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Spacecraft Design-for-Demise implementation strategy & decision-making methodology for low earth orbit missions

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Abstract

Space missions designed to completely ablate upon an uncontrolled Earth atmosphere reentry are likely to be simpler and cheaper than those designed to execute controlled reentry. This is because mission risk (unavailability) stemming from controlled reentry subsystem failure(s) is essentially eliminated. NASA has not customarily implemented Design-for-Demise meticulously. NASA has rather approached Design-for-Demise in an *ad hoc* manner that fails to entrench Design-for-Demise as a mission design driver. Thus, enormous demisability challenges at later formulation stages of missions aspired to be demisable are evident due to these perpetuated oversights in entrenching Design-for-Demise practices. The investigators hence propose a strategy for a consistent integration of Design-for-Demise practices in all phases of a space mission lifecycle. Secondly, an all-inclusive risk-informed, decision-making methodology referred to as Analytic Deliberative Process is proposed. This criterion facilitates in making a choice between an uncontrolled reentry demisable or controlled reentry. The authors finally conceive and synthesize ~~objectives hierarchy, attributes,~~ and Quantitative Performance Measures of the Analytical Deliberative Process for a Design-for-Demise risk-informed decision-making process.

Keywords: Design-for-Demise; Analytic Deliberative Process (ADP); Multi-attribute utility theory (MAUT); Atmosphere reentry; Orbital debris; Space debris

1. Introduction

Spacecraft Design-for-Demise (DfD) entails the intentional design of spacecraft hardware such that the spacecraft will completely ablate (demise) upon uncontrolled reentry into the Earth atmosphere. Atmospheric reentry typically occurs during the post-mission disposal phase of the space mission lifecycle. Different spacecraft parts exhibit different ablation behaviors depending on their shapes, sizes and material composition. Demisability is necessary to reduce the risk of human casualty and damage to property on Earth, hence ensuring public and property safety during uncontrolled reentries by spacecraft into the Earth atmosphere. Debris surviving atmospheric reentry for NASA sanctioned missions must satisfy Requirement 4.7-1 of NASA Technical Standard 8719.14—Process for Limiting Orbital Debris. Requirement 4.7-1 dictates the risk of human casualty anywhere on Earth due to reentering debris with KE $\geqslant$ 15 J be less than 1:10,000 (0.0001) (NASA, 2012).

DfD may offer a relatively cheaper, simplified and more effective means of meeting NASA's Earth atmosphere reentry requirement for Low Earth Orbit (LEO) missions. An uncontrolled reentry mission that ablates does not require an integrated provision to execute a controlled reentry. Consequently, not only will such a mission design be relatively simpler and cheaper, but also spacecraft unavailability risk due to a controlled reentry subsystem failure(s) is essentially eliminated. Absence of a controlled reentry subsystem would hence improve mission on-orbit reliability and robustness. Design-for-Demise can be implemented in a wide range of LEO missions independent of the nature of the mission function (~~Waswa et al., 2012).~~

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Nomenclature

A_i	area of object surviving re-entry, m^2
D_A	Total Debris Casualty Area, m^2
KE	kinetic energy, (J)
N	number of objects surviving reentry
N_{QPM}	number of Quantifiable Performance Measures (QPM) for attribute i determined by AHP
PI_j	Performance Index for alternative j
$R_c(t)$	controlled reentry subsystem reliability
$R_s(t)$	space segment reliability
λ	failure rate, components per hour
t	time, hours
v_{ij}	values associated with the Quantifiable Performance Measures (QPMs) for attribute i determined by Analytic Hierarchy Process (AHP)
w_i	Analytic Hierarchy Process (AHP) determined weight for attribute i

Attention to DfD intensified within NASA after the premature de-orbit of the non-demisable Compton Gamma Ray Observatory (CGRO) mission on 4 June 2000 due to the zero fault tolerance policy adopted by NASA after one of the three gyroscopes required for controlled reentry failed (CGRO, 2012). Another NASA mission, the Fermi Gamma-ray Space Telescope (formerly known as Gamma-ray Large Area Space Telescope—GLAST), launched on 11 June 2008 explored further the issue of designing for demise (Fermi, 2012). However, despite detailed demisability analysis indicating that Fermi would comply with the NASA human casualty risk requirement, the controlled reentry option was preferred due to uncertainty in the surviving debris KE threshold (Leibee et al., 2004). The Global Precipitation Measurement (GPM) mission presently in the formulation phase is intended to be the first fully designed for demise LEO mission. The post mission disposal objective is to meet Requirement 4.7-1 stated above exclusively by hardware parts design practices.

Given the above stated significance and prior DfD experiences, this investigation examines the previous NASA approach to DfD and proposes a two-part DfD strategy. First, a consistent integration of DfD practices in all phases of a mission lifecycle. Secondly, an all inclusive risk-informed-decision making criteria that facilitates in deciding whether to design a demisable LEO reentry mission or opt for a controlled reentry mission. Reentry analytical techniques employed in DfD analysis predict the atmospheric reentry behavior of different object shapes, sizes and materials. These tools investigate breakups, temperature history and demisability of objects reentering Earth's atmosphere. The reentry analysis method employed can either be (a) object oriented; which analyzes the individual parts of a spacecraft, or (b) spacecraft oriented; which models the complete spacecraft as close as possible to the real design.

Currently, the major object oriented reentry analysis tools are NASA's Debris Analysis Software (DAS) and Object Reentry Survival Analysis Tool (ORSAT); and the Spacecraft Entry Survival Analysis Module (SESAM) developed by the ESA (Lips and Fritsche, 2005). The major spacecraft oriented tool is ESA's Spacecraft Atmospheric Reentry and Aero-thermal Breakup (SCARAB) code. Comparing the two NASA tools, ORSAT is more comprehensive and has a higher fidelity assessment of an object's thermal destruction during ballistic reentry than DAS. However, unlike DAS, ORSAT is not readily available and only personnel at the Johnson Space Center, Orbital debris program office run it. Nonetheless, in practice, further analysis by higher fidelity tools like ORSAT is only necessary if reentry analysis in DAS show a human casualty risk >0.0001.

2. Strategy for Design-for-Demise

To facilitate the realization of a demisable space mission wherever possible, it is paramount to engage a comprehensive approach entrenching DfD practices in all the mission life-cycle activities.

2.1. Traditional NASA approach to Design-for-Demise

Traditionally, DfD of Earth atmosphere reentry NASA missions has been handled within the framework of Limiting Orbital Debris as stipulated in Procedural Requirement 8715.6A—Limiting Orbital Debris (NASA, 2009), and the actual mission requirements details are specified in the Technical Standard 8719.14—Process for Limiting Orbital Debris (NASA, 2012). However, no formal mission design requirements specific to DfD exist. Therefore, DfD is more or less implemented in an *ad hoc* manner within NASA mission design practices. Moreover, prior to August 2007, the more 'DfD friendly' thresholds for the human casualty risk of 1:10,000 and a15 J KE threshold for objects impacting the earth as stipulated in the Technical Standard 8719.14—Process for Limiting Orbital Debris (NASA, 2012) were still evolving. Thus, traditional DfD engagement in NASA mission formulation can be succinctly represented by the schematic in Fig. 1.

Note that DfD is only emphasized in some formulation phases and hence loosely integrated throughout the entire mission life cycle. This approach is inherently weak because overlooked DfD considerations perpetuate into subsequent mission phases resulting in formidable DfD design

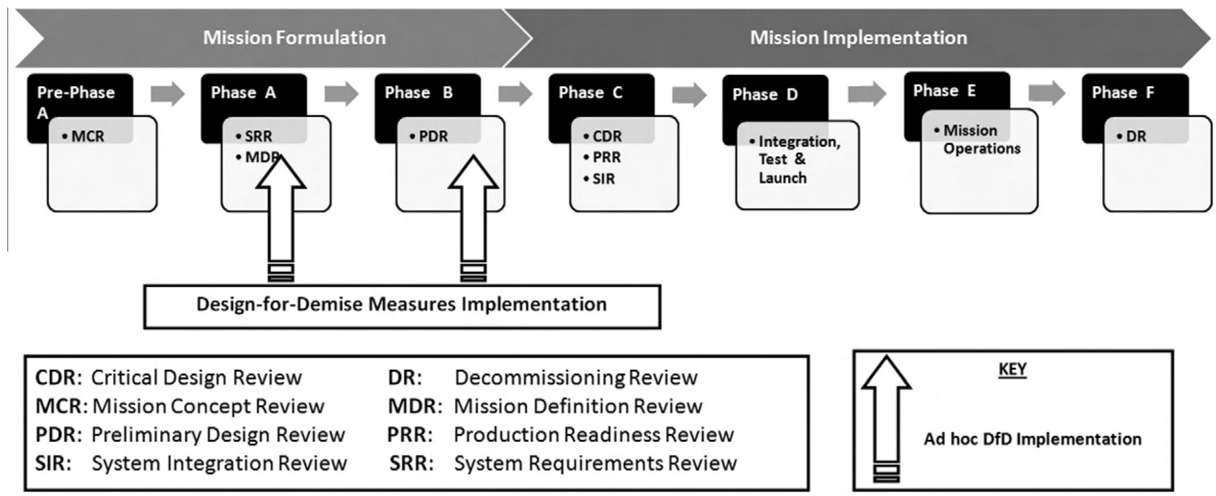

Fig. 1. Traditional NASA Design-for-Demise implementation in LEO reentry mission life cycle.

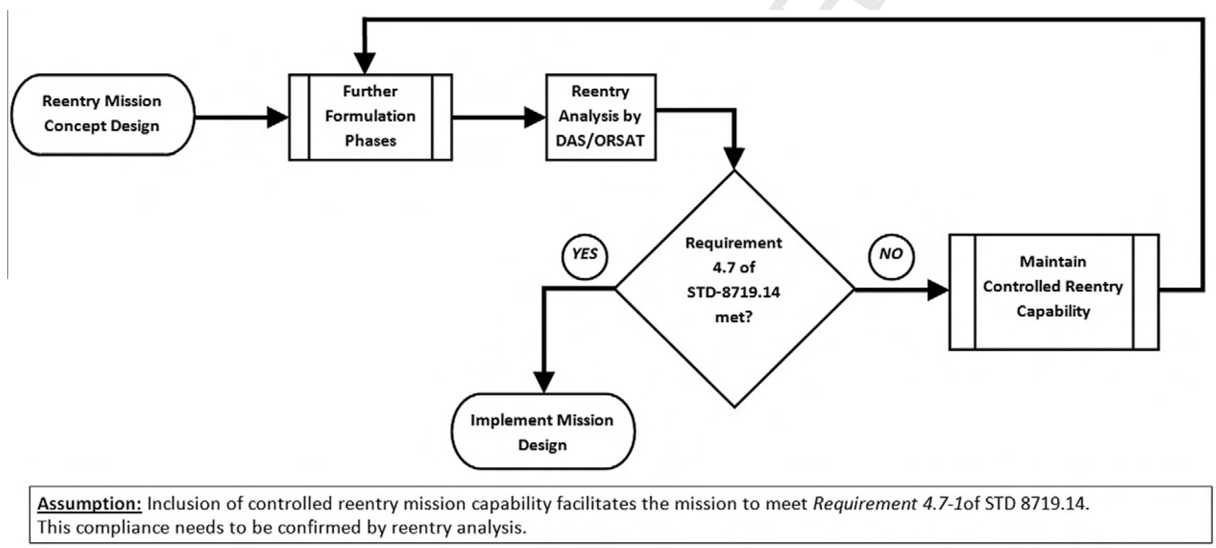

Fig. 2. Current NASA Design-for-Demise execution strategy.

obstacles. For example, if demisability is not defined as a mission objective in Phase A, then demisability top-level system requirements are not identified and progress related to DfD technology maturity, risk analysis; mission safety and assurance will not be updated in Phases B and C. In general, DfD objectives are not accommodated in preparation for Key Decision Points (KDP) and in other activities associated with a particular phase. The flow diagram in Fig. 2 summarizes the current NASA execution strategy of DfD during mission formulation. The referenced 'Further Formulation Phases' comprise Phases A and B of mission lifecycle. 'Reentry Analysis' examines the spacecraft parts demisability likelihood.

The practices outlined above clearly do not make DfD a mission design driver resulting in lost opportunities to exploit would be advantages due to DfD, i.e., relatively simpler, cheaper and more robust space mission designs. A controlled reentry capability was logically retained instead of exploring a tortuous demisable mission 'redesign' in order to pass formal reviews.

2.2. Proposed approach to Design-for-Demise

This research proposes making DfD a mission design driver to facilitate the realization of a demisable LEO mission in complying with stipulated NASA Earth atmosphere reentry requirements. DfD would be entrenched and executed at all mission formulation phases as shown in Fig. 3. With this approach, demisability requirements are adequately considered in all activities of each phase of the mission lifecycle.

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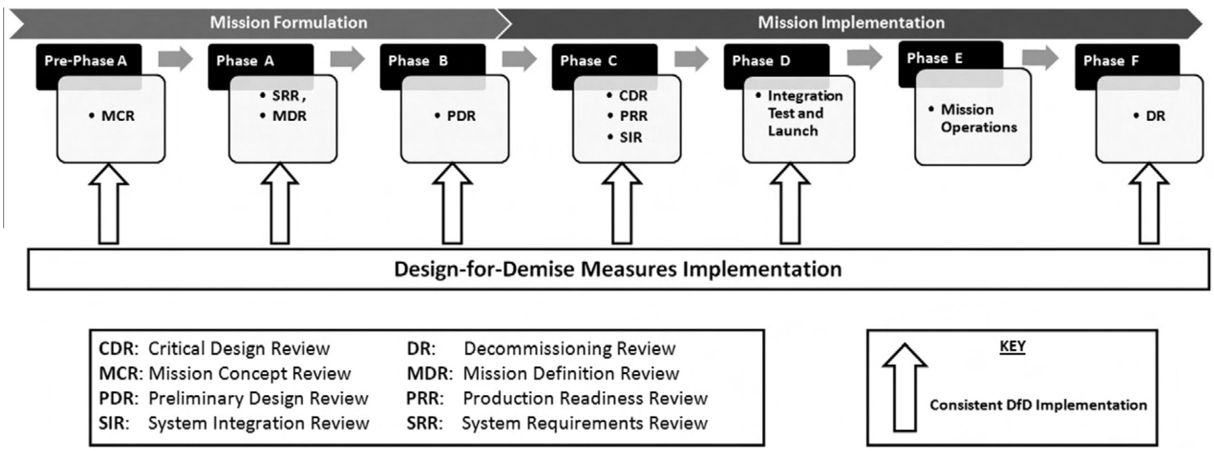

Fig. 3. Proposed Design-for-Demise implementation in reentry LEO mission life cycle.

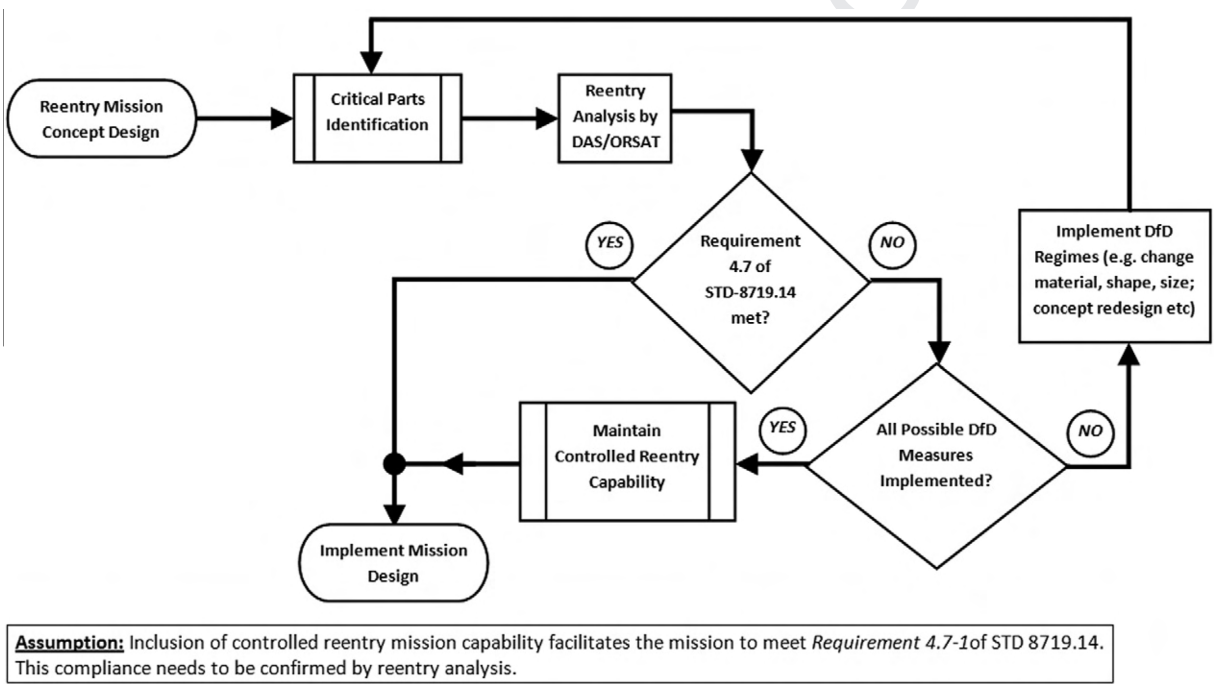

Fig. 4. Proposed Design-for-Demise execution strategy.

Preparations for KDPs comprehensively accommodate DfD objectives and they include adopted DfD benchmarks that have to be satisfactorily met before the mission proceeds to the next phase. This scenario is further expounded in Fig. 4, which shows the proposed DfD execution. The 'Critical Parts Identification' process identifies non-demisable spacecraft parts. 'DfD measures' are the spacecraft part modification methods that would transform a previously non-demisable part to a demisable one. A controlled reentry capability must of course be implemented for a non-demisable LEO mission after all possible DfD measures have been exhausted without achieving demisability.

3. Design-for-Demise decision-making methodology

In choosing whether to design a demisable reentry spacecraft, or a reentry spacecraft possessing a controlled reentry subsystem; it is essential to formulate a decision-making framework that facilitate this decision. The authors here propose the Analytical Deliberative Process (ADP). Developed by the Risk Assessment and Analysis Group at Massachusetts Institute of Technology (MIT), ADP is a Multi-attribute utility theory (MAUT) that provides a preliminary ranking of decision options. It brings together the decision maker, experts and stakeholders in a decision-making process that organizes information in a manner that distinguishes benefits and risks associated with candidate decision options. The ADP keeps track of uncertainty and aggregates both objective and subjective information while assisting in the systematic identification of the objectives of making a particular decision and the respective associated performance of the various decision options. ADP combines analytical methods with a deliberation that scrutinizes the analytical results and produces a ranking of decision options and a detailed understanding of why certain options outperform others. ADP is based on two guiding principles (National Research Council, 1996):

(i) *Analysis,* which uses rigorous, replicable methods, evaluated under the agreed protocols of an expert community—such as those of disciplines in the natural, social, or decision sciences, as well as mathematics, logic, and law to arrive at answers to factual questions.
(ii) *Deliberation*, which is any formal or informal process for communication and collective consideration of issues.

As shown in Fig. 5, ADP begins with the framing of a specific decision problem, defining the context in which the decision is to be made and identifying the ~~decision maker~~ (DM), Subject Matter Experts (SME) and ~~stakeholders~~ (SH). The DM is a senior member(s) of the design team; SMEs possess pertinent expertise in different areas of the design and can characterize available design options; SHs are individuals or organizations materially affected by the decision's outcome but are outside to the organization making the decision (NASA, 2010).

Having these definitions and roles clearly specified at the beginning of the process is important. All subsequent analysis and risk characterization must be done in the context of the specific decision problem at hand and it must answer the specific questions that are of interest to the DMs, SMEs and SHs.

Once the DMs, SHs and SMEs understand the decision problem and the context in which it is being addressed, they must identify all of the elements that each individual believes are important to consider in evaluating decision options. Forming an ~~objectives hierarchy~~ captures this information, as shown in Fig. 6 (Stamatelatos et al., 2006).

Goal: Statement explaining the overall purpose of making the decision.

Objectives: They are the broad categories of elements that the DM, SMEs and SHs feel must be achieved in order for a decision option to meet the goal. These broad objectives may be further divided into sub-objectives as needed.

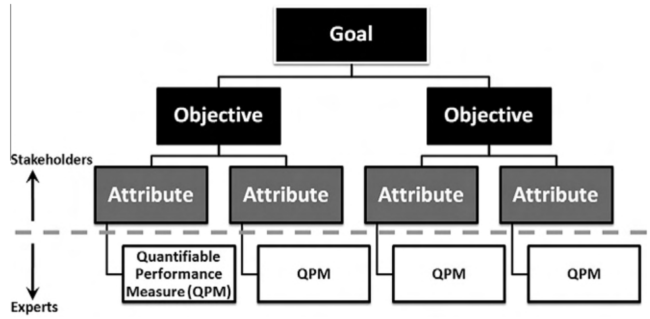

Fig. 6. Schematic objectives hierarchy.

Attributes: They are the largest set of elements a DM or SH is indifferent between (e.g. a SH wants to minimize total spacecraft mass and does not care if this is the power subsystem or propulsion subsystem mass; then we say this individual is indifferent between power subsystem and propulsion subsystem mass). Attributes describe how to achieve the objective they lie below. It is helpful to think of attributes as the most detailed level of sub-objective the DM or SH wishes to consider. With input from the DM, and the SHs, the SMEs will attempt to create a consensus hierarchy and prepare a set of definitions for each objective and attribute. While the DM and SHs need not agree on the structure of the hierarchy, it greatly simplifies the analysis if consensus can be reached.

Quantifiable Performance Measure (QPM): Specify the extent to which an option satisfies an attribute by reporting the level of performance of each option with associated uncertainty. QPMs are developed by first examining the attributes and then determining a set of appropriate metrics to measure each QPM. Once these metrics are established, the range of performance that any reasonable decision option might have is determined and then the relative desirability of different points in this range is assessed. This information is captured in a value function that takes on numbers between zero, for the least desirable performance level, and unity, for the most desirable (Pagan et al., 2004). The range of performance levels and the corresponding values form a constructed scale. The constructed scale can be continuous, with a unique desirability value for every possible performance level, or discrete, with one value corresponding to a range of possible levels. Constructed scales allow any metric to be measured in terms of a common unit and they capture risk aversion to different levels of performance.

A metric and its constructed scale form a QPM. QPMs can be based on quantitative metrics, such as a number of kg, or qualitative ones, such as a subjective understanding

Fig. 5. Steps in the Analytic Deliberative Process.

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of a degree of complexity. They must, however, be metrics for which a constructed scale can be developed. In cases where more than one QPM is used to evaluate a single attribute, QPMs are equally weighted to lead to a single score for the attribute.

In the context of the QPMs, the DM and the SHs must determine how relatively important each attribute is to achieving the overall goal. To capture these preferences, the Analytic Hierarchy Process (AHP) is used (Saaty, 2004). AHP requires each individual to make a series of pair-wise comparisons between attributes, and then objectives, saying which of the pair is more important to achieving the goal and then how much more important. The constructed scales are critical in providing the necessary context to make these comparisons. As an example, in the absence of context, if an individual is asked to compare safety with a monetary attribute, he or she will likely report that maintaining safety is extremely more important. The constructed scale, however, may reveal that the maximum consequences to safety are minor while the maximum consequences to the monetary attribute are extreme. With this context, the individual may weigh the two attributes differently.

Results from pair-wise comparisons lead to a series of person-specific weights for the attributes. Consider two stakeholders and the objectives Reduce Cost and ~~optimal spacecraft performance~~. In context, SH_1 believes reducing cost and optimal spacecraft performance are equally important while SH_2 believes that optimal spacecraft performance is twice as important as reducing cost. The AHP process would result is the weights shown in Table 1. As these weights reveal fundamental differences in the way individuals perceive a decision problem, no attempt it made to reach consensus weights at this stage.

Analytic Hierarchy Process results in a set of person specific weights, w_i, for the attributes that indicate the relative importance of attribute i in the overall context of the decision problem. The weights across the entire set of attributes sum to unity. With all of this information collected, the objectives hierarchy is fully specified and the ADP process proceeds to its third step in which decision options are identified.

In the fourth ADP step, each of the decision options is scored according to the set of QPMs. Appropriate modeling and analysis is conducted and combined with the expert opinion of the participants so that the level of performance of each decision option is understood as well as possible. The constructed scales are then used to determine the corresponding value of this performance. Uncertainty in performance levels can be tracked rigorously as each decision option may lead to a distribution of possible values, not just a single point value. In general, this step of ADP is the most time consuming and resource intensive as it is the point where external tools are used to study the decision options. These may include computer modeling and simulation, physical experiments or extensive literature review.

In the final step of ADP, the DM and the SHs select a decision option using a deliberative process. To facilitate deliberation, a preliminary ranking of decision options is produced. Options are ranked according to a Performance Index (PI). The PI for option j is defined as the sum of the values, v_{ij}, associated with the QPMs for attribute i weighted by the AHP determined weight for that attribute, w_i as shown in Eq. (1).

$$\mathrm{PI}_j = \sum_{i=1}^{N_{\mathrm{QPM}}} w_i v_{ij} \tag{1}$$

The decision options can then be ranked according to their expected PIs and the effect of performance uncertainty can be shown. The DM and the SHs each review their individual PIs to understand how the current state of knowledge about the decision options and their individual preferences for the attributes affect the decision problem. Deliberations between individual SHs and DM over their rankings lead to a collective decision. Though ADP may not always identify one best decision, it separates out the components of the decision-making process, hence facilitating a consensus between the decision maker and the stakeholder (Stamatelatos et al., 2006).

In the next sections, the authors propose an objectives hierarchy of the decision to Design-for-Demise over the other post mission disposal options.

3.1. Post mission disposal decision-making

NASA Technical Standard 8719.14—Process for Limiting Orbital Debris (NASA, 2012) requires retiring of a space mission at the end of mission lifetime through atmospheric reentry, maneuvering to a storage orbit, or direct retrieval. Three post mission disposal options are available via the reentry method:

(i) Demisable uncontrolled reentry.
(ii) Controlled reentry.
(iii) Non-demisable uncontrolled reentry with reentry requirements waiver.

This investigation will elaborate on the use of ADP in characterizing the 'demisable uncontrolled reentry' option

Table 1 Q7

Attribute	SH_1	SH_2
Reduce cost	0.5	0.25
Optimal spacecraft performance	0.5	0.75

~~[a]The AHP weighting process.~~

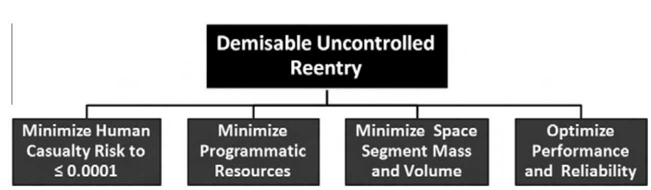

Fig. 7. Demisable uncontrolled reentry goal and objectives.

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since it involves DfD in order to meet NASA post mission disposal requirements. Specifically, the investigators shall dwell on the 'Analysis' phase of the ADP methodology.

3.2. Design-for-Demise ~~objectives hierarchy~~

To achieve the 'demisable uncontrolled reentry' goal for a LEO reentry mission, four objectives have been identified as shown in Fig. 7.

(I) Minimize ~~human casualty risk~~ to ⩽0.0001

As stipulated in NASA Earth atmospheric reentry requirements; during uncontrolled reentry, human casualty risk should be less than or equal to 0.0001. It is therefore assumed that a risk of 0.0001 per mission is the maximum allowed risk but that there may be additional benefit to further reducing the risk.

(II) Minimize ~~programmatic resources~~

Mission programmatic resources are always finite and limited, hence the objective to minimize them while pursuing a demisable space mission.

(III) Minimize ~~space segment mass~~ and ~~volume~~

This objective will not only have far-reaching consequences in the design and on-orbit operation of the spacecraft; but also on the mission as a whole.

(IV) Optimize ~~performance~~ and ~~reliability~~

Mission performance and reliability should not be relatively suppressed compared to a controlled reentry design option or to the stipulated requirements while in pursuit of designing demisable mission.

After identifying the Objectives above, their associated ~~attributes~~ and QPMs are investigated next. In the QPMs analyses, the values of consequence lie between 0 and 1; the value 1 represents the most desirable performance level while 0 represents the least desirable performance level.

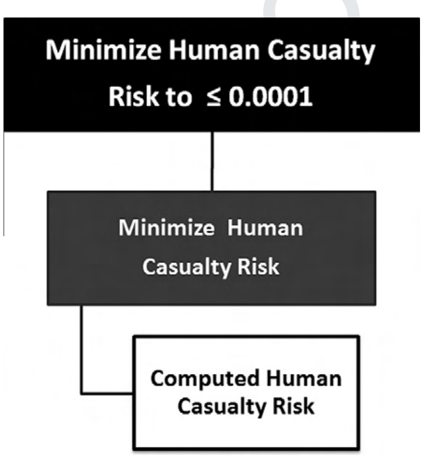

Fig. 8. Minimize human casualty risk objectives hierarchy.

3.2.1. Minimize ~~human casualty risk~~ to ⩽0.0001

One attribute that minimizes the human casualty risk is identified. This attribute along with the associated QPM is shown in Fig. 8.

(a) Minimize ~~human casualty risk~~

The ~~human casualty risk~~ is evaluated from Total Debris Casualty Area (DCA) of a reentering spacecraft and an interpolated population density along the spacecraft ground track. Population density is obtained from a progressive global population database that gives the average population per km^2 under a spacecraft as a function of inclination and year of entry. The number of people ~~optimal spacecraft performance~~ (Opiela and Matney, 2003).

DCA for a piece of surviving debris is the average debris cross-sectional area plus a factor for the cross-section of a standing individual. Consequently the Total Debris Casualty Area is the sum of the debris casualty areas for all individual reentry surviving objects as computed in Eq. (2) (NASA, 2012).

$$D_A = \sum_{i=1}^{N} (0.6 + \sqrt{A_i})^2 \tag{2}$$

0.6 = square root of average cross-sectional area of a standing individual viewed from above which is taken to be 0.36 m^2.

Eq. (3) is hence employed to compute the risk of hitting someone on the ground (Dobarco-Otero et al., 2003; Opiela and Matney, 2003).

$$\text{Casualty Expectation} = \text{Population Density} \times \text{Casualty Area} \tag{3}$$

The probability (i.e., 'one in N', or '1:N') of a surviving object striking a person is the reciprocal of the casualty expectation.

Therefore, the measurable consequence identified as QPM will be:

- Computed ~~human casualty risk;~~ The two extreme performance levels will be determined from the inequalities involving the calculated risk value. The lower value will be zero which corresponds to ~~human casualty risk~~ >0.0001. The higher value 1 corresponds to a ~~human casualty risk~~ ⩽0.0001. This is a binary switch independent from to values between the 0–1 range.

3.2.2. Minimize ~~programmatic resources~~

Three identified attributes that minimize programmatic resources and corresponding QPMs are schematically shown in Fig. 9.

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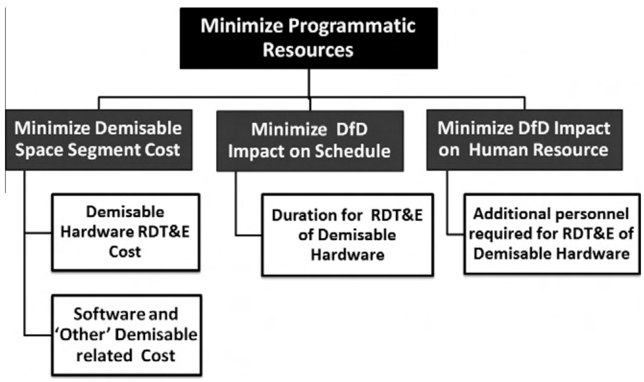

Fig. 9. Minimize programmatic resources objectives hierarchy.

(a) Minimizing space segment cost

Two QPMs are identified for this attribute. A linear interpolation determines the values of consequence within the QPM 0–1 value range.

- Demisable hardware Research Development Testing & Evaluation (RDT&E) cost: Demisable hardware RDT&E costs are additional costs incurred by the project solely due to the development of demisable hardware. The demisability RDT&E range of consequence will vary from 0 to 1. The value 0 corresponds to the assigned but undesired highest possible cost while 1 corresponds to desired lowest cost as determined by the project management. Moreover, the project management can determine the demisability RDT&E cost as a relative function of the entire project RDT&E cost, e.g. acceptable highest demisability RDT&E costs can be limited to $\leqslant$0.05% of the project cost.
- Software plus 'other' demisability related costs: This QPM captures any software reconfigurations and other non-hardware related demisability costs. Similarly, the range of consequence will vary from 0 to 1 corresponding to limits set by the project management.

(b) Minimizing Design-for-Demise impact on project schedule

To minimize DfD impact on project schedule the QPM identified considers the additional time required to exclusively develop and qualify the demisability capability within the space segment.

- Duration of RDT&E of demisable hardware: The range of consequence will be from 0 to 1 corresponding to the durations set by the project management as highest and lowest acceptable RDT&E durations respectively. For instance, the project management may limit the demisability RDT&E period to 10% of the entire mission RDT&E duration.

(c) Minimizing Design-for-Demise impact on human resource

The measurable consequence identified is the additional human resource required solely for redesigning parts of the space segment to demise.

- Additional demisability RDT&E personnel: The range of consequence will be from 0 to 1 corresponding to the demisability RDT&E expertise personnel determined by the project management as the highest and lowest possible acceptable respectively. For instance, the project management may limit additional demisability RDT&E personnel to $\leqslant$7 individuals.

3.2.3. Minimize ~~space segment mass~~ and ~~volume~~

Two attributes and corresponding QPMs identified to minimize space segment mass and volume are schematically given in Fig. 10.

(a) Minimizing spacecraft subsystem mass

To minimize the spacecraft subsystems mass, the measurable consequences (i.e., QPMs) will be the individual subsystem's mass. A total of eight individual subsystems are delineated for this attribute as shown in Fig. 10. To minimize subsystems mass, the range of consequence will

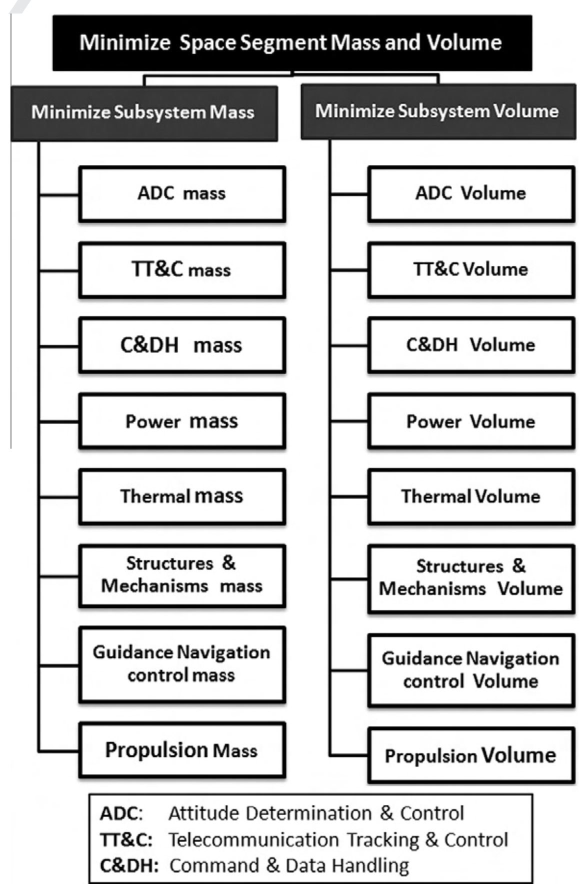

Fig. 10. Minimize space segment mass and volume hierarchy.

be from 0 to 1. For each individual subsystem, the lower value of consequence, 0, corresponds to the highest acceptable subsystem mass budget allocated by the project management. The higher level of consequence, 1, will correspond to the ideal desired (lowest) subsystem mass budget allocated by the project management.

(b) Minimizing spacecraft subsystem volume

A similar procedure to that describing minimization of the spacecraft subsystems mass attribute is followed in analyzing the 'minimize subsystem volume' hierarchy. The range of consequences for the subsystems volume performance levels are determined in a similar manner too. The range of consequence will be from 0 to 1. For each individual subsystem, the lower value of consequence, 0, corresponds to the highest acceptable subsystem volume budget allocated by the project management. The higher level of consequence, 1, will correspond to the ideal (lowest) subsystem volume budget allocated by the project management.

3.2.4. Optimize ~~performance~~ and ~~reliability~~

Mission space segment performance and reliability will individually constitute the attributes for this objective as schematically shown in Fig. 11, which includes the corresponding QPMs.

(a) Optimize performance

Three QPMs are identified for this attribute. A linear interpolation determines the values of consequence within the 0–1 range.

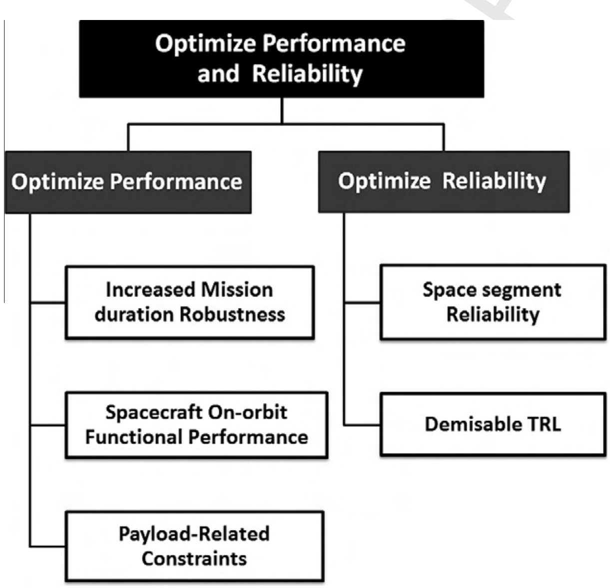

Fig. 11. Optimize performance and reliability objectives hierarchy.

- Increased mission duration robustness: This QPM addresses increased mission duration robustness introduced by designing a mission to demise compared to a controlled reentry mission. Most NASA missions e.g. CGRO, have a zero-fault tolerance after an initial failure in the controlled reentry subsystem. Consequently, this leads to premature mission termination in order to guarantee a successful controlled atmospheric reentry. On the contrary, a demisable spacecraft is relatively independent of such constraints; hence robustness to last the intended mission lifetime is vastly improved. The range of consequence will be from 0 to 1. The lower value 0 corresponds to the lowest empirically predicted Mean Time To Failure (MTTF) of the controlled reentry subsystem given by Eq. (4)

$$\mathrm{MTTF} = \int_0^\infty R_c(t)dt \tag{4}$$

and

$$R_c(t) = e^{\lambda t} \tag{5}$$

The higher value 1 will correspond to the planned mission lifetime. Values within the 0–1 range of consequence correspond to the respective MTTF's resulting from alternate components and system configurations. Since a demisable mission excludes a controlled reentry subsystem, the QPM in this case will always be equal to 1.

- Spacecraft on-orbit functional performance: Re-designing the space segment for demise involves design alterations that may influence normal spacecraft on-orbit functional performance relative to a non-demisable mission. For example, a demisable attitude and propulsion subsystem may affect the spacecraft slew rate, range, pointing accuracy, and settling time; a demisable power subsystem may affect energy storage capacity and efficiency; a demisable structure and mechanisms subsystem may affect the subsystem moment of inertia, bending strength, stiffness, and mechanisms reliability. The range of consequence will be from 0 to 1. The lower value of 0 corresponds to the unacceptable performance of the specific subsystem as determined from the project performance requirements. The higher value of 1 will correspond to the ideal performance of the specific subsystem as determined from the project performance requirements.
- Payload-related constraints: Constraints due the design of a demisable payload can influence mission objective performance in a number of ways. For example, to achieve demisability the size (mass and volume) of the payload may be reduced which may prohibitively impinge on the performance of executing mission objectives. Consequently, an alternative, but lower performing demisable payload may be necessary, and so on. The range of consequence will be from 0 to 1. The lower

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value of 0 corresponds to the unacceptable performance as determined from the payload performance requirements. The higher value 1 will correspond to the ideal performance as determined from the payload performance requirements. A linear interpolation determines the values of consequence within the 0–1 range.

(b) Optimize reliability

Two QPMs are identified for this attribute and the values between 0–1 range determined by a linear interpolation..

- Space segment reliability: This is the computed space segment reliability $R_s(t)$ whose range of consequence will be from 0 to 1. No performance level inference or interpolation is necessary since the $R_s(t)$ values seamlessly confirm to the adopted QPM metric criteria.
- Demisable technology readiness level: The NASA TRL definition (Mankins, 1995) is followed. The range of consequence will be from 0 to 1. The lower value of 0 corresponds to TRL level 1. The higher level of consequence, 1, will correspond to TRL level 9. Similarly, a linear interpolation determines the values of consequence within the 0–1 range, e.g. TRL = 8 and TRL = 3 will yield values equal to 0.875 and 0.25 respectively.

4. Conclusion

The United States Government, NASA and other leading global players in the space arena have made commitments on limiting new orbital debris and ensure acceptable human casualty risk from reentering space debris. Due to these obligations, designing spacecraft destined for uncontrolled atmospheric reentry to demise is highly likely to provide a cost-effective solution to this challenge because it excludes provision for controlled reentry subsystem.

Moreover, DfD would introduce a post-mission disposal paradigm shift in the design of space missions passing through LEO in order to exploit the associated mission simplification. *Ad hoc* implementation of DfD practices especially during later stages of mission formulation is apparent in the traditional NASA DfD execution. This is chiefly attributed to DfD not being initially entrenched as a mission design driver.

The authors presented a more comprehensive DfD phase-by-phase implementation strategy in the mission life cycle that facilitates a comprehensive DfD execution. The strategy shown in Fig. 4 outlined how to implement the intentional redesigning of the spacecraft parts in order to make them demisable in a given phase of the mission lifecycle. This plan will facilitate continuous thorough integration of DfD practices in mission formulation and implementation.

The Analytical Deliberative Process facilitates a risk informed decision-making approach to deciding whether to design a LEO reentry mission to demise or opt to integrate controlled reentry capability. This process facilitates consensus building by bringing together all the DMs, SMEs and SHs. The authors identified the DfD ~~objectives hierarchy~~ and ~~attributes~~. As a final step in the 'Analysis' phase of the ADP framework, QPMs were formulated and the authors detailed how to compute the values corresponding to different performance levels of consequences.

It is important to reiterate that the ADP does not produce one best decision, rather it is designed to separate out the components of the decision making process so that the DM and SHs can reach consensus. The ADP clearly separates the issue of uncertainty in the performance of a decision alternative from variation in the preferences of individuals. The ADP is typically used to show each participant how his or her rankings of alternatives change if preferences are changed or if postulated option performance changes. The DM and SHs can then focus their efforts around only those issues that have high impact on the decision. They might decide to conduct additional modeling to better understand option performance and reduce uncertainty, they might reconcile their preferences or they might find an obvious optimal decision.

Presently, NASA handles demisability as a means of satisfying the requirement to guarantee ground safety within the framework of orbital debris mitigation. Despite this being a crucial undertaking, additional merits associated with DfD do exist that warrant it to be applied in a much broader framework. Furthermore, the NASA Earth reentry requirements need to be extended to include other non-NASA sanctioned missions like LEO commercial communication satellites, military satellites and launch vehicle upper stages.

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