Managing Uncertainty in Systems of Systems Operating in Dynamic Environments

Nicola Ricci, S.M. in Aeronautics and Astronautics (expected in 2013)

Advisors: Prof. Daniel Hastings; Dr. Adam Ross; Dr. Donna Rhodes

nricci@mit.edu

Biography

Nicola Ricci is a graduate student at MIT, pursuing an S.M. in Aeronautics and Astronautics. Prior to attending MIT, he received a B.S. in Aerospace Engineering from Boston University. He also studied in Dresden (Germany) for six months, where he attended TUD (Technische Universität Dresden). His prior research experience includes developing an object-oriented simulation program that helps understanding the performance of System-of-Systems in highly stochastic environments.

Related Publications

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

Walton, M.A., *Managing Uncertainty in Space Systems Conceptual Design Using Portfolio Theory*, Doctor of Philosophy Dissertation, Aeronautics and Astronautics, MIT, June 2002.

Motivation

1. The world changes more and more rapidly, and with increased interconnectedness, it is essential to analyze the impact of dynamic contexts on a system (or SoS) in alternative futures in order to anticipate long term value.
2. Uncertainty is embedded in everything; finding a way to systematically manage uncertain outcomes could be important for ensuring the success of a system.
   - Decisions made during design phases are far separated from consequences of those decisions, but may have a great impact on system performance
   - These decisions are often subject to human cognitive and context-related biases (social, political, etc.). Not addressing these uncertainties may result in unexpected and undesirable outcomes.
3. Systems of Systems are particularly susceptible to the above considerations as they experience dynamics (of operational elements, operational modes, and constituent actors), and as they are exposed to a large variety of uncertainties.

There is **need** for a method that enables decision makers to manage the impact of uncertainty on Systems of Systems that operate in dynamic environments

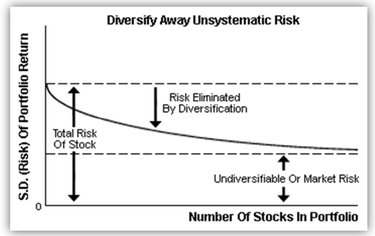
Modern Portfolio Theory

Modern Portfolio Theory (MPT) was introduced in 1952 by Harry Markowitz in a financial context.

MPT attempts to:

- Maximize return, given a certain risk investors are willing to take.
- Minimize risk, given a certain return investors are interested in.

MPT relies on the concept of diversification in investing (illustrated in figure below).



Source: http://www.investopedia.com/articles/06/MPT.asp#axzz1a7FrZ1Wx

The classical portfolio optimization problems are the following:

Minimize Variance	Maximize Return
$\min \frac{1}{2} w^T Q w$	$\max \sum_{i=1}^{n} r_i w_i$
$S.T. \sum_{i=1}^{n} r_i w_i \geq r_*$	$S.T. \frac{1}{2} w^T Q w \leq \sigma_*^2$
$S.T. \sum_{i=1}^{n} w_i = 1$	$S.T. \sum_{i=1}^{n} w_i = 1$
$S.T. w \geq 0$	$S.T. w \geq 0$

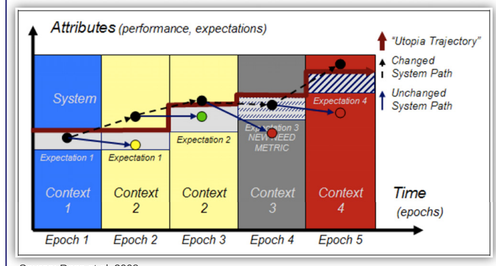
Where r is the expected return, w is the selected weighting of assets, and Q is the covariance matrix (measure of variability in a portfolio).

Source: Walton 2002

Responsive Systems Comparison

Responsive Systems Comparison (RSC) is a method that allows for the comparison of the performance of many proposed systems in a wide variety of possible futures. Using this method, one can identify candidate systems that deliver best value under different future situations.

RSC is an application of Epoch-Era-Analysis (EEA), which allows for the analysis of systems' performance through their lifetime, which is subject to *context* and *expectation* changes.



Source: Ross et al. 2008

The graph on the left illustrates a five-epoch analysis of a responsive system. An epoch is a discrete time period where *expectations* and *context* are fixed. A **sequence** of epochs constitutes an era, which is the system lifetime. It is important to note that the *order* of the epochs matters when concerned with the performance of a system.

Prior Work

Dr. Myles Walton proposed a way of using Modern Portfolio theory in Space Systems applications in his PhD dissertation *Managing Uncertainty in Space Systems Conceptual Design using Portfolio Theory*. Walton highlights basic assumptions and limitations of MPT that ought to be considered and modified when applying the theory to the Space Systems context:

- Uncertainty is represented by a normal distribution of outcomes
- There is no cost in holding assets in portfolio
- Customers are risk-averse

Walton proposed the solution to these problems as given by:

- Semi-variance: use upside and downside covariance matrices to eliminate normality in distribution and introduce a method to consider the benefits one may gain from uncertainty.
- Cost of diversification: quantify the cost of diversification based on the correlation of assets.

The new portfolio optimization problems proposed by Walton in the case of Space Systems concept design is:

$$\max: E(r)w - \frac{k}{2} w' Q_{Downside} w$$
$$s.t.: \sum_{i=1}^{n} w_i = 1$$
$$s.t.: C_p < C_{limit}$$
$$s.t.: w \geq 0$$

$$\max: E(r)w + \frac{1}{2} w' Q_{upside} w - \frac{k}{2} w' Q_{Downside} w$$
$$s.t.: \sum_{i=1}^{n} w_i = 1$$
$$s.t.: C_p < C_{limit}$$
$$s.t.: w \geq 0$$

Source: Walton 2002

Research Approach

Through an exploratory application to a Maritime Security SoS case, this research will seek to:

1. Extend the use of Modern Portfolio Theory to general SoS
   - Define limits and conditions for applicability of theory
   - Make necessary changes to the theory in order to compensate for its application at a multi-system level
2. Combine the use of MPT and RSC
   - Apply MPT to performance and uncertain information of systems that operate through eras (i.e., sequences of discrete epochs)
   - Quantify the uncertainty that propagates through sequences of epochs
3. Explore the concept of a tradespace of system portfolios

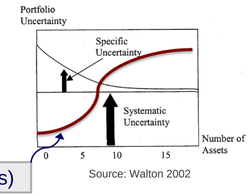
The research will result in analytic and prescriptive guidance on how to evaluate and construct system portfolios for SoS

Challenges

Quantification of cost of diversification of portfolio. Unlike in finance, SoS portfolios are composed of assets whose growth is driven by contributions by asset holders.

- What is the cost as a function of the number and types of assets?

COST = fn (# of Assets)



Source: Walton 2002

Quantification of context-related uncertainties when applying RSC method. These types of uncertainty may include political uncertainty, obsolescence uncertainty, utility uncertainty.

Correlation of system-endogenous uncertainties in different epochs. Obtaining final era uncertainty of system outcomes by relating uncertainties arising within each epoch.

Implementation of a way to represent all attributes important to each decision maker in few dimensions (preferably one).

Can MPT capture the behavior of all outcome distributions? Deviations from normal distributions assumed in MPT must be considered.

- Develop new ways to express uncertainties beyond variance and covariance.

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