Design for Demise: Systems-level techniques to reduce re-entry casualty risk

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Project objectives

- ✓ Identify critical elements in a space system design for the on-ground casualty risk for LEO satellites in the 800–4000 kg class
- ✓ Identify and evaluate design concepts and techniques for Design for Demise at system, sub-system and equipment level
- ✓ Assess the implementation of the identified techniques from a multidisciplinary point of view, evaluate impact at system level
- Apply identified D4D techniques to a real EO mission. Assess the feasibility and system impact of ensuring compliance with the uncontrolled re-entry casualty risk requirement
- Outline the required technology developments to allow the use of D4D in future missions

Introduction

Project team

Elecnor Deimos:

- Object-oriented simulations to identify critical elements and assess D4D techniques
- Roadmap
- Project management

OHB:

- Design of D4D techniques
- Concurrent Engineering Facility sessions for detailed application to example mission
- Systems-level assessment

HTG – Hyperschall Technologie Göttingen GmbH:

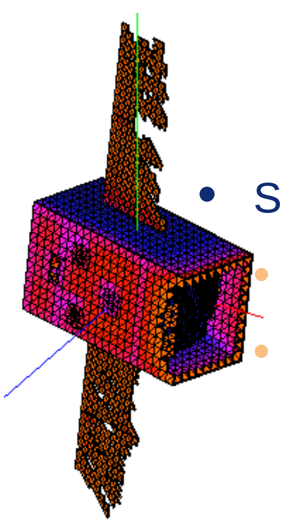
- Spacecraft-oriented simulation of example mission baseline case and four D4D cases

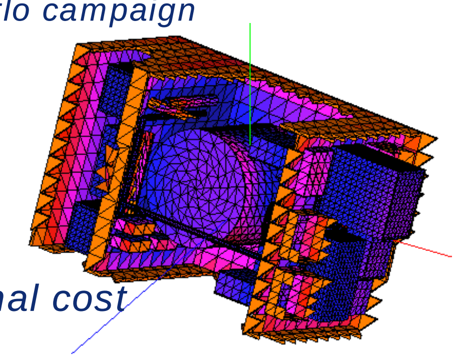
EPFL – École Polytechnique Fédérale de Lausanne:

- Literature review to support identification of critical elements and D4D techniques

Project approach

- Using both spacecraft-oriented and object-oriented simulations
  - Object-oriented – DEBRIS tool developed by Deimos
    - *Rapid simulation of satellite breakup and component demise*
    - *Simplifying assumptions: single breakup event, components demise by ablation*
      - *This approach has been validated against high-fidelity tools*
    - *Can run many simulations quickly:*
      - *examine the effect of different parameters – component mass, aerodynamic coefficients, break-up conditions – allow for uncertainties and run a Monte Carlo campaign*
      - *compare a large number of potential D4D changes*
  - Spacecraft-oriented – SCARAB tool developed by HTG
    - *Detailed modelling of each part in the demise process*
    - *High fidelity results, but high set-up effort and computational cost → can only run a small number of cases*





Modelling approach

Benefits of combining low-fidelity and high-fidelity approaches

- In early phases of work, need to consider D4D at system level
  - Need to quickly assess the level of casualty risk
    - *Do we need to consider D4D at all?*
    - *Is the risk so high that controlled entry can't be avoided?*
  - Design is very preliminary, so not ready to build a detailed model
  - Want to look at lots of options for D4D, trade-off costs and benefits, etc.
  - This needs to be done by the systems engineers, within the design loop

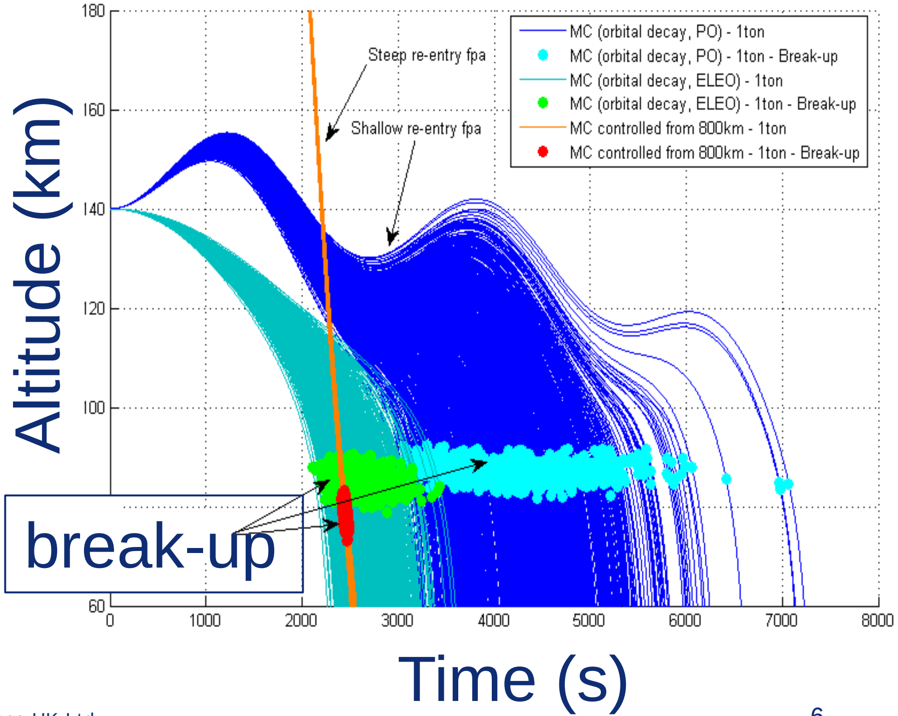
    → Need a quick, easy-to-use tool

- High-fidelity tools are valuable later in the design process
  - Check that a design works as expected
- Low-fidelity results can guide choice of high-fidelity simulations
- Project is developing the design process as well as D4D techniques

Spacecraft breakup

Simulating breakup altitude, one of the main drivers of demisability

- Simulate different re-entry trajectories in DEBRIS
  - From equatorial (ELEO) and polar (PO) orbits
  - Different size satellites: 1 tonne, 3 tonne
  - Compare with controlled re-entry
  - Nominal and Monte Carlo
- Breaks up when outer panels reach melting temperature
- Higher altitude in uncontrolled entry than controlled entry
- Higher from PO than ELEO



Identification of critical elements

What determines whether an object survives to ground?

- The material it's made of:
  - High melting point or high thermal capacity → hard to demise
  - Problematic materials include titanium and steel, aluminium is fine
- Mass
  - All other things being equal, a bigger object is more likely to survive
- Whether it's protected within the spacecraft, or exposed early
- If it's "thermally thin"
  - Size and shape → re-radiating heat, remaining below melting point

Identification of critical elements

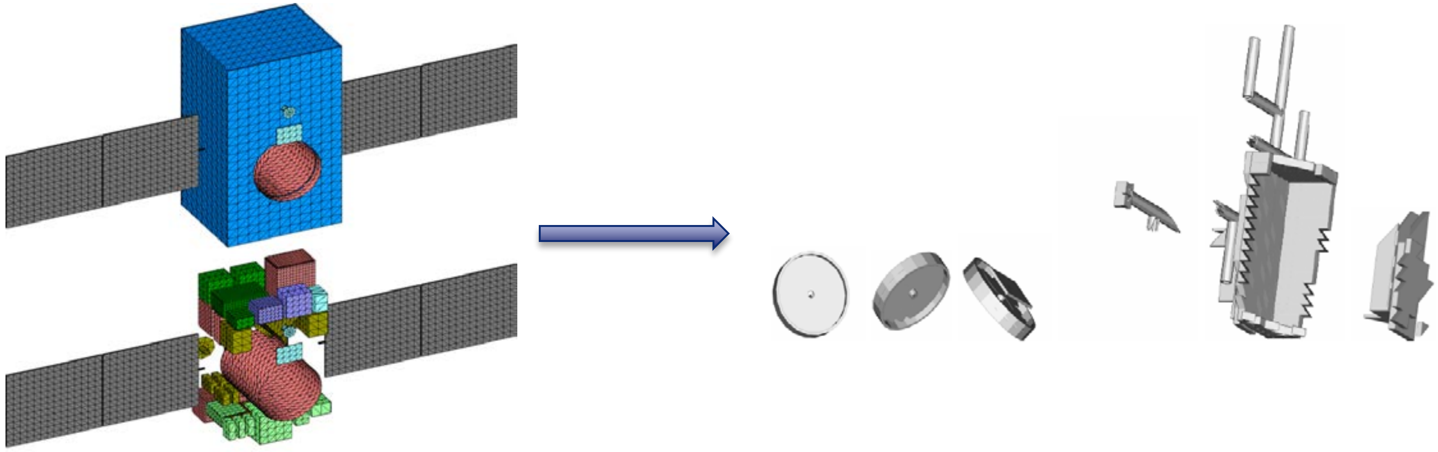
What components are most likely to survive?

- Propellant tanks
  - Very common, made of titanium, **always** survives to ground
- Reaction wheels
  - Heavy and made of steel → demise depends on size, design, exposure
  - Four wheels will impact separately → 4 x the casualty area
- Balance masses
  - Demise depends on material (steel vs aluminium), location in spacecraft
- Magnetorquers
  - Iron core may survive depending on size and location
- Payload components
  - Many different types → need to assess elements for each satellite

Identification of critical elements

What components are unlikely to survive?

- Bus structural elements
- Solar arrays
- Propulsion system elements other than the tank
- Communications hardware
- Battery cells



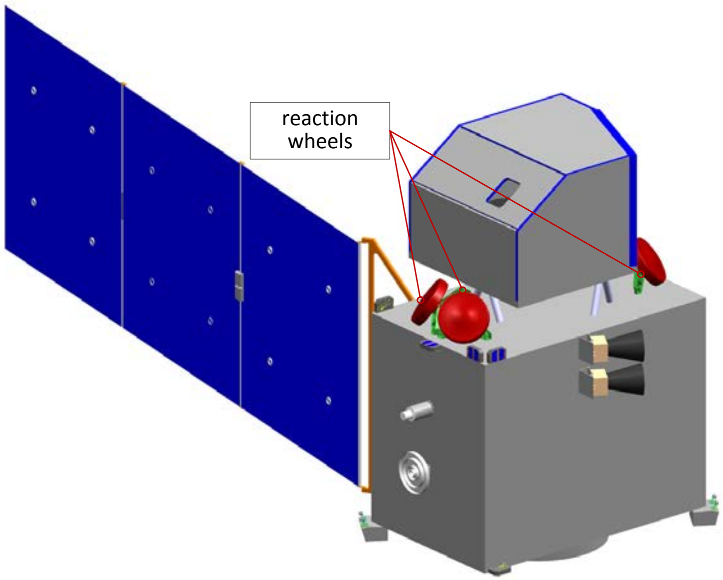
Identification of Design for Demise techniques

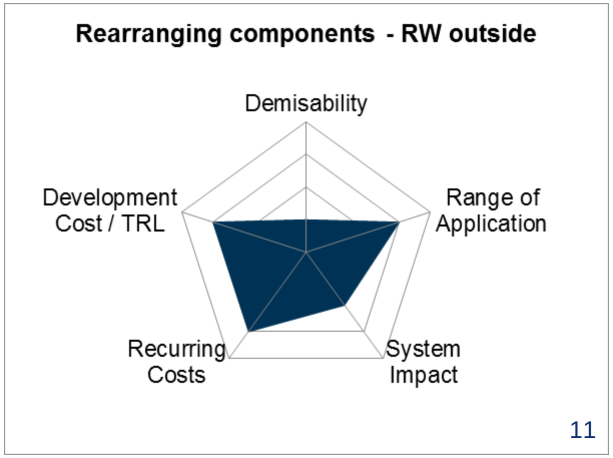
Process

- Lots of initial ideas, downselected and shortlisted based on:
  - Demisability: How big a reduction in casualty area can be achieved?
  - Range of Application: Does it apply to many classes of satellites, or only a few?
  - Systems impact and trade-offs: Higher mass? Shorter lifetime? Lower reliability? Needs big change in satellite design?
  - Recurring costs
  - Development cost / TRL: How expensive would it be to develop? How likely is the technique to be successfully developed?
- Most promising techniques were carried forward to detailed design
- Further downselect of which to apply to the example mission

Rearranging components: Reaction Wheels outside

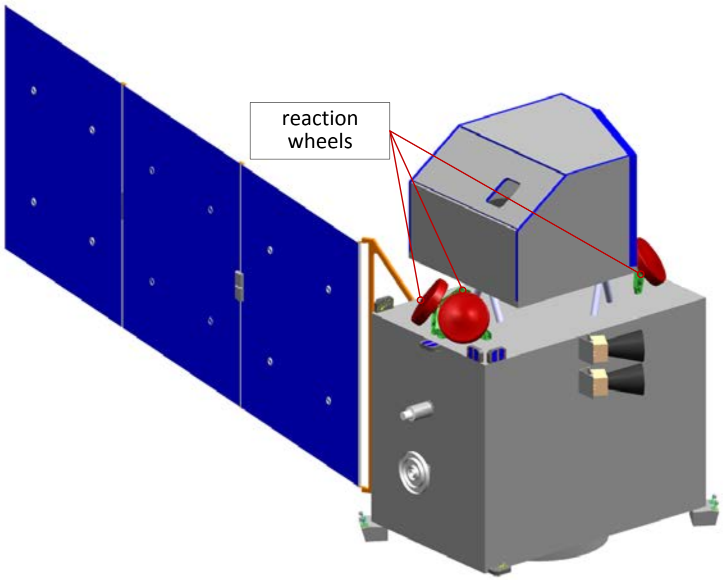
- Mount reaction wheels outside of the main "box"
  - Idea: in the launcher adaptor ring?
- Systems impacts:
  - Sufficient accommodation has to be verified by further analysis
  - AIT benefits, need to ensure that late access to S/C isn't obstructed
  - Thermal aspects have to be analysed
  - Radiation shielding of the wheel electronics has to be analysed
    - *Separate electronics and the wheel itself?*
  - Potentially smaller satellite envelope

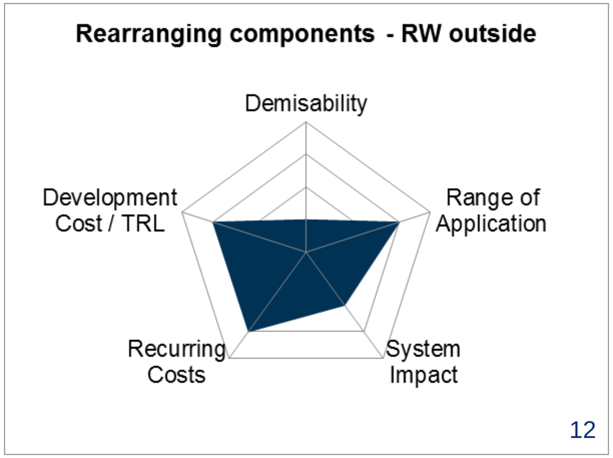




Rearranging components: Reaction Wheels outside

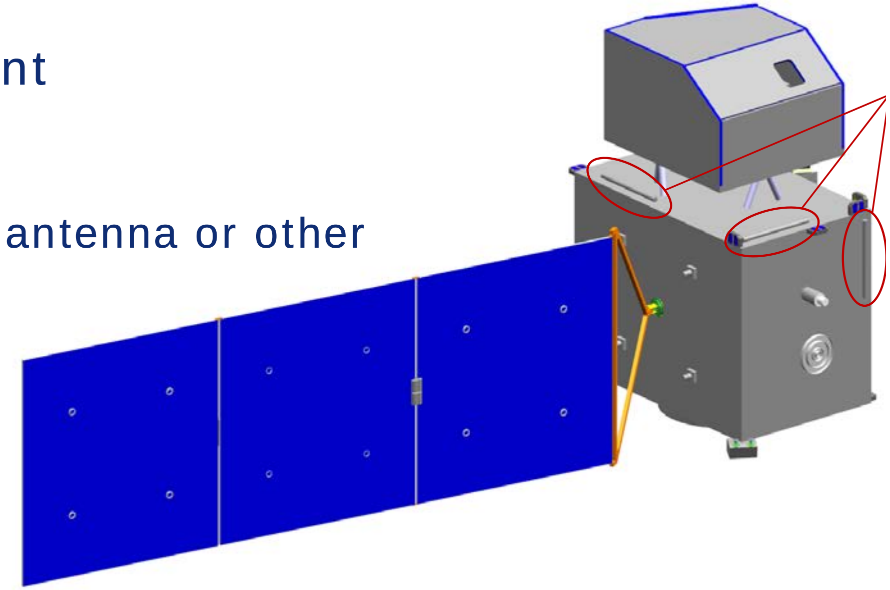
- Demisability:
  - Promotes ablation, may lead to demise if well exposed and attached to low altitude
- Range of Applicability:
  - High – almost all satellites in the reference mission scenario use RWs
- Recurring Costs:
  - No real changes, accommodating existing components in another way
- Technology Development Roadmap:
  - No technology new developments necessary
  - Tests and analyses to verify the unit reorganization

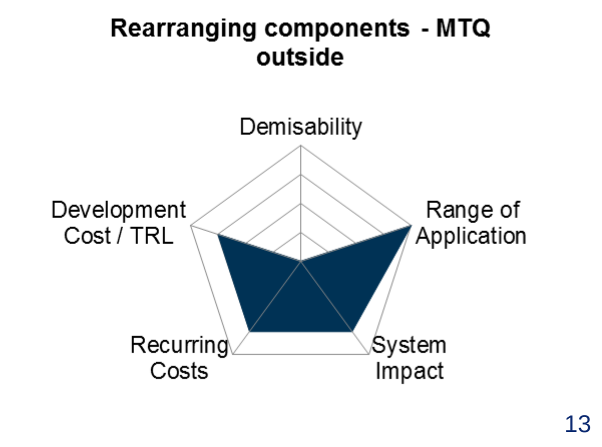




Rearranging components: Magnetorquer outside

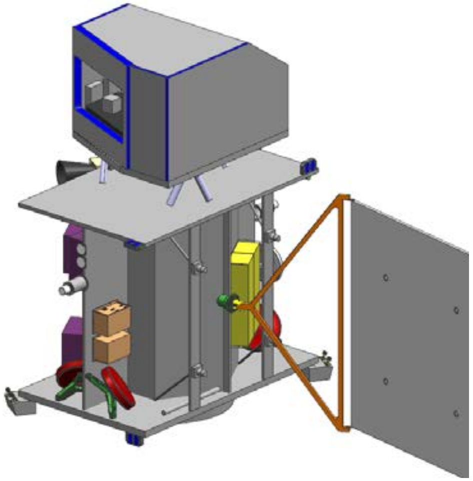
- Overall similar to RWL equivalent
- System Impacts:
  - Potential EMC interferences with antenna or other instruments
  - Shock from the launcher separation and higher radiation is not a problem
  - Influence/dependency on the operating temperature has to be assessed
  - Cut-outs in inner shear panel can possibly be avoided, may increase structure mass
  - Further analysis will show if a sufficient accommodation can be guaranteed



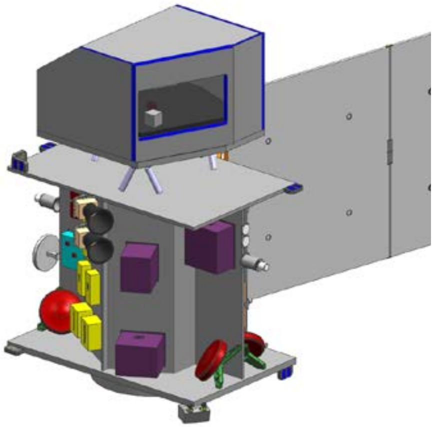


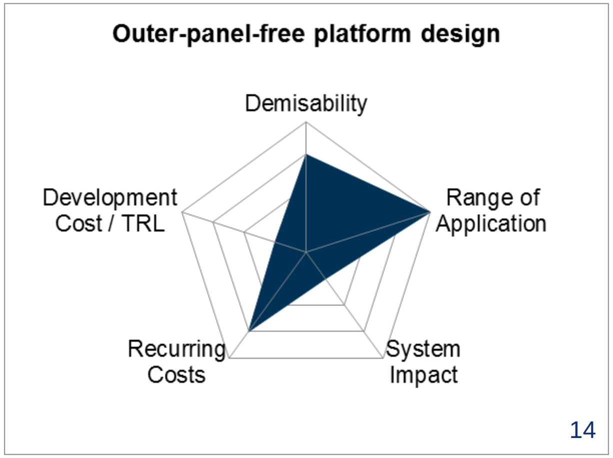
Systems-level D4D techniques

Remove all outer panels

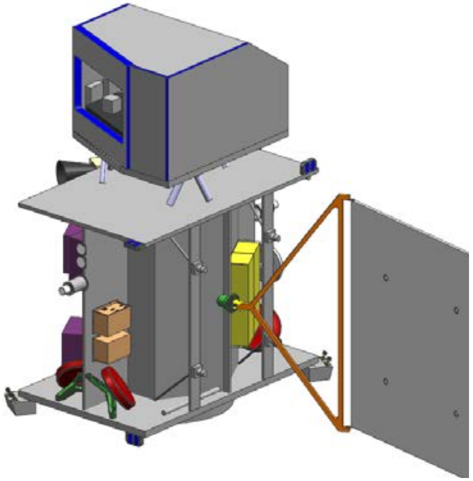


- Increased heat flux on (former) internal components
- System Impacts:
  - Structural stiffness / load carrying structure
  - Radiation protection – shielding
  - MMOD protection
  - Radiator area
  - Accommodation

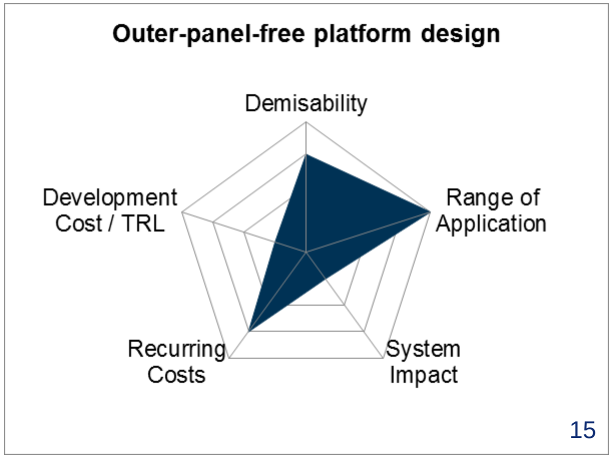




Remove all outer panels

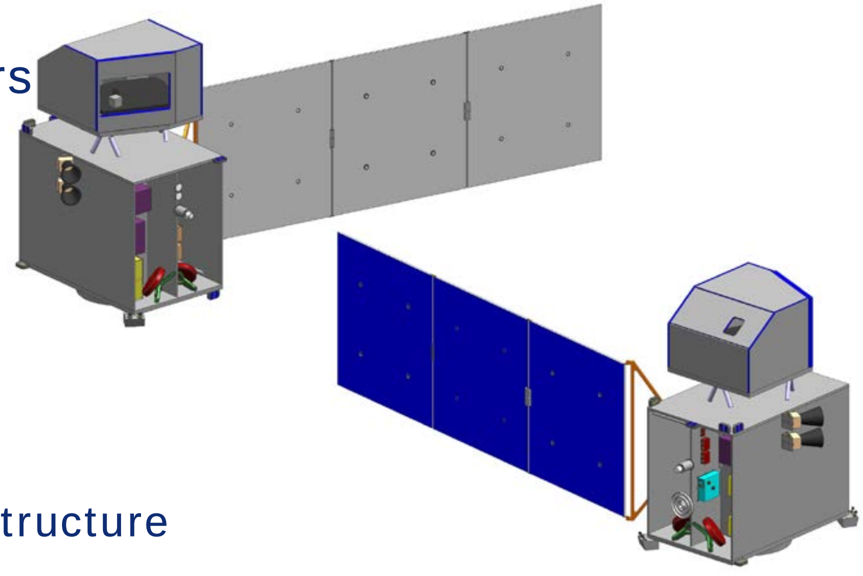


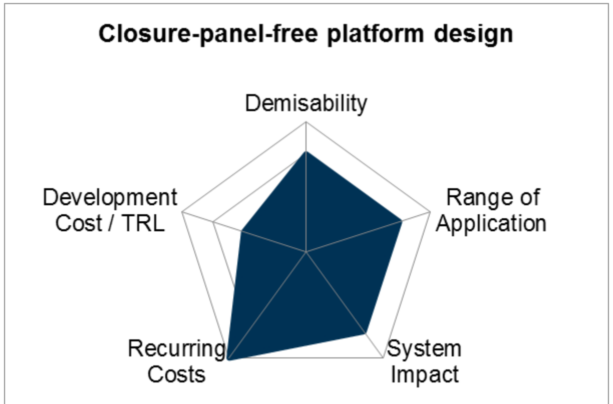
- Demisability:
  - Promotes demise of RWL, MTQ, doesn't help tank
- Range of Application:
  - Very high – cuboid envelope with outer panels is standard in the reference mission scenario
- Recurring Costs:
  - Savings on panels balanced by the expense to address the system impacts
- Technology Development Roadmap:
  - Maybe shielding, stiffness and thermal control techniques necessary
  - Lot of tests and analyses are foreseen to verify the influence of the removal of the outer panels



Remove closure panels

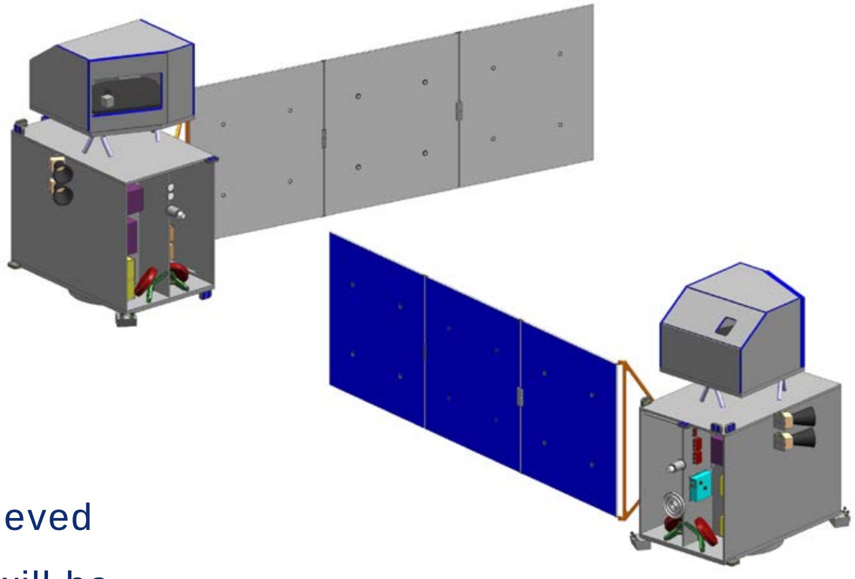
- Remove some panels, retain others
  - Similar to outer-panel-free design
  - Which panels could be removed?
  - Ones which don't accommodate any units or carry significant loads?
- System Impacts:
  - Structural stiffness / load carrying structure
  - Radiation protection – shielding
  - MMOD protection
  - Accommodation / Housing
  - Remaining radiator panels can partly fulfil some of the standard panel functions

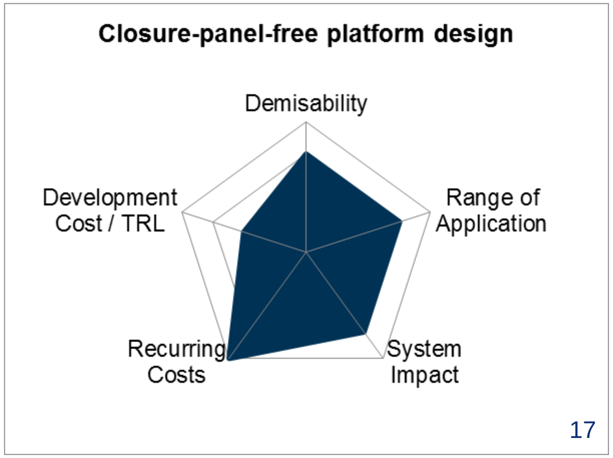




Remove closure panels

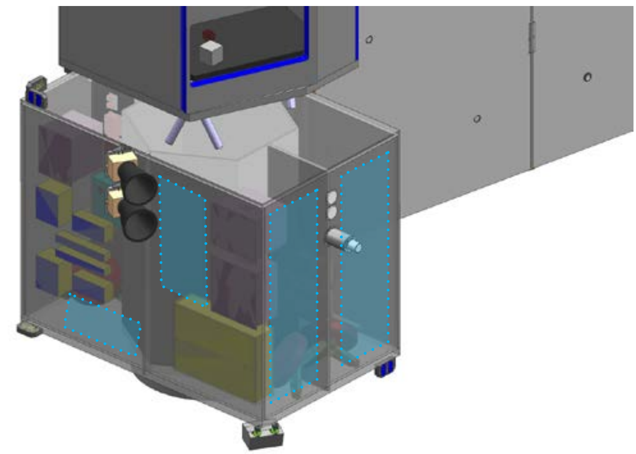
- Demisability:
  - Similar to outer panel free (but less)
- Range of Application:
  - Smaller than for outer-panel-free
  - Not all satellites possess closure panel that can be left out easily
- Recurring Costs:
  - First estimate: Cost reduction can be achieved
  - Effort to counterbalance system impacts will be smaller than the panel savings
- Technology Development Roadmap:
  - Shielding, stiffness and thermal control techniques necessary?
  - Lot of tests and analyses likely to be necessary to verify influence of closure panel removal

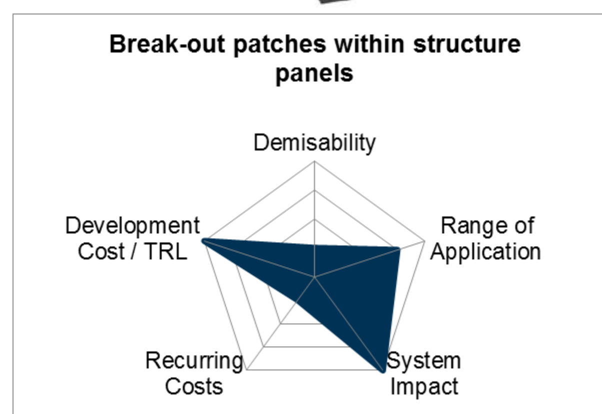




Break-out patches within structural panels

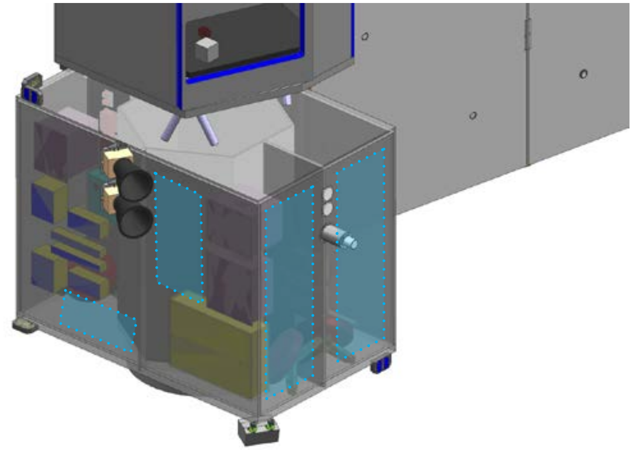
- Cut-outs or weakening of the panel core (density) / facesheet (thickness)
  - Alternative: Cut-outs covered with MLI
- Very versatile technique
- System Impacts:
  - No negative system impacts
  - Already used for mass optimization
  - Cut-outs must not be mass efficient due to needed reinforcements

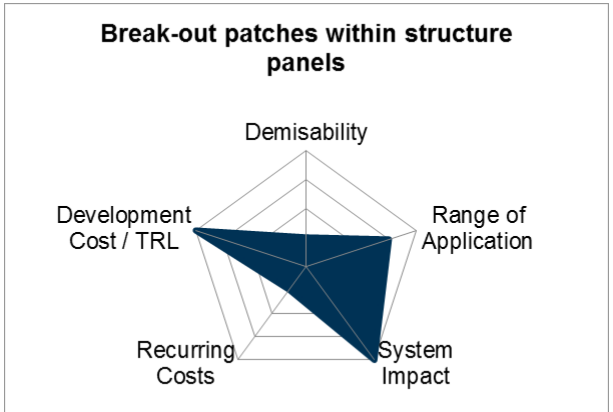




Break-out patches within structural panels

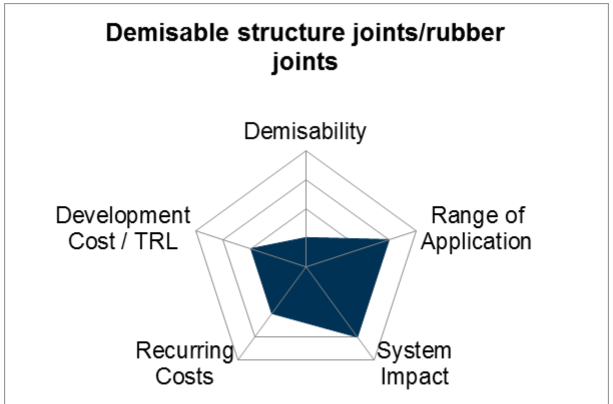
- Demisability
  - Beneficial, but less good than removing panels
- Range of Application:
  - Wide range of applicability
  - But needs to be individually adapted
- Recurring Costs:
  - Most costs are recurring as the technique is highly individual
  - More complex panel manufacturing process
- Technology Development Roadmap:
  - Refinement of panel manufacturing process





Demisable structural joints

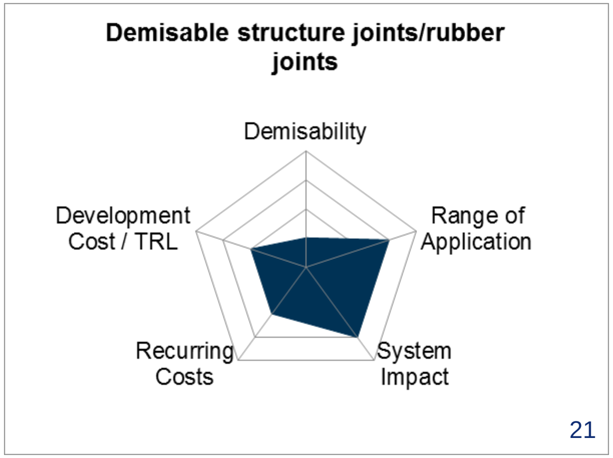
- Design of structural joint to promote break-up at higher altitudes
- Goal: increase exposure of interior components
  → hence promote demise
- System Impacts:
  - Generally very low
  - Stiffness to fulfil the pointing requirements of actual LEO missions must be guaranteed
  - Lower melting temperature must meet system requirements
  - Lifetime performance of new materials



Systems-level D4D techniques

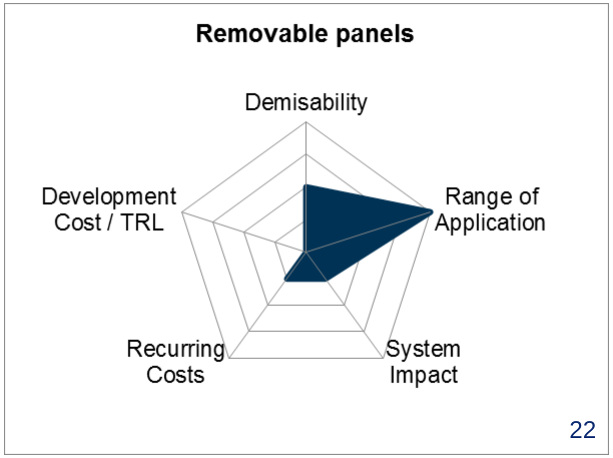
Demisable structural joints

- Demisability
  - Promotes demise of protected parts, improvement depends on activation
- Range of Application:
  - Seems to be applicable to almost all LEO missions
  - Questionable for missions with very high pointing requirements
- Recurring Costs:
  - Additional and novel components have to be added
  - Notable cost increase is expected
- Technology Development Roadmap:
  - New materials and/or alloys have to be developed or at least qualified
  - Tests and analyses to verify the behaviour of the novel components



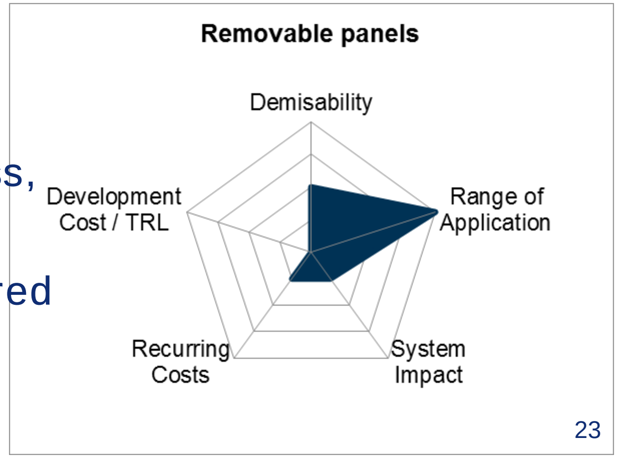
Removable panels

- Panels can be removed at EOL to open the satellite structure
    - Can be realised in a number of ways
- Exposure of internal components can be increased
- System Impacts:
    - Panels must stay attached to S/C if removed before passivation
    - Destruction of non-structure connections (e.g. harness)
    - Adds complexity and risk
    - Increased satellite mass



Removable panels

- Demisability
  - Promotes demise, improvement depends on design
- Range of Application:
  - Should be applicable to all LEO missions
- Recurring Costs:
  - High cost increase is expected
  - Several new components and extra mechanisms have to be added
  - Increased complexity
- Technology Development Roadmap:
  - Destruction non-structure connections (harness, heat-pipe cutters or alternative HP-routing)
  - A lot of analysis, testing and verification required to bring the technique to a sufficient level



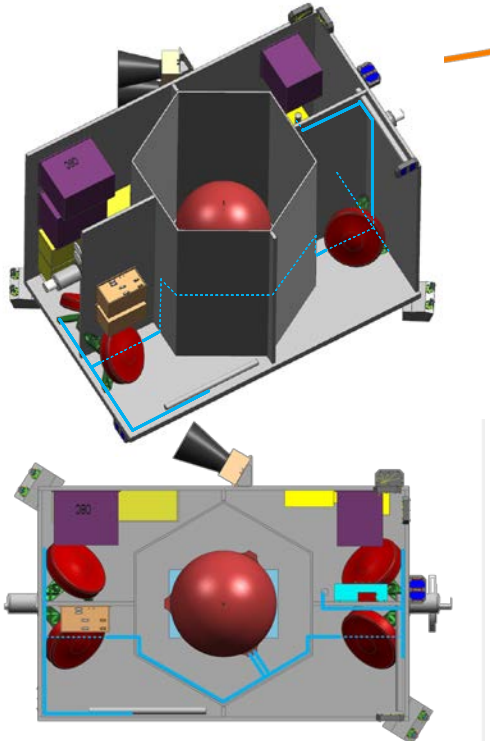
Containment

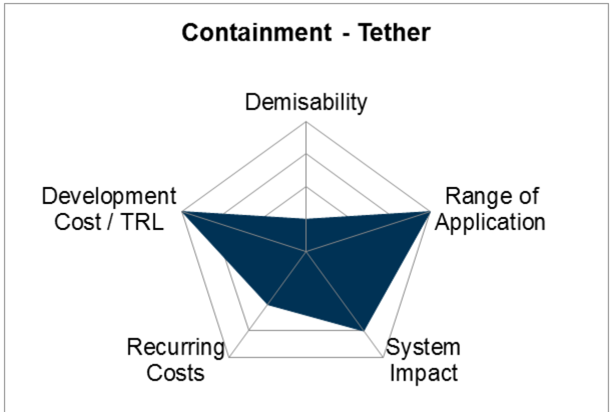
- Number of debris items has a large effect on casualty area
- Contain hard-to-demise components to keep the casualty area as small as possible
- Different design solutions are practicable:

	Rigid	**Flexible**
Held from inside	Bracket	Tether
Held from outside	Box	Net

Containment: Tether

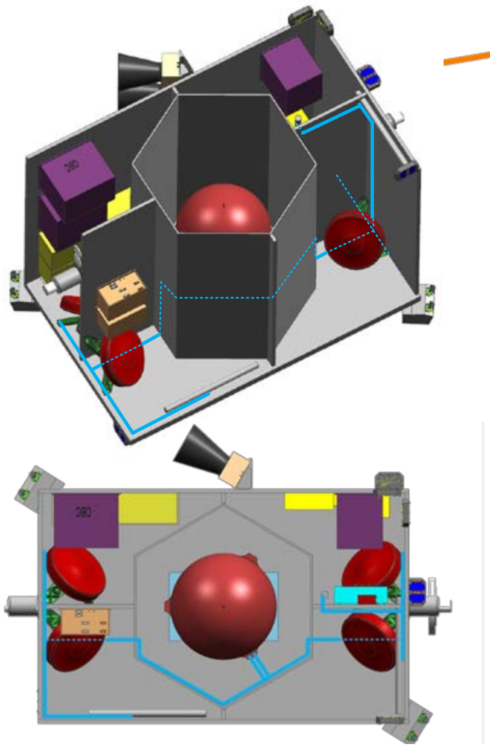
- Keep hard-to-demise components attached using a (non-demisable) tether
- Possible material and thickness has to be analysed in more detail
- Challenges:
  - Single point failure if using just one tether
  - Unit fixation must be investigated
- Besides these points the system impacts are negligible
  - Tether seems to be a low cost solution

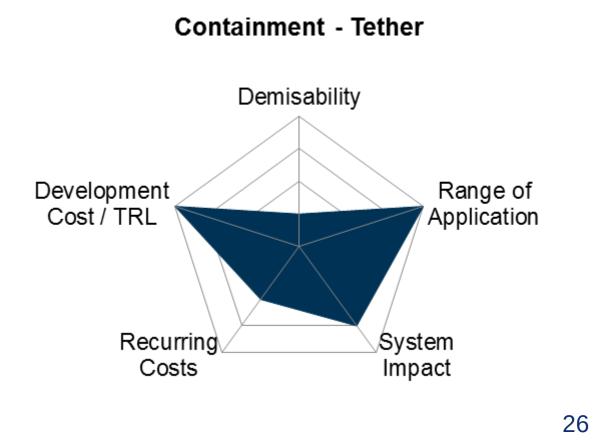




Containment: Tether

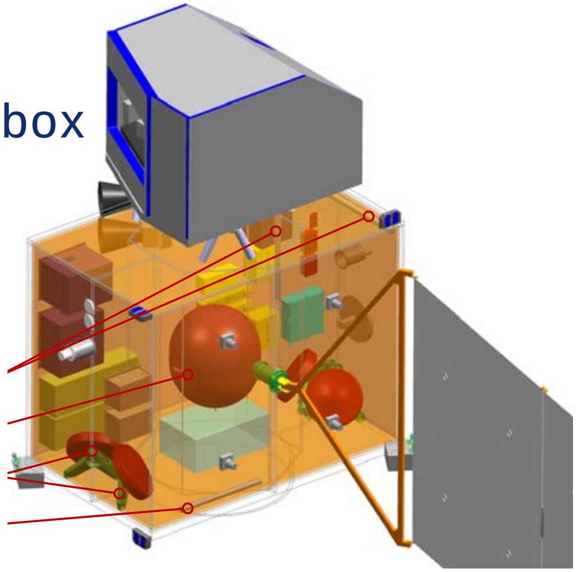
- Effect on casualty area:
  - Can be quite large depending on how closely the parts can be kept together
- Range of Applicability:
  - No constraints for reference mission
- Recurring Costs:
  - Notable recurring cost increase
  - Tether must be added to configuration
- Technology Development Roadmap:
  - Unit fixations
  - Tether material and quality
  - Testing and verification

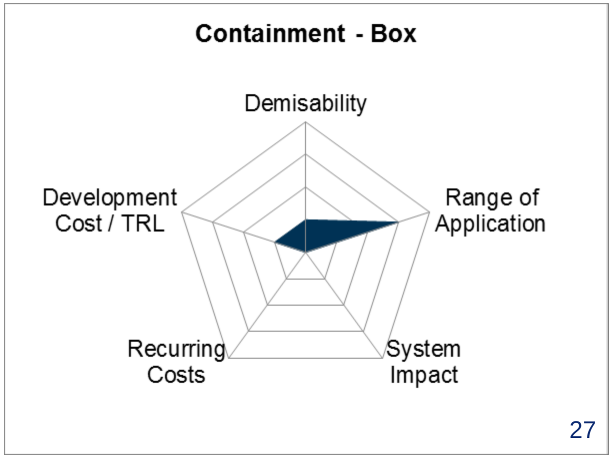




Containment: Box

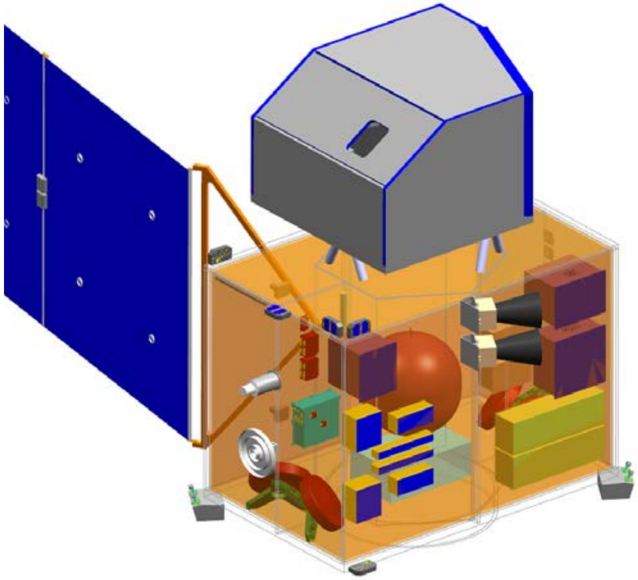
- Contain hard-to-demise components in one box
  - Idea: Use central tube as containment box?
- System Impacts:
  - Interference with the load path in a shear web concept
  - Huge system and mass impacts
  - Extreme case: Use outer satellite box as carrying structure and containment box simultaneously?

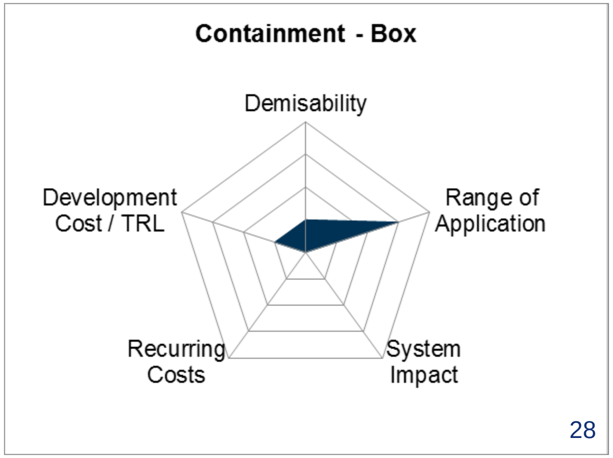




Containment: Box

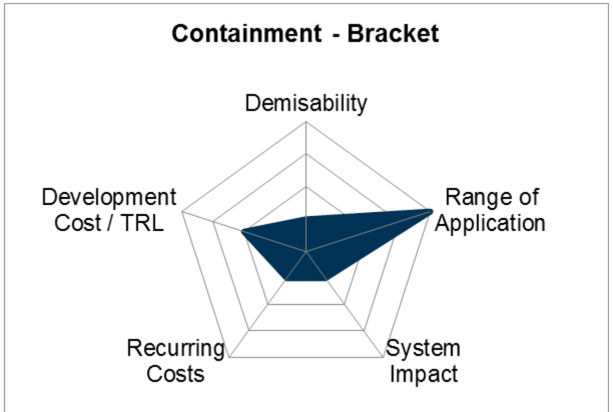
- Significant reduction of casualty area
- Range of Application:
  - In general feasible for reference mission scenario (not considering huge system impacts …)
- Recurring Costs:
  - Extreme cost increase
  - Material cost for the box
- Technology Development Roadmap:
  - New load path concept needed
  - Material for the box
  - A lot of analysis and testing is necessary to verify the concept





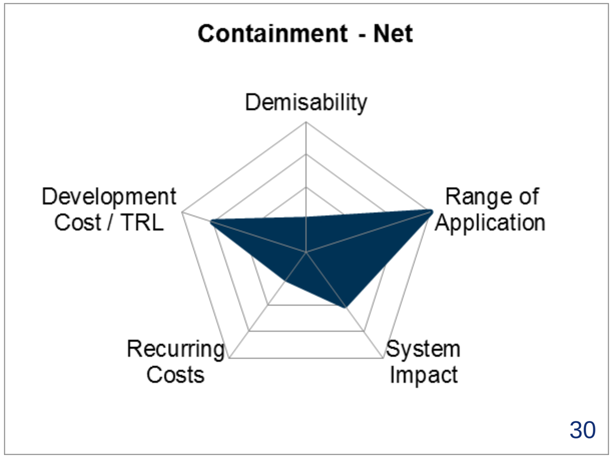
Containment: Bracket

- Bracket to contain the hard-to-demise components
- Single large bracket (e.g. made of titanium) is not feasible
- Thermal issues, as tanks and RW have to be thermally decoupled
- Complex centre of mass adjustment if using a monolithic bracket
- Alternative approach: bracket to hold only one type of component (e.g. RWs)



Containment: Net

- Hard-to-demise components are contained within a net
- Similar to the tether concept
- No need for unit fixations
- Net weights more than a tether
- AIV integration and accessibility of other units could become difficult



Selection of D4D techniques for example mission

Recall the ordering in each category (ties broken by all others)

Demisability	Systems impact	Broad applicability	Fast availability
Closure-panel-free platform design	Break-out patches within structure panels	Containment - Tether	Containment - Tether
Outer-panel-free platform design	Closure-panel-free platform design	Rearranging: MTQ outside	Break-out patches within structure panels
Removable panels	Containment - Tether	Outer-panel-free platform design	Rearranging: MTQ outside
Containment – Tether	Rearranging: MTQ outside	Containment – Net	Rearranging: RW outside
Break-out patches within structure panels	Demisable structure joints/rubber joints	Containment - Bracket	Containment - Net
Rearranging: RW outside	Rearranging: RW outside	Removable panels	Closure-panel-free platform design
Containment – Net	Containment - Net	Closure-panel-free platform design	Demisable structure joints/rubber joints
Demisable structure joints/rubber joints	Outer-panel-free platform design	Break-out patches within structure panels	Containment - Bracket
Containment – Bracket	Containment – Bracket	Rearranging: RW outside	Outer-panel-free platform design
Containment – Box	Removable panels	Demisable structure joints/rubber joints	Containment – Box
Rearranging: MTQ outside	Containment - Box	Containment - Box	Removable panels

Selection of D4D techniques for example mission

Highest scoring design in each category + some others of interest

Demisability	Systems impact	Broad applicability	Fast availability
Closure-panel-free platform design	Break-out patches within structure panels	Containment - Tether	Containment - Tether
Outer-panel-free platform design	Closure-panel-free platform design	Rearranging: MTQ outside	Break-out patches within structure panels
Removable panels	Containment - Tether	Outer-panel-free platform design	Rearranging: MTQ outside
Containment – Tether	Rearranging: MTQ outside	Containment – Net	Rearranging: RW outside
Break-out patches within structure panels	Demisable structure joints/rubber joints	Containment - Bracket	Containment - Net
Rearranging: RW outside	Rearranging: RW outside	Removable panels	Closure-panel-free platform design
Containment – Net	Containment - Net	Closure-panel-free platform design	Demisable structure joints/rubber joints
Demisable structure joints/rubber joints	Outer-panel-free platform design	Break-out patches within structure panels	Containment - Bracket
Containment – Bracket	Containment – Bracket	Rearranging: RW outside	Outer-panel-free platform design
Containment – Box	Removable panels	Demisable structure joints/rubber joints	Containment – Box
Rearranging: MTQ outside	Containment - Box	Containment - Box	Removable panels

Conclusions

Project outcomes

- A number of critical elements of satellites have been identified
  - Fuel tanks, reaction wheels, balance masses, MTQ, payload components
- Techniques to allow engineers to identify the critical elements of any spacecraft have been developed
- Design-for-Demise techniques have been identified
  - Systems-level techniques to reduce the overall casualty risk
  - Subsystems-level techniques to increase the demisability of specific components
- Done generic design and shortlisting of D4D techniques
- Detailed design and assessment for a realistic satellite starts with CEF study next month