Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Computer Science 00 (2014) 000–000

Procedia Computer Science

www.elsevier.com/locate/procedia

Conference on Systems Engineering Research (CSER 2014)

Eds.: Azad M. Madni, University of Southern California; Barry Boehm, University of Southern California; Michael Sievers, Jet Propulsion Laboratory; Marilee Wheaton, The Aerospace Corporation
Redondo Beach, CA, March 21-22, 2014

Design for Affordability in Complex Systems and Programs Using Tradespace-based Affordability Analysis

Marcus Shihong Wu*, Adam M. Ross and Donna H. Rhodes

Systems Engineering Advancement Research Initiative (SEAri), Massachusetts Institute of Technology, Cambridge, MA.

Abstract

With growing emphasis on affordability, the conceptual design of complex systems and programs is no longer confined to maximizing technical performance, but also to minimizing cost and schedule related attributes. By defining affordability as the property of becoming or remaining feasible relative to resource needs and resource constraints over time, Multi-Attribute Tradespace Exploration and Epoch-Era Analysis can be used to find affordable solutions. Single-epoch, multi-epoch and single-era analysis were conducted for a Space Tug program case study to demonstrate the application of these tradespace-based methods and a design with the best tradeoffs among performance, cost and schedule factors was obtained.

© 2014 The Authors. Published by Elsevier B.V.
Selection and peer-review under responsibility of the University of Southern California.

Keywords: affordability; systems engineering; tradespace exploration; utility; expense; epoch; era

* Corresponding author. Tel.:+1-917-982-4951.
E-mail address: marcuswu@mit.edu

1877-0509 © 2014 The Authors. Published by Elsevier B.V.
Selection and peer-review under responsibility of the University of Southern California.

1. Introduction and Background

As the architecting of complex engineering systems faces much uncertainty with respect to their dynamic operating contexts and the evolving needs of stakeholders, conceptual design formulation and system development are often subjected to multiple revisions that lead to unanticipated delays and changes in technical specifications. The accumulation of these outcomes often leads to rising costs and schedule slippages, which can eventually compromise the success of the system or program in development. High-profile failures in system and program delivery in the last decade, especially in the defense and aerospace industry, have resulted in a paradigm shift in systems architecting and acquisition. Performance is no longer regarded as *sine qua non*, and simulation of complexity in these systems and programs often require considerations and analysis beyond a single cost attribute[1]. This has necessitated the need to additionally account for multiple cost and schedule parameters elicited from stakeholders during early-phase design. This emerging paradigm in systems engineering is the *design for affordability*[2,3], where systems and programs are architected to satisfy multiple performance, cost and schedule needs of stakeholders. Affordability has thus emerged as a high priority ility that directs the early stage design process towards developing systems with greater cost effectiveness and schedule effectiveness.

1.1. Establishing the Current Affordability Paradigm

Affordability became prominent within systems engineering semantics after the recent issuance of defense memorandums that "mandated affordability as a requirement" for future defense acquisitions[2,3]. Since then, many attempts have been made to propose frameworks for affordability analysis[1,4,5], and integrate them with existing systems engineering methods to generate affordable design solutions. With the push for "designing for affordability as a requirement*"* in acquisition management, various systems engineering approaches have been taken to better design systems or programs that are more manageable under explicit cost, schedule and performance considerations. Quantitative methods like lifecycle cost decomposition[1], probabilistic interval schedule and cost estimation[4], and plotting of Sand Charts[5] have been used alongside numerous visualization tools to quantify affordability during the systems architecting process.

However, current processes for performing early lifecycle affordability tradeoffs remain under-developed. Affordability tradeoffs have been limited to static tradeoffs of systems between performance and costs in current operating environments, or in single point futures. There is also a lack of a consensual definition and a set of guiding principles for affordability within the systems engineering community. This gap in knowledge about the meaning and implications of pursuing affordability has resulted in the variety of approaches currently in existence, with few being able to explicitly capture the dynamic elements of the system or program and its operating environment over its lifecycle. A common definition and a common set of principles for affordability can integrate approaches taken by the government, industry and academia into a concerted effort for reducing overall system or program costs and schedule slippages. Given that systems and programs exist in a dynamic and uncertain world, designing for affordability not only necessitates new methods capable of evaluating them across many possible alternative futures, but also a new philosophy for treating the affordability paradigm.

1.2. Defining Affordability as an Ility

The systems engineering discipline has been advanced through the use of non-traditional design criteria called "ilities"[6], which are system properties that often manifest and determine value after a system is put into initial use. Ilities concern wider impacts with respect to time and stakeholders and can better promote the development of successful systems as compared to solely technical criteria. Commonly known ilities such as survivability[7] and evolvability[8] have already been defined in many engineering fields and their inclusion in the design process often leads to desirable outcomes. Affordability can thus be treated as an ility that drives the design of more affordable yet technically sound architectures. With affordability as an ility, advanced systems engineering methods like *tradespace exploration* can be applied in the enumeration, evaluation, identification and selection of affordable designs.

In this paper, affordability is defined as *the property of becoming or remaining feasible relative to resource needs and resource constraints over time*. This property can be applied to any entity, be it a system or a program, with the latter warranting a higher degree of complexity and more attributes and resources for consideration. A resource may be defined as the aggregation of cost, schedule and other non-monetary factors necessary for architecting, development and operation. Resource needs are the set of resource requirements elicited from stakeholders, and resource constraints are the statements of restrictions on these requirements that limit the range of feasible solutions. As these entities and their operating contexts may be dynamic, resource needs and resource constraints may change over time. Consequently, architectural solutions for these entities become feasible if they fulfill resource needs and function within the resource constraints for a fixed context. As contexts change, these entities may remain in, enter, or exit the feasible set of solutions. Affordable solutions are thus those that remain in or enter the feasible set of solutions. Therefore, the general goal of affordability analysis is to identify solutions that remain feasible throughout or for a large part of the system lifecycle. Using this operationalization, an affordable solution will be one that is capable of satisfying changing resource requirements and resource constraints over the system lifecycle.

2. Performing Affordability Analysis using Tradespace-based Methods

To conduct affordability analysis and perform affordability tradeoffs during conceptual design, methods for systems engineering tradeoff analysis are required to demonstrate changes in resource expenses as major decision parameters and times to completion are varied. The minimization of resource expenses, while maintaining or increasing performance specifications across changing contexts over time, motivates the construction of tradespaces with considerations of temporality. Leveraging the increased availability of computation power, affordability analysis can be conducted through *tradespace exploration*, which is the model-based investigation of many design alternatives in order to find better design solutions, while avoiding premature fixation on point designs and narrow requirements[9]. Tradespace exploration allows a holistic consideration of capabilities and mission utility during early-phase design, instead of being locked too early into requirements and key performance parameters. As tradespace exploration entails the enumeration and evaluation of a large number of potential designs, this method is most relevant to the design of complex engineering systems with multiple dimensions of benefits and expenses, which are often difficult to optimize and rarely intuitive[9]. The use of tradespaces instead of simple tradeoffs of several point designs can thus lead to better lifecycle results for the system or program of interest.

As tradespace exploration enables the promulgation of affordability as an ility, this paper's goal is to introduce tradespace-based methods for designing for affordability in systems or programs. With complex engineering systems as the target application, *Multi-Attribute Tradespace Exploration (MATE)*[10] can be used in the value-driven search for affordable designs by aggregating multiple dimensions of benefits into a single utility metric. Tradespaces have been traditionally viewed as two-dimensional plots bounded by the parameters of utility and costs, representing the high level tradeoff of "what you put in" (i.e. cost) and "what you get out" (i.e. utility). Since this paper is interested in more than just cost, there is a need to replace "cost" with a more general aggregate measure for resource expenses to enable affordability analysis. The *Multi-Attribute Expense (MAE)*[11] function can be used to aggregate cost, schedule and other non-monetary factors into a single expense metric. Finally, to account for how the performance, cost and schedule attributes of a system or program evolve over time across dynamic operating environments, *Epoch-Era Analysis (EEA)*[12] will be used. EEA is a design approach used to clarify the impacts of time and context on the value of the system or a program, and can be modified and applied to enable affordability analysis over multiple epochs (periods of fixed contexts) and multiple eras (ordered sequences of epochs).

2.1. Multi-Attribute Tradespace Exploration (MATE)

MATE will be used to begin the affordability analysis and it begins with the establishment of design variables (factors within the designer's control that will drive the attributes), and epoch variables (factors that parameterize uncertain potential operating contexts). At this stage, design-to-value mapping of performance, as well as cost and schedule parameters, is conducted. Both design and epoch variables are combined under logical assumptions and scientific principles to produce a tradespace model that will evaluate potential designs in different epochs in terms of

attributes (including performance, cost, and schedule). Each attribute delivers a unique independent utility and can be combined with other attributes to produce an overall utility for a design. MATE often uses a multi-attribute utility (MAU) function to aggregate, which combines different single performance attribute utilities, ranging from 0 to 1, with 0 defined as minimally acceptable and 1 as the point where no further benefit is gained. The MAU function can be a linear weighted sum if the attributes are independently contributing to the aggregate utility. Similarly, each expense attribute can be defined and then combined in the same manner using the MAE function. Fig 1 is the modified MATE method for affordability analysis.

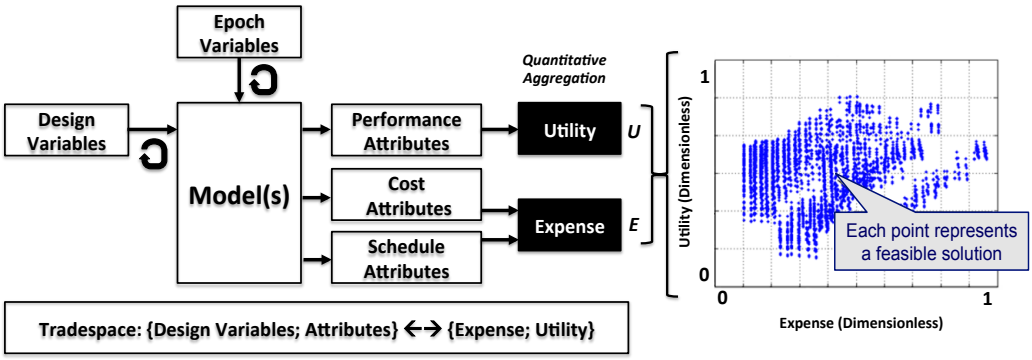

Fig. 1. Multi-Attribute Tradespace Exploration data flow for affordability analysis.

2.2. Multi-Attribute Expense (MAE)

Designing for affordability requires the consideration of both cost and schedule parameters. However, temporal considerations like schedule and other non-monetary factors are often difficult to represent in dollars. Additionally, different 'colors' of money may be spent with differing degrees of ease and all of these different expenses may have different levels of acceptability to stakeholders just like performance attributes. The MAE function is formulated similarly to a MAU function proposed by Keeney and Raiffa[13], with the utility function replaced by an expense function $E(X)$. Using the MAE function allows the aggregation of these different types of dollar budgets, and it first involves the determination of the single-attribute expense curves E_i and their respective multi-dimensional weighting factors k_i. N represents the number of attributes and K is a multiplicative constant for normalization.

$$KE(X) + 1 = \prod_{i=1}^{N}[Kk_iE_i(X_i) + 1] \quad (1)$$

The notion of expense is akin to the notion of negative utility. Quantified on a 0 to 1 scale, an expense level of 1 denotes complete dissatisfaction and an expense level of 0 denotes minimal dissatisfaction. A rational stakeholder will typically demand maximal utility and minimal expense in an ideal design. Like MAU, an MAE function requires careful construction through stakeholder interviews to elicit informed responses and aggregate preferences to capture articulated value. Since MAE is a dimensionless, non-ratio scale metric, an entity with twice the MAE number over another does not imply that it is twice as expensive in terms of monetary value. Since temporal elements have extensive leverage on the different 'colors' of money[14], the MAE can be extended to affordability applications in system and program design. Instead of simply comparing monetary costs against utility, MATE can be modified to compare MAE against MAU in order to perform affordability-driven analysis.

2.3. Utility and Expense Constraint Levels

After establishing the tradespace bounded by MAE and MAU, external constraints that are independent of stakeholder's preferences can be reflected as *constraint levels*. As a rational stakeholder's true preferences, especially towards expense, are often higher than any externally imposed restrictions such as maximum budget or fixed deadlines, constraints and preferences have to be considered separately. Setting a stakeholder's minimum

preference level at the constraint value without the use of additional constraint levels will make it difficult to determine what designs have become unaffordable due to changes in resource constraints since they will not be reflected in the tradespace. Furthermore, stakeholders may not be aware of these constraints initially and they establish their own preferences without knowledge of the environment. It is also likely that even if a stakeholder sets preference levels according to the external constraint, the latter may change due to volatility in mission or budgetary requirements. Therefore, applying constraint level and making a distinction between constraints and preferences enables a realistic depiction of the relationship between stakeholders and their environment.

Shown in Fig 2, *constraint levels* for *minimum utility* and *maximum expense* can represent the minimum required performance levels and maximum budget respectively that are imposed as constraints by external sources. If no external constraints are available, the default value will be an acceptable preference level specified by the stakeholders. These can be calculated by first setting the constraints on individual performance and expense attributes. The minimum constraint level for expense can then be obtained by the intersection between the minimum utility constraint level and the design point with the minimum expense on the tradespace. The vertical line through this design is referred to as the *derived minimum expected expense constraint level*. The two points at the corners of the affordable solution region are actual evaluated design points in the solution space. The affordable solution region is thus the intersection of the possible solution space and the area bounded by the planes representing the minimum utility, the derived minimum expected expense and the maximum expense constraint levels. An "affordable" solution then will be any solution that falls within the affordable solution space.

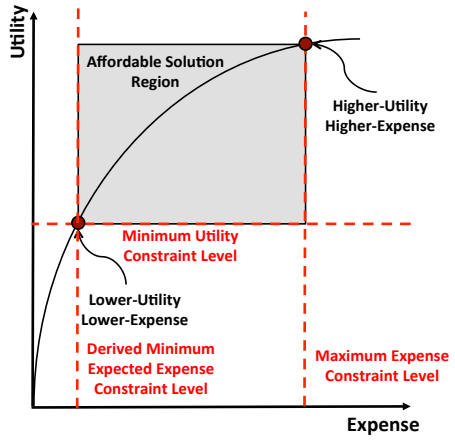

Fig. 2. Defining the affordable solution space using external constraint levels for a fixed context.

2.4. Epoch-Era Analysis (EEA)

EEA discretizes the lifecycle according to impactful changes in the operating environment, stakeholders, or the system itself, through the constructs *epochs* and *eras*, instead of traditional system milestones. Epochs are time periods defined by a fixed set of epoch variables describing the context in which the system operates, and when assembled into ordered sequences, epochs form eras that describe a potential progression of contexts over time. This framework provides an intuitive base upon which to perform analysis of value delivery over time for systems under the effects of changing circumstances and operating conditions. This is an important step to take when evaluating large-scale engineering systems with long lifespans. EEA can be used in conjunction with MATE during conceptual system design, allowing for the evaluation and comparison of the value-over-time of many different potential designs across different operating contexts. For affordability analysis, EEA can be modified to assess the temporal progression of a system as resource needs and contexts change so as to adopt a more resource-centric approach to evaluating system design concepts. Fig. 3a and 3b are the original EEA diagram and the modified version for affordability analysis respectively. In both figures, the vertical columns represent the epochs that are time-ordered to

form an era, while different colors of these epochs represent changes in context. Changes to the original EEA are reflected in Fig. 3b, where the vertical axis has been modified to measure resource needs rather than performance needs, and the bounded regions now represent affordable regions instead of expectation levels. The horizontal bands are the constraint levels illustrated in Fig. 2 and they represent the minimum resource needs and maximum allowance resource needs levels for that epoch. Affordable regions can change independently of one another as shown by the different horizontal bands.

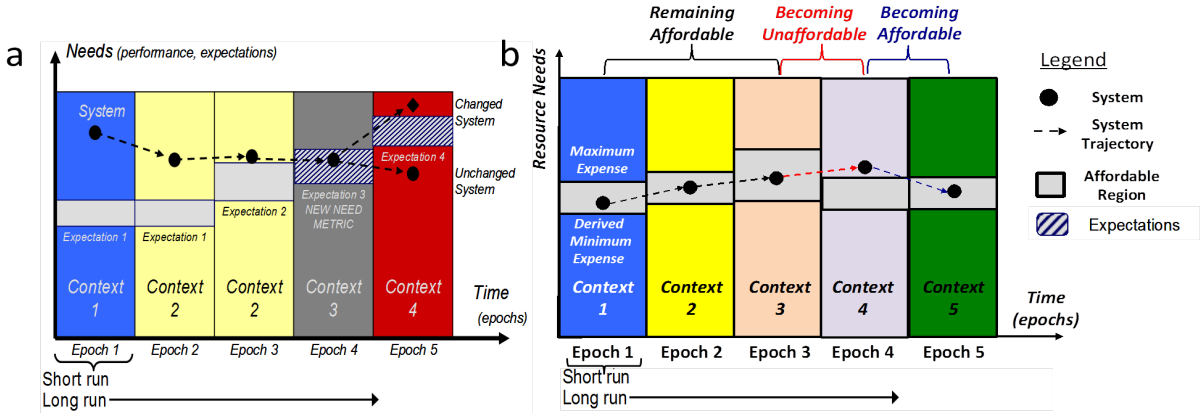

Fig. 3. (a) Original Epoch-Era Analysis Diagram[12]; (b) Modified Epoch-Era Analysis diagram for Affordability Analysis.

The trajectory of the system over time in Fig. 3b can be interpreted in the following manner: as the system traverses through the first 3 epochs while staying within the affordable region unique to each epoch, the system is *remaining affordable*. In the transition to Epoch 4, the system has now exceeded the maximum constraint level of the affordable region, thus *becoming unaffordable* by the end of the epoch. Finally, the system transits back to the affordable region in Epoch 5 and is said to be *becoming affordable*. The system state transitions of remaining affordable and becoming affordable are thus illustrated in the EEA diagram modified for affordability analysis. Therefore, MATE, MAE and EEA can be combined to establish a tradespace-based method for affordability analysis and facilitate the search for design solutions that can remain affordable across a range of alternative futures. By explicitly accounting for cost, schedule and performance requirements over time, the method is able to account for system changes due to shifts and perturbations, manage lifecycle differences between subsystem components, evaluate feedback, and be adaptive to evolving system behaviors. As affordability is a concept evaluated over time, such a method can provide structured options for improvement to enable enhanced design for affordability.

3. Application of tradespace-based methods to conduct affordability analysis for a Space Tug program

To demonstrate how affordability analysis can be conducted using these methods, a simple case study involving the design of a Space Tug program is now presented. The Space Tug is a single general-purpose space transportation vehicle designed to transfer space systems between orbits[15]. Described by McManus and Schuman[15], a single Space Tug system is parameterized by three design variables: manipulator capability, propulsion type, and fuel mass. Manipulator capability can be low, medium, high or extreme; propulsion type can be storable bipropellant, cryogenic, electric or nuclear; and propellant mass can be 30, 100, 300, 600, 1200, 3000, 10000 or 30000kg. There are 128 possible designs for a single Space Tug system. A Space Tug program consists of combined development and launch of two (possibly different) systems to achieve in a more complex mission. The program-level was chosen over the system-level for this demonstration due to its higher degree of complexity to reflect a broader set of affordability considerations. This serves as a preliminary demonstration of how the additional inclusion of cost and schedule parameters influence the spatial distribution of design points, and how tradespaces can become reflective of performance, cost and schedule considerations of importance to the stakeholders of a complex engineering project. MATE was conducted for the Space Tug program, with the MAE function used to calculate expenses of alternative programs. Epochs were then constructed for EEA.

3.1. Generating tradespaces for a Space Tug program with affordability considerations

The Space Tug program has five performance attributes: program mass capability, program delta-V, program transfer speed, probability of success, and mission time. As mass capability of a single vehicle is a function of vehicle manipulator capability, the program mass capability is the lower of the two values for the two Space Tugs, so that the program is able to fulfill at least the minimum requirement or better. Delta V of a single vehicle is a function of the vehicle mass and specific impulse. Similar to mass capability, the program delta V is also the lower of the two system values. Transfer speed is the measure of how fast a vehicle can transfer between orbits and it can either be fast or slow as a result of propulsion type. With two tugs, the program transfer speed can exist in four combinations: Slow/Slow, Slow/Fast, Fast/Slow, Fast/Fast. Each tug can have different reliability levels and orbit locations, which are introduced as new design variables to the Space Tug program model. The probability of success is calculated as the product of probabilities for each tug based on reliability level, which can be in Low/Low, Low/High, High/Low, High/High configurations. The last performance attribute, mission time, is the duration taken to perform the mission. It can be long or short, which is indirectly dependent on orbit location. Each vehicle can be orbiting in low earth orbit (LEO) or geostationary earth orbit (GEO). The location combinations for the two vehicles can be LEO/LEO, LEO/GEO, GEO/LEO or GEO/GEO. If the two vehicles are in the same orbit, they can be launched at the same time on the same launch vehicle and can perform the mission quickly. If they have different orbits and different launch times, only one vehicle can be launched first and this hampers the speed at which the mission can be conducted.

The three expense attributes are program development cost (PDC), program launch cost (PLC) and program development schedule (PDS). The PDC is simply the sum of development costs for the two vehicles, which is the total cost required to develop the hardware of the Space Tug and is calculated as a function of dry mass. The PLC can either be the sum of launch costs of individual vehicles if they are launched to different orbits on separate launch vehicles, or two-thirds of the sum if they are launched to the same orbit on a single launch vehicle. The launch cost of a single vehicle is a function of the wet and dry masses of a vehicle. The PDS will be the higher of the development schedules of the two vehicles if they are launched to the same orbit on a single launch vehicle, or the lower of the two if they are launched to different orbits on separate launch vehicles. The development schedule of a Space Tug increases with manipulator capability and complexity of propulsion type. For the purposes of EEA, 16 different epochs were constructed using 8 different preference sets and one context variable with 2 levels[16]. The context variable is the technology level, which can either be present or future levels and has bearings on the manipulator capabilities, propulsion type, development cost and development schedule.

3.2. Single-Epoch Affordability Analysis for a Space Tug Program

A single-epoch affordability analysis was first conducted for the Space Tug program. The MAE and MAU values of all designs in Epoch 1 were calculated and they form the tradespace of the Space Tug program shown in Fig. 4.

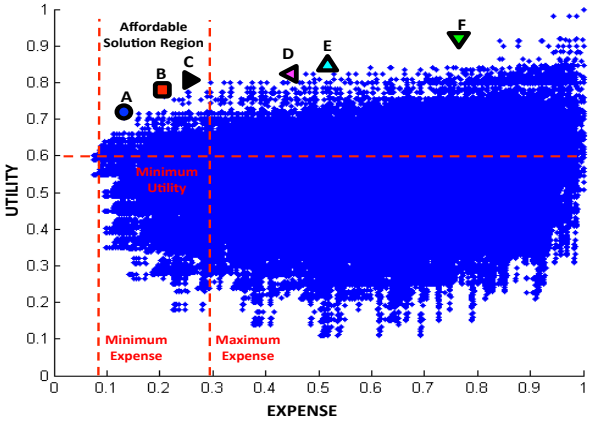

Fig. 4. Tradespace for a Space Tug program in Epoch 1. 6 designs along the Pareto front were chosen and labeled A to F.

To facilitate ease of analysis, six designs along the Pareto front were selected, which are labeled A to F in the direction of increasing expense alongside with their unique color and shape identifiers. Performance and resource attributes of the Space Tug program for these six are shown in Table 1. Commonalities among the designs include Fast/Fast program speed, short mission time, low mass program payloads and relatively short development schedules. Not reflected in Table 1 are that all designs are in LEO/LEO orbit and High/High reliability configurations. Large ranges of values for program Delta-V, PDC and PLC are observed as the designs chosen were spaced apart. Constraints for performance and resource attributes, which have values greater than minimum preference levels of stakeholders were established for Epoch 1, yielding values for the constraint levels on minimum utility and maximum expense, as well as the derived minimum expected expense for this particular epoch. As a first-pass analysis, constraint levels on performance attributes in Epoch 1 are set at values slightly lower than the attributes of Design A (see Table 1). Constraint levels on resource attributes are set at a multiplicative factor of 1.5-2 of the values for Design A. The resultant constraint level values for attributes are shown in Table 2. The constraint levels define the affordable solution region for Epoch 1 and are shown in Fig. 4. Designs A, B and C are affordable solutions within this epoch, while D, E, and F are not (they violate maximum expense constraint). Single-epoch analysis is straightforward after calculating the constraint levels and establishing the affordable solution space.

Table 1. Performance and Resource Attributes for Designs A to F in Epoch 1.

	Performance Attributes				*Resource Attributes*					
Design (Number)	Program Payload (*kg*)	Program Speed	Program Delta-V (ms^{-1})	Prob. Success	Mission Time	PDC (*$mil*)	PLC (*$mil*)	PDS (*mths*)	Utility	Expense
A (26836)	300	Fast/Fast	6147	0.96	Short	940.5	376.8	8	0.715	0.131
B (28900)	300	Fast/Fast	8091	0.96	Short	1805	808	8	0.774	0.208
C (59860)	300	Fast/Fast	12645	0.92	Short	2090	764	14	0.800	0.254
D (125908)	1000	Fast/Fast	8910	0.88	Short	3420	1212	28	0.823	0.448
E (127972)	1000	Fast/Fast	16150	0.88	Short	4750	1800	28	0.840	0.517
F (194020)	3000	Fast/Fast	10984	0.86	Short	8550	3080	42	0.915	0.763

3.3. Multi-Epoch and Single-Era Affordability Analysis for a Space Tug program

As programs operate in dynamic environments over their lifecycle, it is important to find out how the utility and expense of the program changes across multiple epochs. Multi-epoch analysis can be performed to find out how many epochs during which designs remain affordable. Epochs 1, 5, 6, 13 and 14 were chosen for multi-epoch analysis, as the expense preferences were most distinct from one another. Varying constraint levels for performance and resource attributes were chosen for each epoch, giving rise to different utility and expense constraint levels that yield different affordable solution regions. The constraint values and the resultant constraint levels are shown in Table 2.

Table 2. Performance and Resource Constraints for a Set of Epochs (sequenced as an Era) (Epochs 1,5,6,13,14)

	Performance Constraints				*Resource Constraints*				*Constraint Levels*		
Epoch	Program Payload (*kg*)	Program Speed	Program Delta-V (ms^{-1})	Prob. Success	Mission Time	PDC (*$mil*)	PLC (*$mil*)	PDS (*mths*)	Minimum Utility	Derived Minimum Expense	Maximum Expense
1	300	Fast/Fast	5500	0.95	Short	2000	500	12	0.605	0.087	0.294
5	300	Fast/Fast	7000	0.90	Short	3000	900	12	0.661	0.178	0.349
6	1000	Fast/Fast	4000	0.90	Short	4000	1000	12	0.576	0.293	0.389
13	300	Fast/Fast	6500	0.95	Short	5000	1200	24	0.643	0.079	0.583
14	1000	Fast/Fast	7000	0.90	Short	3000	1600	24	0.681	0.175	0.527

In a simple demonstration of multi-epoch analysis, the expenses of all designs across all epochs are studied. Fig. 5a shows that Designs A, B and C are affordable in most epochs, but only Design C is affordable in all 5 epochs. From Fig. 5b, all designs except for A are always above the minimum performance constraints across all epochs.

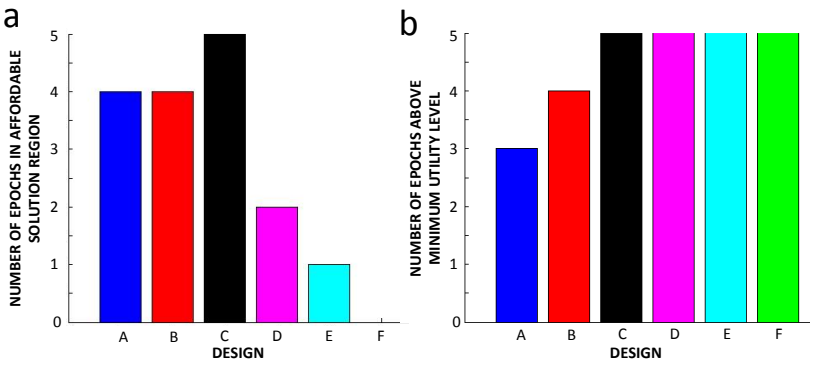

Fig. 5. (a) Number of epochs in affordable solution region for every design; (b) Number of epochs above minimum utility level for every design.

Multi-epoch analysis becomes single-era analysis when the epochs are viewed as an ordered sequence that fits the program lifecycle. Era analysis requires the tracing of both expense and utility trajectories of designs over the defined era. Tracing the trajectories of the design utilities over the era in Fig. 6b shows that Designs B to F always remain above the minimum utility constraint levels throughout the era and are thus possible candidates for the final design. However, the value of considering resources in addition to performance comes in tracing the expense trajectories for these designs. Fig. 6a shows that Designs A and B become unaffordable in the transition to Epoch 8, but becomes affordable again later in Epochs 13 and 14, while Designs D and E have only one instance of being affordable in Epoch 13. Design F is the most expensive and remains unaffordable throughout the era. As such, only Design C remains within the affordable solution regions across all ordered epochs and it is the most affordable solution in this constructed era.

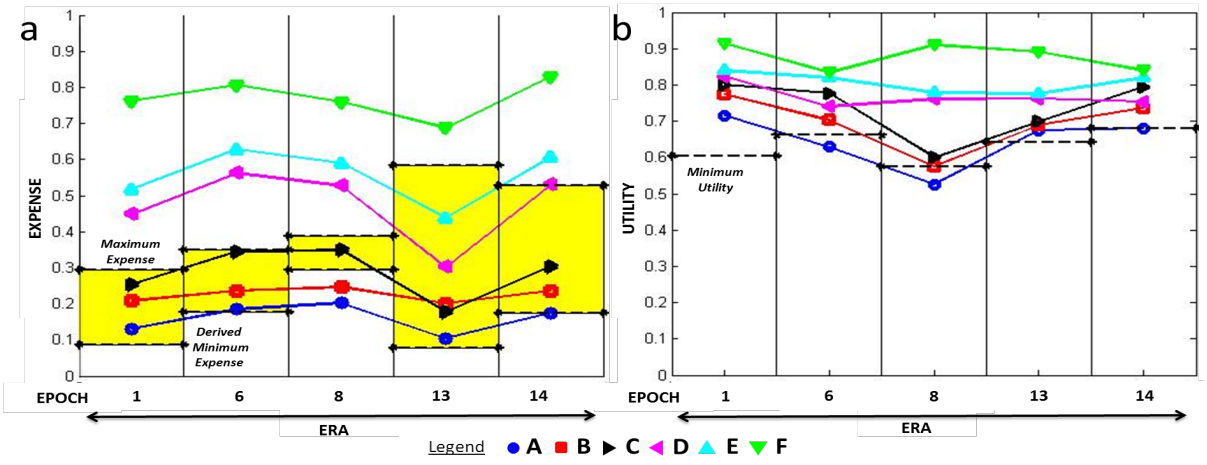

Fig. 6. (a) EEA with expense considerations in a single era; (b) EEA with utility considerations in a single era.

Combining the results from tracing both utility and expense trajectories, it can be seen that Design C (see Table 1) has the best tradeoffs among performance, cost and schedule attributes over time. Given its midrange values for all performance and expense attributes, Design C is indeed the most affordable solution that is always above the minimum utility constraint levels. It remains feasible relative to the resource needs and resource constraints over the era. Conducting affordability analysis using tradespace-based methods in the form of MATE and EEA thus facilitates a resource-centric approach in the down-selection and identification of affordable designs.

4. Discussion of Research Extensions

This paper has demonstrated how the added consideration of cost and schedule parameters, and the use of the MAE function and affordable solution regions in a tradespace, can facilitate the conduct of MATE and EEA for affordability analysis. As single-epoch, multi-epoch and single-era analysis were conducted, an obvious extension to this research is the conduct of multi-era analysis with different performance and expense attributes across different eras. Should systems architecting be conducted for multiple ilities, the notion of affordability can be combined with existing ilities like changeability[17] to yield "affordably changeable" designs. This requires a higher degree of complexity in affordability analysis, and usage of current tradespace-based metrics for measuring changeability. Affordability analysis can be extended to portfolios, which are multiple programs with different functionalities that may or may not be interacting together. Portfolio-level analysis will require additional cost, schedule and non-monetary factors like skill of labor force or subject matter expertise, which are characteristic of the development of multiple programs in concert. With many potential areas for research expansion, MATE, EEA and MAE can be used in the design for affordability to avoid cost overruns and schedule slippages in the long run.

Acknowledgements

The authors gratefully acknowledge funding for this research provided through MIT Systems Engineering Advancement Research Initiative (SEAri, http://seari.mit.edu), Skolkovo Institute of Science and Technology Strategic Innovation Research Group (SIRG), and its sponsors. This material is based upon work supported by the Naval Postgraduate School Acquisition Research Program under Grant No. N00244-12-1-0060.

References

1. Tuttle P and Bobinis J. Affordability Specification. Retrieved from http://www.mors.org/UserFiles/file/2012%20%20Meeting%20Affordabilty%20Analysis/Read%20Aheads/Affordability%20Specification%20MORS.pdf, 2012
2. Carter AB. Better buying power: Guidance for obtaining greater efficiency and productivity in defense spending [Memorandum]. Retrieved from http://www.acq.osd.mil/docs/USD_ATL_Guidance_Memo_September_14_2010_FINAL.PDF, 2010a.
3. Carter AB. Better buying power: Mandate for restoring affordability and productivity in defense spending [Memorandum]. Retrieved from http://mil-oss.org/resources/us-dod_policy-memo_carter-memo-on-defense-spending-28-jun 2010.pdf, 2010b.
4. Kroshl WM and Pandolfini PP. Affordability Analysis for DARPA Programs. *John Hopkins APL Digest*, Volume 21, Number 3 , 2000.
5. Emmons DL, Lobbia M, Radcliffe T, and Bitten RE. Affordability assessments to support strategic planning and decisions at NASA. *Aerospace Conference, 2010 IEEE*, vol., no., pp.1,13, 6-13 March 2010. doi: 10.1109/AERO.2010.5446893, 2010
6. de Weck OL, Ross, AM, and Rhodes DH. Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities). *3rd International Conference on Engineering Systems*, TU Delft, the Netherlands, June 2012.
7. Richards MG, Ross AM, Hastings DE, and Rhodes DH. Multi-Attribute Tradespace Exploration for Survivability. *7th Conference on Systems Engineering Research*. Loughborough University, UK, 2009.
8. Beesemyer JC. Empirically Characterizing Evolvability and Changeability in Engineering Systems. Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2012.
9. Ross AM and Hastings DE. The Tradespace Exploration Paradigm. *INCOSE International Symposium 2005*. Rochester, NY, 2005.
10. Ross AM, Hastings DE, Warmkessel JM, and Diller NP. Multi-Attribute Tradespace Exploration as a Front-End for Effective Space System Design. *AIAA Journal of Spacecraft and Rockets*, pp. 20-28, Jan/Feb 2004
11. Diller NP. Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements Engineering. S.M. Thesis. Massachusetts Institute of Technology. Cambridge, MA, 2002.
12. Ross AM, and Rhodes DH. Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis. *INCOSE International Symposium 2008*. Utrecht, the Netherlands, 2008.
13. Keeney RL and Raiffa H. *Decisions with Multiple Objectives-Preferences and Value Tradeoffs*. Cambridge, UK, Cambridge University Press, 1993.
14. Wiggins S. The Federal Budgeting Process and The Color of Money. Retrieved from http://resources.ncmahq.org/chapters/Beach_Cities/Shared%20Documents/Presentations/Color%20of%20Money%2011-10-09.pdf, 2009.
15. McManus H and Schuman T. Understanding the Orbital Transfer Vehicle Trade Space. *AIAA Space 2003*, Long Beach, CA, September 2003.
16. Fitzgerald ME and Ross AM. Mitigating Contextual Uncertainties with Valuable Changeability Analysis in the Multi-Epoch Domain. *6th Annual IEEE Systems Conference*, Vancouver, Canada, March 2012.
17. Ross AM. Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration. Doctor of Philosophy Dissertation, Engineering Systems Division, MIT, June 2006.