Available online at www.sciencedirect.com
SciVerse ScienceDirect
ELSEVIER
Procedia Computer Science 16 (2013) 718 – 727
Procedia Computer Science

Conference on Systems Engineering Research (CSER'13)
Eds.: C.J.J. Paredis, C. Bishop, D. Bodner, Georgia Institute of Technology, Atlanta, GA, March 19-22, 2013.

A Generalized Options-based Approach to Mitigate Perturbations in a Maritime Security System-of-Systems

Nicola Ricci*, Adam M. Ross, Donna H. Rhodes

Systems Engineering Advancement Research Initiative (SEAri), Massachusetts Institute of Technology, Building E38-574, Cambridge, MA 02139

Abstract

Due to the complex and highly dynamic contexts in which systems operate nowadays, it has become crucial that, early in the architecting phase, System Architects take into account options to be utilized throughout the system's lifecycle to improve performance and lifecycle properties, such as flexibility. This paper introduces a preliminary approach that allows for the identification of relevant options, which are capable of mitigating perturbations negatively impacting a system of interest. The approach consists of the generation, evaluation and selection of relevant generalized options (enabling both changeability and robustness), and is demonstrated by application to a Maritime Security SoS case study. The inputs to the process are a list of desired design principles to implement in the system, and a list of perturbations that may affect the delivery of value to stakeholders (options are meant to mitigate perturbations). Four different metrics for option evaluation are proposed, together with techniques that can help during the process of selection of options.

Keywords: Option; Design Principle; Perturbation; System-of-Systems; Risk Mitigation.

1. Introduction

Having options to employ at future points in time is a strategy widely used in different fields, from finance to sport teams, to increase the probability of success of an endeavor. This paper introduces an approach for including generalized options in engineering systems. The activity of identifying convenient options can be cognitively and computationally intensive when performed for such systems and, therefore, may require a significant amount of time. The approach proposed gives guidance for the generation, evaluation and selection of options in a relatively timely fashion.

The world in which systems engineers practice has undergone a significant metamorphosis over the past twenty years. The advent of high-speed computation and communication, paralleled by increased complexity and interconnectedness, has contributed to the rise of rapidly changing operational environments for systems. Additionally, this very dynamic pace can lead to stakeholders varying their needs and preferences through the lifecycle of the system. It has therefore become an increasing challenge for systems engineers to anticipate and

* Corresponding author. Tel.: +1-617-901-7791; fax: +1-617-253-3641.
E-mail address: nricci@mit.edu.

1877-0509 © 2013 The Authors. Published by Elsevier B.V.
Selection and/or peer-review under responsibility of Georgia Institute of Technology
doi:10.1016/j.procs.2013.01.075

design for the success of a system. If focused solely on designing for the present state of the world, engineers may incur into designing systems that, at some point in the future, operate in contexts for which they were not designed [1], and deliver capabilities that are no longer of interest to stakeholders.

Given the abovementioned problems faced by systems engineers, it is important that they start thinking about what options to include in the system architecture early in the design phase, so that they can reduce the risk of having systems that do not deliver value to stakeholders. The socio-technical environments in which such systems are architected (and will eventually operate) can change rapidly, and, therefore, it is ideal that the identification and evaluation of options occur in a timely manner.

In the context of this paper, a generalized option can be of two flavors: resistance option or change option, and these are treated as equally important. In general, an option is the ability to execute a design feature that will change or prevent change to the system in order to respond to perturbations. Change and resistance options are in turn a combination of path enablers (PE) and change mechanisms (CM), and path inhibitors (PI) and resistance mechanisms (RM), respectively [2]. A path variable (be it PE or PI) is the entity that allows for the actuation of mechanisms (CM or RM), which are the action taken to respond to the effects of perturbations (e.g., armor is the PI that enables the hit absorption RM). The main difference between a resistance option and a change option is that the latter, when employed, implies a change in the design of the system while operating. The number of mechanisms that a path variable can enable is termed its *optionability* [3], an important metric that will be further discussed in section 2.

Uncertainty is ubiquitous, especially in highly dynamic environments. When considering complex SoS, it can take a variety of different shapes and impacts [4]. In general, uncertainty can stem from endogenous and exogenous sources, where the latter are usually related to context and expectation changes [5]. Early analysis of system's boundaries and possible dynamic behaviors is helpful toward the determination of possible sources of uncertainty. In the context of this paper and the approach proposed for the case study, uncertainty is parameterized into *perturbations*, which are unintended state changes in a system's design, context, or stakeholder needs that could jeopardize value delivery [2]. Moreover, perturbations are subdivided into "shifts in context and/or needs", and disturbances, which are "finite-(short) duration changes of a system's design, context, or needs that could affect value delivery" [2]. In order to design value robust and well-performing systems, capable of mitigating the impact of perturbations, systems architects often draw inspiration from design principles. Design principles can be thought of as "guiding thoughts [for design] based on empirical deduction of observed behaviour or practices that prove to be true under most conditions over time" [6]. They serve to help intentionally create desirable properties in a system.

2. Preliminary approach for options identification

The preliminary approach described henceforth is a first order attempt toward the development of a generalized prescriptive method for the identification of relevant options in systems. The approach has three steps: generation, evaluation and selection of options. These will be described and demonstrated (via a case study) in the following paragraphs.

2.1. Case study background information

The case study used to demonstrate the preliminary approach proposed is a Maritime Security (MarSec) System-of-Systems (SoS), whose main operational goal is to provide maritime security for a particular littoral area of interest. The system is required to detect, identify and board boats that constantly enter and exit the area of interest. Moreover, upon request, it must be capable of providing for search and rescue of sinking boats or entities in danger within the area of interest. The architecture of the SoS has already been defined and includes, among other things, UAVs (two different types), planes, helicopters, patrol boats, and radar towers. It is also possible to change operational variables such as the segmentation of the area (in terms of what is covered by different UAVs), task assignment (what functions are performed by the different constituent systems), and the number of operators per UAV. Given the defined MarSec SoS architecture, it is now desired to find options that can be added to this current architecture.

The MarSec SoS falls within the general definition of system-of-systems ("collaborative system"), as proposed by Maier [7]. The SoS has constituent systems that can "fulfill valid purposes in their own right" (e.g., helicopters can continue to operate and fulfill purposes outside of the MarSec SoS), and are "managed (at least in part) for their own purposes, rather than the purposes of the whole" (e.g., patrol boats are managed by the local port authority). Since MarSec is an SoS, it is exposed to some additional uncertainties that an otherwise monolithic system might not face. For example, one of the perturbations considered for MarSec is the temporary inability of port authority-managed assets to participate to the cause of the overall SoS. The fact that this paper demonstrates the proposed approach with an application to a system-of-systems does not preclude the possibility of performing the approach on "traditional" (i.e. non-SoS) systems.

2.2. Generation of options

The inputs into the first task of the proposed approach are relevant design principles and perturbations identified for the system of interest. It is assumed here that the identification of these two inputs has taken place during early analysis of system's purpose and boundaries. The goal of this activity is to generate as many options as possible. The process of generating options starts by mapping design principles to perturbations, i.e. brainstorming instantiations of design principles that can (partially) mitigate the damage caused by a given perturbation. An aid for the completion of this task is the matrix shown in Fig. 1, where design principles are listed as rows and perturbations (shifts and disturbances) as columns. The empty cells in the matrix contain instantiations of design principles in the form of both path variables (PE or PI) and mechanisms (CM or RM). They are filled in during this task.

	SHIFT					DISTURBANCE				
DESIGN PRINCIPLES	S1	S2	S3	S4	S5	D1	D2	D3	D4	D5
DP 1										
DP 2										
DP 3										
DP 4										
DP 5										

Fig. 1: Design principles to perturbations mapping matrix.

An application of this task to the MarSec SoS is shown in Fig. 2. In the case of MarSec, design principles and perturbations have been previously identified. The design principles (DP) have been derived from ilities of interest: as shown in Fig. 2, each set of design principles enables a specific ility. The perturbations have been derived from system boundary and dynamic operational environment analyses [8]. In this case, for illustrative and space-related reasons, only disturbances are shown as a subset of the perturbations. Although only one instantiation at most has been listed per cell for illustrative purposes, more than one idea can be brainstormed for a certain DP-perturbation combination. An example flow for this activity would be that, when thinking about ways to resist to a serious attack (perturbation), armor comes to mind as an instantiation of the design principle of hardness.

After the DP to perturbation matrix has been filled out, the next step is to discern among the four entries to the matrix (PE, PI, CM and RM) and sort them into four lists, one per entry type. Then, it is possible to match compatible PEs and CMs (and PIs and RM) appropriately in order to generate a comprehensive list of change (and resistance) options. In order to perform the matching of PEs to CMs and PIs to RMs for the generation of options, a matrix listing PEs (PIs) as columns and CMs (RMs) as rows (or vice verse) can be produced. If a path enabler (or path inhibitor) is an enabler of a given change mechanism (resistance mechanism), a change (resistance) option is created! The content of the cell mapping the row becomes the option ID.

The application of this process to MarSec is showed in Fig. 3, where the top matrix shows change options and the bottom one resistance options. Here, a distinction between path enablers and latent path enablers is made: the latter is a feature that is already part of the architecture, and therefore would require little to no cost at all.

VALUE SURVIVABILITY / DESIGN PRINCIPLES		DISTURBANCES: Serious Attack	Asset Unavailable	Storm (decreased situational awareness)	Tsunami (SoS seriously damaged)	Information Attack
SUSCEPTIBILITY	Prevention	Only use boats for intercept	buy spares	Water repellant layer on windshield	bring assets back to base promptly	
SUSCEPTIBILITY	Mobility	Vary flight paths and speeds		enhanced control system	move to non-affeccted region	
SUSCEPTIBILITY	Concealment	Higher Altitude				Higher Altitude
SUSCEPTIBILITY	Deterrence					
SUSCEPTIBILITY	Preemption					
SUSCEPTIBILITY	Avoidance	Vary flight paths and speeds		fast planes	move to non-affeccted region	Vary flight paths and speeds
SUSCEPTIBILITY	Defensive Posture	Only use boats for intercept		bring assets back to base promplty	anchor boats to specific location	
SUSCEPTIBILITY	Deflection	Decoys	Decoys			
SUSCEPTIBILITY	Authentication					
SUSCEPTIBILITY	Reserves		spares		spares	
VULNERABILITY	Hardness	Armor		more stable structure	Armor	Double Authentication
VULNERABILITY	Redundancy					
VULNERABILITY	Margin	Increase wing Coeff of lift (fly on one wing)	Use UAVs that are able to change role (detection/identification, etc)			
VULNERABILITY	Heterogeneity		Multi-role Asset		Multi-role Asset	Satellite and Direct Links
VULNERABILITY	Failure Mode Reduction					
VULNERABILITY	Decentralization	Geographical Distribution				Distribute/decentralize authority
VULNERABILITY	Fail-safe					
VULNERABILITY	Modification	UAV Flight path change				
VULNERABILITY	Containment	Geographical Distribution			bring assets back to base	
VULNERABILITY	Stable Intermediate Instances	Training personnel in multiple tasks/ irregular ops	go to pre-validated design		Use only radar towers for detection	Training personnel in multiple tasks/ irregular ops
RESILIANCE	Replacement	Spares	Replace unavailable asset with one at disposal		train personnel for prompt vehicle replacement	
RESILIANCE	Repair	Trained Repair Crews			train personnel for prompt vehicle repair	Trained Repair Crews
RESILIANCE	Adaptation	Change detection UAV to Interception UAV	Use UAVs that are able to change role (detection/identification, etc)	enhanced control system		Training personnel in multiple tasks/ irregular ops
RESILIANCE	Contingency					
RESILIANCE	Reversion					

Fig. 2: Example design principles to perturbations mapping applied to MarSec (for disturbances only).

CHANGE OPTION	Path Enabler									Latent Path Enabler			REALIZABILITY
Change Mechanism	Extra Interception UAV	Contract with Aircraft Supplier	Extra Cameras	Sea Planes	Pre-Validation Process	Long Range UAV	Workforce Buffer	Dispersed Com Network	Spares	Multi-Role Asset	Central Authority	Satellite Relay	
Adding Vehicle	C1	C2	-	-	-	-	C3	-	C4	-	-	-	4
Change Task Assignment	C5	-	C6	C7	-	-	-	C8	-	C9	-	-	5
Change Geographic Segmentation	-	-	-	C10	-	C11	-	C12	-	-	-	C13	4
Change Number of Operators per UAV	-	-	-	-	C14	-	C15	-	C16	-	-	-	3
Go back to Pre-Validated Set	-	-	-	-	C17	-	-	-	-	C18	-	-	2
Change Authority distribution	-	-	-	-	-	-	-	-	-	-	C19	C20	2
Add extra features to Asset	-	C21	C22	-	-	-	-	-	-	-	-	-	2
OPTIONABIITY	2	2	2	3	2	1	2	2	2	2	1	3	

RESISTANCE OPTION	Path Inhibitor								Latent Path Inhibitor		REALIZABILITY
Resistance Mechanism	Workforce Buffer	Armor on UAV	Better UAV Control System	Long range Signal Transimtter	Spares	Pre-Validation Process	High-Altitude UAV	Decoy	Multi-Role Asset	UAV Swarm	
Overstaffing	R1	-	-	-	-	-	-	-	-	-	1
Change Trajectory of Flight	-	-	R2	R3	-	-	R4	-	-	-	3
Increase Asset Hardness	-	R5	-	-	-	-	-	-	-	-	1
Disperse around AOI	-	-	R6	R7	-	-	-	-	-	R8	3
Multiple Assets perform Same Function	-	-	-	-	R9	-	-	-	R10	R11	3
Rapidly Recover against Asset Loss	-	-	-	-	R12	R13	-	-	R14	-	3
Distract Hostile Attacks	-	-	-	-	-	-	-	R15	-	-	1
Training Personnel for Multiple Tasks	R16	-	-	-	-	R17	-	-	-	-	2
OPTIONABIITY	2	1	2	2	2	2	1	1	2	2	

Fig. 3: Generation of change options (top) and resistance options (bottom).

Finally, all options generated can be listed as shown in Fig. 4. The lists contain the option ID number and the mechanisms and path variables that compose it.

Change Options			Resistance Options		
	Mechanism	Path Enabler		Mechanism	Path Inhibitor
1	Adding vehicle	Extra interception UAV	1	Overstaffing	Workforce buffer
2	Adding vehicle	Contract with aircraft supplier	2	Change trajectory of flight	Better UAV control system
3	Adding vehicle	Workforce buffer	3	Change trajectory of flight	Long range signal transmitter
4	Adding vehicle	Spares	4	Change trajectory of flight	High altitude UAV
5	Change task assignment	Extra interception UAV	5	Asset resistance to attacks	Armor on UAV
6	Change task assignment	Extra cameras	6	Disperse around AOI	Better UAV control system
7	Change task assignment	Sea planes	7	Disperse around AOI	Long range signal transmitter
8	Change task assignment	Dispersed Com network	8	Disperse around AOI	UAV swarm
9	Change task assignment	Multi-role asset	9	Multiple assets perform same function	Spares
10	Change geographic segmentation	Sea planes	10	Multiple assets perform same function	Multi-role asset
11	Change geographic segmentation	Long Range UAV	11	Multiple assets perform same function	UAV swarm
12	Change geographic segmentation	Dispersed Com network	12	Rapidly recover against asset loss	Spares
13	Change geographic segmentation	Satellite Relay	13	Rapidly recover against asset loss	Pre-validation process
14	Change number of operators per UAV	Pre-validation process	14	Rapidly recover against asset loss	Multi-role asset
15	Change number of operators per UAV	Workforce buffer	15	Distract hostile attacks	Decoy
16	Change number of operators per UAV	Spares	16	Training personnel for multiple tasks	Workforce buffer
17	Go back to pre-validated set	Pre-validation process	17	Training personnel for multiple tasks	Pre-validation process
18	Go back to pre-validated set	Multi-role asset			
19	Change authority distribution	Central authority			
20	Change authority distribution	Satellite relay			
21	Add extra features to assets	Contract with aircraft supplier			
22	Add extra features to assets	Extra cameras			

Fig. 4: Final list of all options generated for MarSec SoS.

2.3. Evaluation of options

After a comprehensive list of options to consider for inclusion in the system architecture has been generated, the next step in the proposed approach is to perform an evaluation. All generated options are evaluated in terms of the following four proposed metrics:

1. *Optionability* (O): the number of options that are linked to a particular path enabler/inhibitor. Its range is [0 M], where M is the total number of options previously generated. The optionability count for options generated for the MarSec SoS is shown as the last row of the matrices in Fig. 3. This score solely depends on the path enabler (inhibitor) that composes the given option to be evaluated.
2. *Number of Uses* (NU): the number of times a particular option can be employed (usually related to its path enabler/inhibitor). The range for this metric is composed of three possible assessments, [1 N ∞], where 1 is for options that can be only used once, N is for options that can be used a finite number of times, and ∞ is for options that can be used an unlimited number of times. For example, C4 (adding vehicle via spares) can only be used a finite number of times (N), until there are no more spare vehicles available. On the other hand, R5 (resistance to an attack using enhanced UAV armor) is an option that, once executed, can be used for the entire existence of the SoS, therefore scoring ∞. This metric can be useful when performing dynamic analysis of the system, establishing what options will be left as time goes by.

   Fig. 5 shows the assessment of this metric in the case of options generated for the MarSec SoS. The completion of this task is performed more effectively if carried out with the aid of domain experts.
3. *Cost* (C): Approximate cost of including (acquiring and executing) the option in the system architecture. This is a qualitative assessment carried out with the help of domain experts. The range used in the context of the MarSec application is the following: [no low medium high]. Of course, depending on the expertise of people

performing this task, and the level of detail they are willing to go into, the precision of the evaluation can vary widely. Similarly to NU, it is advisable that this task is performed with the aid of domain experts.
The assessment of cost for options identified for MarSec is shown in Fig. 5, next to the assessment of NU. It is important to note that options that can be employed with the use of latent path variables are approximated to have no cost.

Change Option: Option Number	Number of Uses [1 N ∞]	Cost [low med high]
C1	1	high
C2	∞	low
C3	∞	medium
C4	N	high
C5	1	high
C6	N	low
C7	N	high
C8	∞	low
C9	∞	no
C10	N	high
C11	N	high
C12	∞	low
C13	∞	low
C14	∞	no
C15	∞	medium
C16	N	high
C17	∞	no
C18	∞	no
C19	∞	low
C20	∞	low
C21	∞	low
C22	N	low

Resistance Option: Option Number	Number of Uses [1 N ∞]	Cost [low med high]
R1	∞	medium
R2	∞	medium
R3	∞	low
R4	N	high
R5	∞	medium
R6	∞	medium
R7	∞	low
R8	∞	no
R9	N	high
R10	∞	no
R11	∞	no
R12	N	high
R13	∞	no
R14	∞	no
R15	1	medium
R16	∞	medium
R17	∞	no

Fig. 5: Evaluation of options (first column) in terms of number of uses (second column) and cost (third column) applied to Marsec SoS.

4. *Perturbation coverage* (PC): a metric that takes into account impact and probability of perturbations covered by a given option. This metric is proposed to be a proxy for risk attenuation. Once again, domain experts can be very helpful in assessing this metric, and the fineness of the assessment very much depends on the level of knowledge and expertise of the people in charge of this task. Their contribution is threefold: assessment of likelihood of occurrence of perturbation, assessment of perturbation impact on system value delivery (upon occurrence), and assessment of whether or not a given perturbation is (partially) covered by the option. A proposed way of using this information produced is to compile probability (P) and impact (I) assessments directly into the following perturbation coverage metric:

$$PC = \sum_{i=1}^{n} P_i^{\gamma} I_i \quad (1)$$

Where n is the total number of perturbations covered by a given option, P_i is the probability of occurrence of perturbation i, I_i is the impact of perturbation i on the system, and γ is the risk aversion factor for the assessor's perceived probability. The use of probability and impact is common for Probabilistic Risk Assessment (PRA) [9] across various disciplines, from finance to engineering.
In the application to MarSec, the range used for assessment of both probability and impact is [low medium high]. The assessment of perturbations' probability and impact is shown in Fig. 6.

Perturbation	SHIFT								DISTURBANCE				
	Tech Level	Workforce Availability	Info Sharing Availability	Boat Arrival Rate	Pirate Percentage	Smuggler Percentage	Search & Rescue	Jamming	Serious Attack	Asset Unavailable	Storm (decreased situational awareness)	Tsunami (SoS seriously damaged)	Information Attack
Probability [Low Med High]	low	med	med	high	med	high	low	med	low	med	med	low	med
Impact [Low Med High]	med	med	low	med	high	med	high	high	high	high	low	high	med

Fig. 6: Assessment of perturbations' probability and impact for MarSec case study.

In order to complete the evaluation of perturbation coverage, an assessment of whether or not a perturbation is covered by a given option must be carried out. A helpful tool to perform this task is a matrix mapping options to perturbations. Fig. 7 shows such a matrix for the case of MarSec. The matrix includes options listed as rows and perturbations as columns, and it displays information about whether options cover perturbations ("1" vs. empty cell), how well an option can mitigate against the full set of perturbations (sum across columns), and how well a perturbation is mitigated against (sum across rows). The table shows that C2 (adding vehicle via a contract with aircraft supplier) is the most "perturbation-mitigating" change option, while tsunami is the most commonly mitigated perturbation by the set of options listed (this is probably because its impact on the system is widespread and many things can be done to mitigate against it). The score of the sum across columns can be an alternative (more simple) metric to the one given in equation (1) for perturbation coverage.

It is important to note that the simple model used in this approach implies that an option either fully covers a perturbation or it does not cover it at all. More complex approaches can be used and are mentioned in the discussion section (Section 3).

Perturbation			SHIFT								DISTURBANCE					Σ
			Tech Level	Workforce Availability	Info Sharing Availability	Boat Arrival Rate	Pirate Percentage	Smuggler Percentage	Search & Rescue	Jamming	Serious Attack	Asset Unavailable	Storm (decreased situational awareness)	Tsunami (SoS seriously damaged)	Information Attack	
Probability [High-Medium-Low]			low	med	med	high	med	high	low	med	low	med	med	low	med	
Impact [High-Medium-Low]			med	med	low	med	high	med	high	high	high	high	low	high	med	
Change Option ___ Uses [1, N, ∞]	C1	1				1	1	1			1	1	1	1		7
	C2	∞	1		1	1	1	1	1		1	1		1		9
	C3	∞			1	1	1	1			1	1		1		7
	C4	N			1	1	1	1			1	1	1	1		8
	C5	1					1	1	1			1				4
	C6	N	1				1	1	1							4
	C7	N					1	1	1			1				4
	C8	∞	1				1	1	1			1				5
	C9	∞			1		1	1	1			1				5
	C10	N				1			1					1		3
	C11	N				1			1					1		3
	C12	∞				1			1	1					1	4
	C13	∞	1			1			1	1				1	1	6
	C14	∞		1							1	1	1			4
	C15	∞		1		1							1			3
	C16	N									1	1	1			3
	C17	∞		1							1	1		1		4
	C18	∞		1							1	1		1		4
	C19	∞							1	1				1	1	4
	C20	∞	1						1	1			1	1	1	6
	C21	∞					1	1					1			3
	C22	N					1	1	1				1			4
Resistance Option ___ Uses [1, N, ∞]	R1	∞		1	1	1	1	1								5
	R2	∞							1	1	1	1	1	1	1	7
	R3	∞							1	1				1	1	4
	R4	N								1	1	1		1	1	5
	R5	∞					1				1					2
	R6	∞					1						1	1		3
	R7	∞					1		1				1	1	1	5
	R8	∞					1		1						1	3
	R9	N				1				1	1	1		1		5
	R10	∞		1		1			1	1	1	1		1	1	8
	R11	∞							1		1	1			1	4
	R12	N					1				1	1		1		4
	R13	∞					1				1	1		1		4
	R14	∞		1			1				1	1		1		5
	R15	1					1				1					2
	R16	∞		1	1	1	1	1	1					1	1	8
	R17	∞		1			1	1	1				1	1	1	7
Σ			5	9	6	13	22	14	21	9	18	20	12	23	13	

Fig. 7: Perturbation coverage matrix for MarSec SoS case study.

2.4. Selection of Options

So far, all generated options have been evaluated in terms of the metrics proposed. The next and last activity performed is to downselect promising options. In this activity, systems engineers (with the aid of stakeholders) decide what options to include in the system architecture. The list of selected options can be final or preliminary, depending on their preferences. In the first case, the options selected are included in the system architecture directly. In the second case, the selected options are further analyzed by means of Modeling and Simulation (M&S), prior to making final decisions.

Different techniques to facilitate decision-making can be used at this point. The first one, used in the MarSec case study, is a visualization enhancement tool that allows for consideration of multiple metrics simultaneously (see Fig. 8a). It consists of a risk chart [10] on which perturbations (shifts in purple and disturbances in green) are located depending on their probability and impact. Associated with the perturbation is a list of options (green for change options and red for resistance options) that defines the “coverability” of the perturbation, i.e., how well a perturbation is covered given the comprehensive list of options initially generated. These options are in turn characterized by different shapes that correspond to different number of uses (NU). The next step would be to include the option ID number within the shapes, so to identify options that appear more frequently or mitigate very risky perturbations (top-right corner). Another interesting analysis that can be performed at this point is to separately plot different subsets (portfolios) of options, and investigate the ones that have a more homogeneous coverage of the perturbation set.

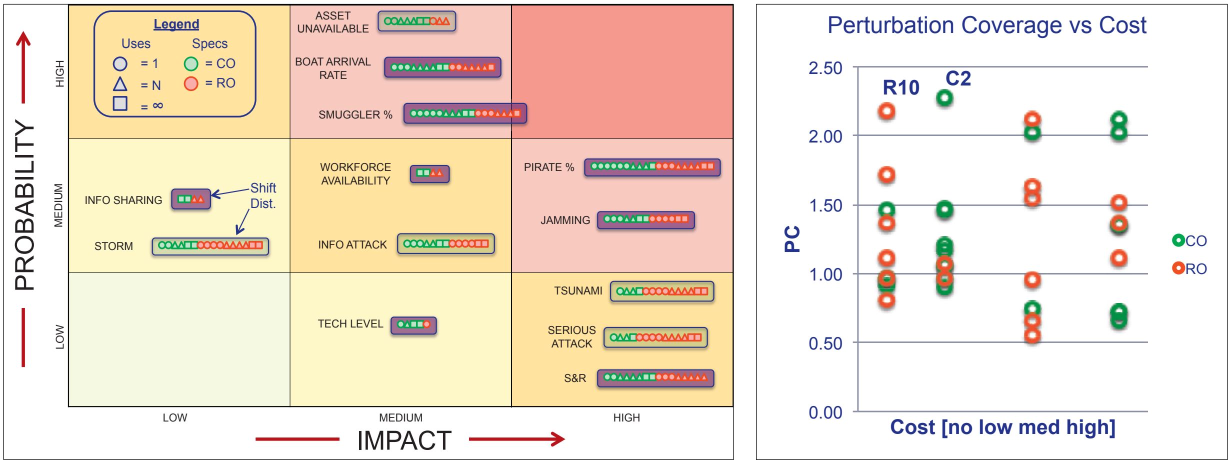

Fig. 8: (a) Visualization of perturbation coverage by the comprehensive set of options identified; (b) Visualization of perturbation coverage versus cost tradespace.

The second proposed tool is a risk-benefit analysis technique, which consists of trading perturbation coverage (PC – proxy for *risk* mitigation) versus cost (whose minimization is considered *beneficial*) on a two-dimensional space, in order to identify distinct options that are Pareto efficient in terms of PC maximization and cost minimization. Preliminary results from the MarSec case study, shown in Fig. 8b, illustrate how resistance option R10 and change option C2 are very efficient in terms of these two objectives, and should be seriously considered for inclusion in the system. Here, equation (1) has been used to calculate PC.

The next step (which will be taken in the near future) is to explore risks and benefits associated with investing in subsets (i.e., *portfolios*) of options. In a similar manner to financial portfolio theory [11], this approach will allow for the identification of sets of options that, through diversification, can either (1) maximize risk mitigation for a certain budget constraint, or (2) minimize cost for a preferred level of risk mitigation. Additional analysis with regard to the exploration of the dynamics of the PC versus cost tradespace can also be made by taking into account the number of executions (NU metric) associated with the options present in a given set.

3. Discussion

The preliminary approach for the identification of relevant perturbation-mitigating options presented in this paper is a first order attempt to tackle a problem that is very broad, and that includes many complex issues. Many of these issues stem from the evaluation part of the approach. Evaluation of cost and risk are not straightforward activities to perform. The latter, for example, can be a very abstract concept, and have many layers of complexity embedded in it (e.g., evaluation of probability and impact of a perturbation). Quantification of risk is often based on fragile assumptions about the future and human behaviors: this is true even for financial analyses, where much is based on risk estimations [11]. There are several relevant points that the development of this approach (as demonstrated in the MarSec SoS case) has brought up. Some of these are:

- The assessment of certain metrics, such as perturbations' probability and impact, as well as cost, strongly depends on the level of knowledge and expertise of the people involved in the evaluation task. The fineness of the grid of the risk chart (see Fig. 8a), for instance, depends on the degree of differentiation one can make among different levels of probability and impact. In general, a grid that is at least 5 by 5 is suggested for systems engineering practices, if one can reasonably estimate the assignment of alternatives to these levels [10].
- The perturbation coverage quantification problem is not a simple one. First, options do not usually mitigate the full impact of a perturbation. They often mitigate a portion of the total damage a perturbation causes. Considerations related to the lifetime of a perturbation [13] and option utilization timing ought to be made in order to incorporate partial damage coverage in the analysis. For instance, in equation (1), a factor that takes into account the percentage of the perturbation that is covered can be included. Second, the use of multiple options together can bring about *emergent* perturbation coverage.
- The union of path variables and mechanisms forms options. In the process of evaluating the option, especially for some of the metrics, a problem arises: it is not clear if one should consider each option as its own entity (PE and CM). Some path enablers can enable more than one mechanism, and, while there are PEs that once are linked to mechanisms can not be separated anymore, there are others that can be reused for the enabling of different mechanisms at different times. It is not easy to add these considerations into the evaluation of options, and future research will be done in this direction.
- As stated in the introduction of this paper, the time component is a very important one to consider for systems. Throughout the approach presented, this issue was tackled only by the number of uses (NU) metric. In order for this metric to become most effective though, it is important that one be able to consider the approximate number of occurrences of a perturbation through time as well. This way, a dynamic analysis of perturbation coverage could be performed.
- The assessment of cost was performed on discrete levels in order to generate initial cost differentiation among the various options. However, the detailed quantification of the cost of an option would be quite complex and include many cost types: initial cost (i.e., acquisition cost), carrying cost (associated with maintaining the ability to execute the option at a future point in time), and execution cost [2]. Moreover, when considering the inclusion of a set of options, it is important to keep in mind that higher degrees of diversification of the options in the set (i.e., heterogeneity) can result in higher costs. Lastly, if the set of options is known to vary over time, switching costs must be considered as well [14].
- As proposed in the paper, the approach can be used to help screen important options. The metrics and ranges proposed, although based on assessments made by (collaborating) systems engineers and domain experts, lead to useful results in terms of differentiating between options. This *differentiation* is then the foundation of the option selection activity. As for all methods that use estimated input data, the validity of the results is directly proportional to the accuracy of the inputs. While it could be possible to reach appropriate estimates for the assessment of cost (requiring more time), it is harder to do so for probabilistic risk assessments. In fact, since many of the considered perturbations could be low-frequency or entirely novel, empirical data for validation could be lacking. Even so, the approach is scalable to the availability and confidence analysts have in the data (e.g. use fewer levels with more uncertain data). Sensitivity analysis on uncertain data can give valuable information about the robustness of insights. Of course, the more analytical parts of the approach (such as PC calculation and portfolio analysis) become more relevant as the quality and resolution of the data improves. Another important benefit of the approach is that it stimulates discussion among experts, and forces engineers to think about aspects of the problem that could have been disregarded otherwise.

Overall, the illustrated approach allows for relatively quick identification of options that can be relevant for a given system architecture. Currently, complex techniques such as Valuation Approach for Strategic Changeability (VASC) [15] are effective in terms of quantitatively evaluating options, but can require significant time, as the simulations (of change and resistance mechanisms) and analyses associated with it can be very complex and extensive. Given systems have high interconnectedness, fast technology advancement, and high information exchange rate, decision time is becoming an increasingly crucial factor to consider. Delivering "the findings on engineering issues and solution trade-offs to decision makers in timely fashion" has become very important [16]. The approach illustrated, due to its rapid evaluation processes, would allow for making trades on what options to include when there is insufficient time to perform a more extensive activity. Moreover, other contributions of this approach are in terms of systems risk-benefit analysis techniques, an area that is also identified as in need of advancement by Neches and Madni [16].

Acknowledgements

The authors gratefully acknowledge funding for this research provided through MIT Systems Engineering Advancement Research Initiative (SEAri, http://seari.mit.edu) and its sponsors.

References

1. A.M. Ross, and D.H. Rhodes. "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," *Paper presented at the INCOSE International Symposium 2008*, Utrecht, the Netherlands, 15-19 June.

2. J.C. Beesemyer, Empirically Characterizing Evolvability and Changeability in Engineering Systems, *Master of Science Thesis*, Aeronautics and Astronautics, MIT, June 2012.

3. T. Mikaelian, D.E. Hastings, D.H. Rhodes, D.J. Nightingale, "Model-based Estimation of Flexibility and Optionability in an Integrated Real Options Framework." 3rd *Annual IEEE Systems Conference, Vancouver, Canada, March 2009.*

4. H. McManus and D.E. Hastings. "A Framework for Understanding Uncertainty and Its Mitigation and Exploitation in Complex Systems." *IEEE Engineering Management Review*. 34(3): 81-94. (2006)

5. A.A. Rader, A.M. Ross, and D.H. Rhodes, "A Methodological Comparison of Monte Carlo Methods and Epoch-Era Analysis for System Assessment in Uncertain Environments." *Paper presented at the 4th Annual IEEE Systems Conference*, San Diego, CA, 5-8 April, 2010.

6. C.S. Wasson, "Systems Analysis, Design and Development." *Published by John Wiley and Sons, Inc., Hoboken, New Jersey, 2006.*

7. M.W. Maier, "Architecting Principles for Systems of Systems." *In Systems Engineering, volume 1, issue 4*: pp. 267-284, 1998.

8. A.M. Ross, H.L. McManus, A. Long, M.G. Richards, D.H. Rhodes, and D.E. Hastings, "Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change". *Paper presented at AIAA Space 2008, San Diego, CA, 9-11 September.*

9. H. Kumamoto, and E.H. Henley, "Probabilistic Risk Assessment and Management for Engineers and Scientists", *published by IEEE Press*: pp. 1-18, 1996.

10. National Aeronautics and Space Administration, "NASA Systems Engineering Handbook." *NASA/SP-2007-6105 Rev1,* NASA Headquarters, Washington, D.C. 20546. (2008)

11. H.M. Markowitz, "Portfolio Selection." *The Journal of Finance*. 7(1): 77-91. (1952)

12. P. Swisher, and G.W. Kasten, "Post-Modern Portfolio Theory." *Journal of Financial Planning*, 26(9): 1-11. (2005)

13. M.G. Richards, D.E. Hastings, D.H. Rhodes, A.M. Ross, and A.L. Weigel, "Design for Survivability: Concept Generation and Evaluation in Dynamic Tradespace Exploration." *2nd International Symposium on Engineering Systems, Cambridge, MA, June 2009.*

14. N. Ricci, A.M. Ross, and D.H. Rhodes, "Developing a Dynamic Portfolio-Based Approach for System-of-Systems Composition", SEAri Working Paper WP-2012-2-1, http://seari.mit.edu/papers.php [cited 12-01-2012]. (2012)

15. M.E. Fitzgerald, A.M. Ross, and D.H. Rhodes, "Assessing Uncertain Benefits: a Valuation Approach for Strategic Changeability (VASC)." *INCOSE International Symposium 2012, Rome, Italy, July 2012.*

16. R. Neches, and A.M. Madni, "Towards Affordably Adaptable and Effective Systems", *Systems Engineering Journal*. Article first published online: 19 Oct. 2012. DOI: 10.1002/sys.21234.