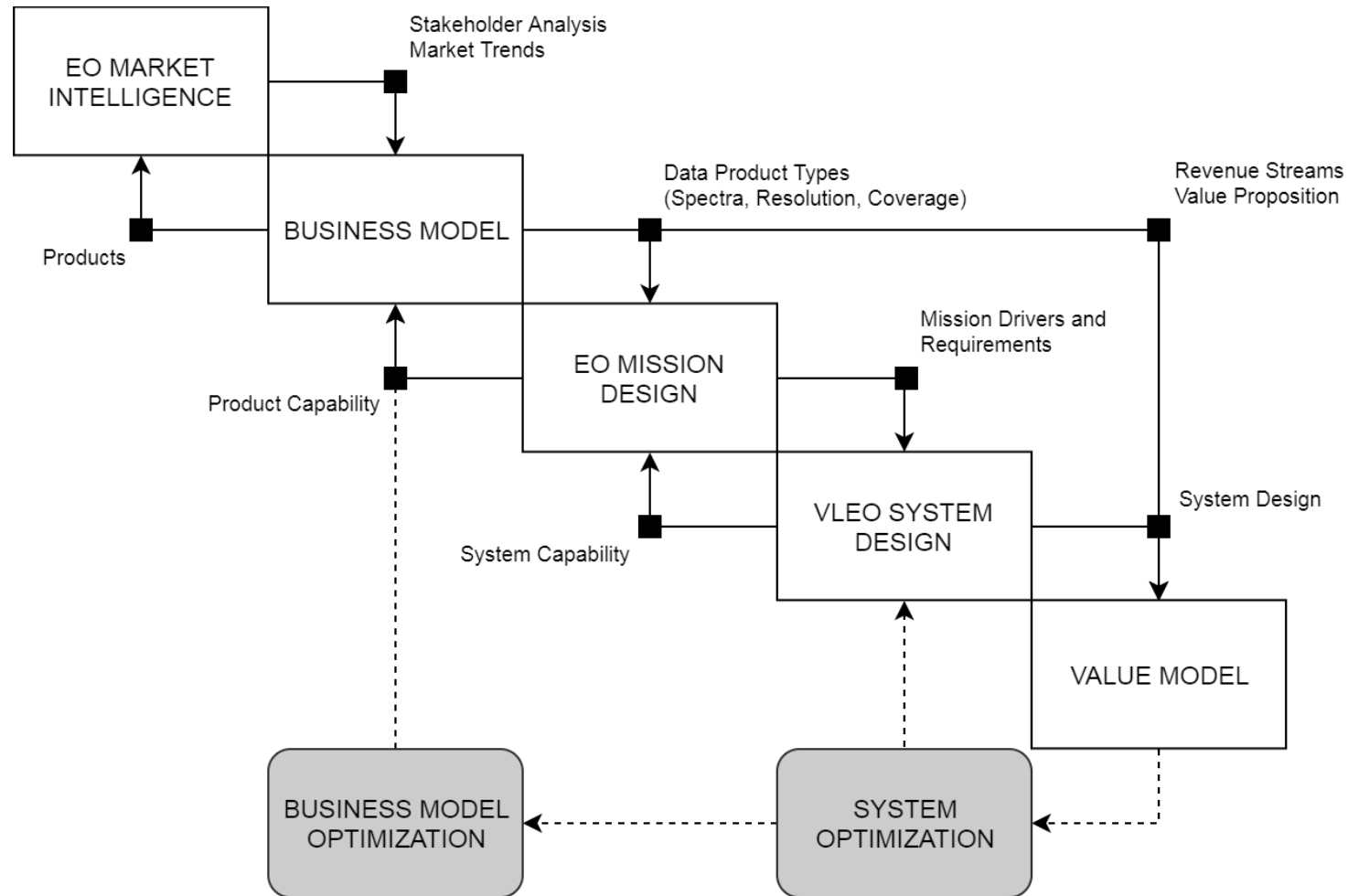
The Value Chain
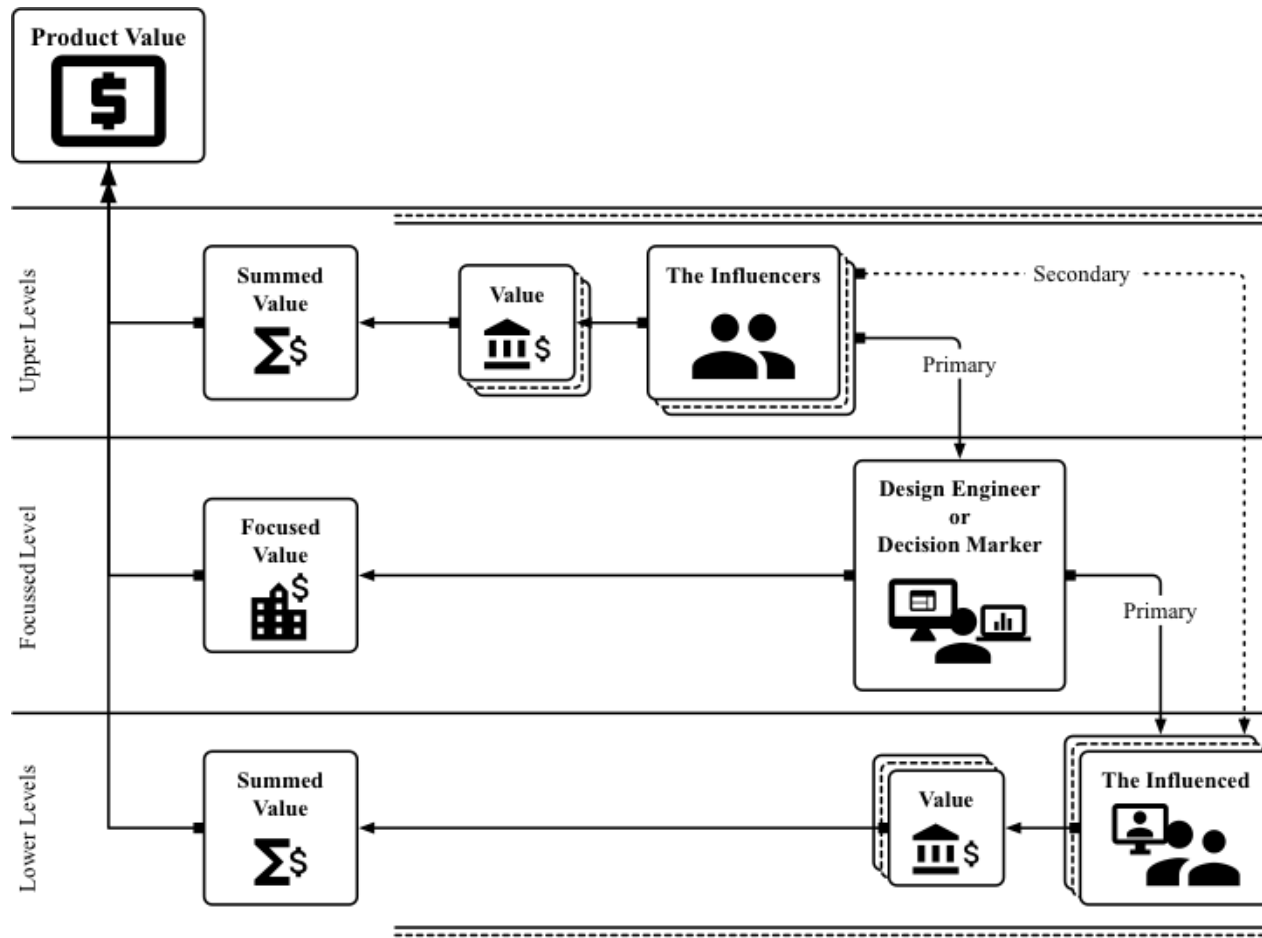
L. Vengadasalam, Value-Centric Design (VCD) – A Generic Framework, 2017