SEAri Working Paper Series

Title: Developing a Dynamic Portfolio-based Approach for Systems-of-Systems Composition

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Paper Number: **WP-2012-2-1**

Revision Date: May 15, 2012

Developing a Dynamic Portfolio-Based Approach for Systems-of-Systems Composition

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Abstract. This paper explores the possibility of generalizing the use of Modern Portfolio Theory (MPT) for the problem of System of Systems (SoS) composition (e.g., the selection of constituent systems and their interconnections). Through the coupling of MPT with Epoch-Era Analysis (EEA), it is proposed that the resulting approach will enable decision makers to identify portfolios of constituent systems that are robust to uncertainties associated with SoS that operate in uncertain and dynamic environments. Mitigation of *uncertainty* is possible by using MPT, while EEA is used to analyze the impact of *dynamic contexts* on the SoS. The underlying analogy between financial and SoS portfolios is investigated, and preliminary observations are made regarding violated assumptions in MPT when applied to SoS portfolios. An approach for generalizing MPT with EEA is described, along with desired characteristics of case studies that can be used for method validation.

Introduction and Motivation

Over the past twenty years, the way human beings live and coexist has radically changed. The rise of high speed data and communication networks has transformed the way information is accessed and decisions are made. Information travels at the speed of light, ideas disseminate widely, technology improves at a high rate, and decisions are made much more promptly, and often have immediate repercussions. All of these factors have contributed to a rapidly changing world. As an enabler, as well as an outcome, system interconnectedness and interdependence has also increased, leading to greater challenges for engineers to anticipate and design for system success in a dynamic world.

This metamorphosis is very much pronounced in systems engineering, where important decisions about systems are made throughout their lifecycles, but where the consequences of those decisions may not be felt until many years later, when leverage may already be lost. A system could find itself operating in a context for which it was not designed, delivering capabilities that are no longer of interest to stakeholders.

Traditional systems engineering approaches often focus on eliciting needs and requirements in a static world. Considering the world as static may no longer be a reasonable assumption given the rise of this new fast-paced era. In fact, in recent decades, scenario planning has become an ever more important strategic activity, with the purpose of conceptualizing possible future scenario in which the system will operate. A common practice is to look at "point futures;" that is, specific future situations in which the context, expectations and requirements for systems analysis are static (i.e., static systems perspective) (Roberts *et al.* 2009). However, as systems exist in a rapidly changing world, they often come to operate in contexts for which they were not intended when originally conceived (Ross and Rhodes 2008). Therefore, it has now become of increasing importance to analyze the impact of dynamic contexts on a system (i.e., a *dynamic systems perspective*). In order to do so, one can perform an analysis of systems' performance in a sequence of alternative futures, in order to anticipate long-term value.

Uncertainty is embedded in everything, more so in highly dynamic environments. When considering complex SoS, uncertainty can take a variety of different shapes and impacts (McManus and Hastings 2005). In general, uncertainty could stem from endogenous sources, linked to the performance of the constituent systems and the SoS as a whole. Uncertainty could also stem from exogenous sources, having to do with context and expectation changes (Rader, Ross and Rhodes 2010). There are innumerable sources of uncertainty that could influence a particular decision. While endogenous uncertainties are easier to conceive and model, it is trickier to faithfully capture the exogenous ones in the system's analysis. In fact, the latter may arise from factors that transcend designers' imagination and the current state of the world. Addressing all these types of uncertainties may result in a very complex process, but not addressing them could quite lead to unexpected and undesirable outcomes.

In response to these uncertainties one might think that the goal would be to remove, or at least reduce the impact of, such uncertainties, but it is not so straightforward. Not only should systems be able to mitigate uncertainty that has a negative impact, but also, when possible, they should intelligently exploit opportunities arising in uncertain scenarios (McManus and Hastings 2005). However, very often decisions made during the design phase are far separated from the consequences of those decisions, even though they may have a significant impact on SoS performance. Therefore, decision makers often face very complex problems, with only a fragile foundation on which to base their conclusions.

SoS are particularly susceptible to the above considerations as they experience dynamics (e.g., of operational elements, operational modes, constituent actors, intended missions), and as they are exposed to a large variety of uncertainties. As a consequence, it becomes very difficult for systems architects to select which constituent systems should be incorporated in the composition of an SoS. In this regard, the selection of the constituent systems plays a crucial role in defining the quality of the SoS and its capacity to deliver value and respond to uncertainty.

Concluding, 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. The composition of the SoS is the frame on which its performance and uncertainty take shape. This paper proposes a method that allows designers to gain insights into robust portfolios of constituent systems for SoS composition. The method is a combination of two already existing methods: Epoch-Era Analysis and a generalized version of Modern Portfolio Theory.

Overview of Modern Portfolio Theory

In general, lowering risk when making choices is of value to decision makers. To this end, various techniques have been developed through the years in the context of different disciplines. A very influential method, known as Modern Portfolio Theory, was developed in 1952 by Harry Markowitz (Markowitz 1952). It was meant for use in the financial industry as a strategy for investing in a portfolio of financial assets. In finance, a portfolio of financial assets is a collection of investments (stock, bond or cash) held by an investor or investing company, characterized by the numbers and types of different investments.

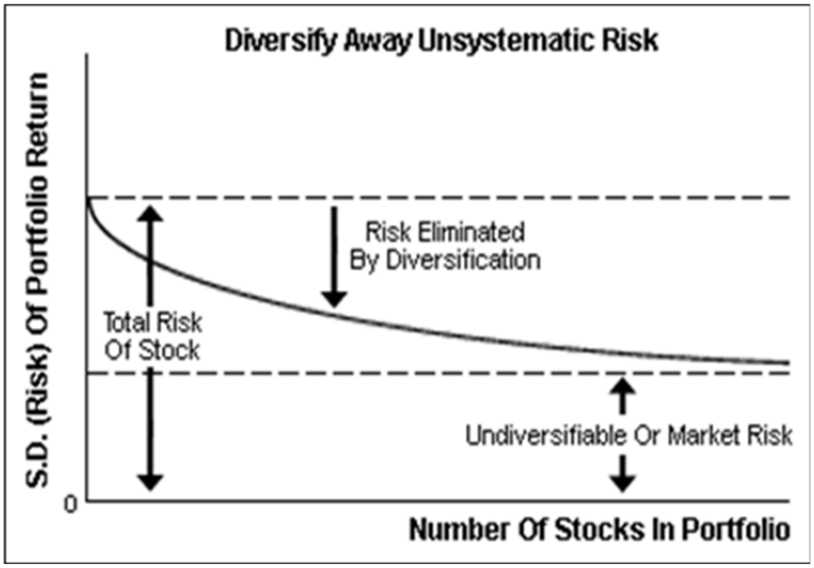

Figure 1. Undiversifiable, systematic risk vs. risk that can be eliminated by diversification of portfolios.
Source: http://www.investopedia.com/articles/06/MPT.asp#axzz1a7FrZ1Wx

MPT can be used for two fundamental purposes: (1) *maximizing portfolio expected return, given a certain risk investors are willing to take; or (2) minimizing portfolio risk, given an expected return investors are interested in*. MPT relies on the concept of diversifying portfolios in such a way that allows the collection of assets to have lower risk than any individual asset.

There are essentially two types of risk that affect a portfolio of assets: systematic risk and specific risk. Systematic risk is inherent to the market and inexorable. Specific risk, on the other hand, is the one that can be eliminated by means of diversification, as shown in Figure 1.

For a stock portfolio, the mathematical foundation of the theory comes from basic probability and statistical inference. MPT represents the return of each asset as a normally distributed function, and risk as the standard deviation of this function. The portfolio is modeled as a weighted combination of assets, and the portfolio return is the weighted combination of individual assets' returns. A covariance matrix describes the uncertainty and correlation of assets. The final goal of MPT is to reduce the variance (i.e., "risk") of the combined return function by combining different assets whose returns are not perfectly positively correlated. Mathematically, the expected return is given by:

$$E(R_p) = \sum_i w_i E(R_i) \qquad (1)$$

Where R_p is the expected portfolio return, R_i is the expected asset i return, and w_i is the weighting factor of the i^{th} asset. All the weighting factors must add to one. The variance of the portfolio return function can be expressed as:

$$\sigma_p^2 = \sum_i \sum_j w_i w_j \sigma_i \sigma_j \rho_{ij} \quad (2)$$

Where σ_p is the standard deviation of the portfolio return function, σ_i is the standard deviation of the i^{th} asset, and ρ_{ij} is the correlation coefficient between the returns of any two assets *i* and *j*.

MPT has numerous underlying assumptions that should not be overlooked, especially when trying to extend its use to other fields. Among these, the most important is that the asset return functions are assumed to be normally distributed random variables. Moreover, fixed correlation coefficients and risk-aversion are also assumed.

Over the years, many attempts have been made to improve the model, especially by using more realistic assumptions. An interesting extension of MPT is Post-Modern Portfolio Theory (PMPT). This theory has no single author, but it combines theoretical research of several people and institutions. The advancement in PMPT essentially resides in the fact that it adopts non-normally distributed measures of risk, and in particular, seeks to minimize "downside risk" rather than mean variance (Swisher and Kasten 2005).

There have also been efforts in the application of MPT to other fields. Of particular relevance is the work carried out by Dr. Myles Walton who, as his PhD dissertation, extended the use of MPT to space systems design selection. Although not considering SoS, Walton recognized some of the key limitations of the theory and made opportune modifications to it. In particular, in an attempt to account for the upside potential from uncertainty (e.g., "opportunity," as intended in Option Theory), he introduced the concept of semi-variance (upside and downside) as measures of one-sided uncertainty (Walton 2002).

Overview of Epoch-Era Analysis

Modern SoS operate in a rapidly changing world, and it is very important to consider their performance in different contexts that may arise in the future. Epoch-Era Analysis (EEA) is a computational scenario planning method that can be used for the analysis of systems that operate in dynamic environments. EEA considers changes in stakeholders' expectations and contexts (exogenous), and the system itself (endogenous). One of the advantages of the method is that it allows for the consideration of the temporal component in the analysis of system performance. EEA discretizes the lifetime of a system into a sequence of epochs. An epoch is a time period of fixed expectations and context, and each can be described by a start time, duration, expectations and context (Ross and Rhodes 2008).

An epoch is a particular encapsulation of uncertain future contexts and expectations for a system. Critical exogenous uncertainties can be used to propose "epoch variables" which could take on different values (e.g. economy could be "booming" or "in recession" or policy regulations could be "stringent" or "lax"). Particular sets of values for the epoch variables describe alternative point futures that could occur. The particular epochs considered in analysis is dependent on the key exogenous uncertainties that could impact the success of a system. Many possible epochs could unfold over time and this discretization of alternative futures is a way to allow for classical "static" analysis within epochs, as well as analysis across alternative epochs. "Multi-Epoch Analysis" is one approach for investigating how systems perform across various possible "point futures." (Ross *et al.* 2009)

A sequence of epochs constitutes an era, which represents a possible experienced lifetime for a system. Figure 2 shows an example of a constructed era from five epochs. "Era-level Analysis" investigates how a system performs through a sequence of epochs, allowing for consideration of path-dependent effects, such as accumulation of costs or "damage." Each individual epoch has specific context and value expectations band. If the system performs within or above the expectation, it is deemed valuable (Ross and Rhodes 2008). This type of approach can be used to identify time-dependent strategies for maintaining lifecycle value of a system in the long run.

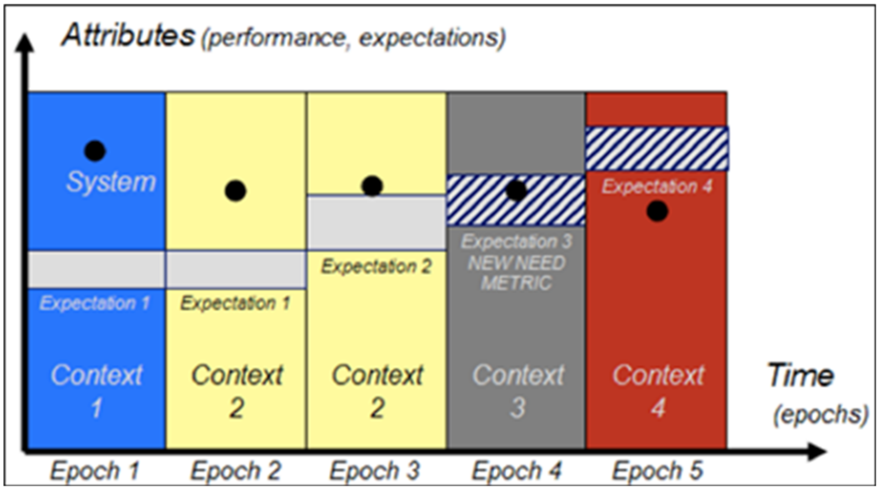

Figure 2. Era-level analysis with a system analyzed for performance through a sequence of different epochs (Ross and Rhodes 2008)

Dynamic Portfolio-Based Approach for SoS Composition

The ultimate goal of this investigation is to produce an analytic and prescriptive guidance on how to evaluate and construct system portfolios for SoS. This guidance would help decision makers to better manage the uncertainties associated with SoS that operate in highly dynamic environments. In order to achieve this end, a research approach is proposed that will go through two fundamental phases: the first consists of making the appropriate generalizations and adjustments to MPT and EEA in order to develop adequate theoretical and analytic means for the analysis of SoS composition; the second is to test the method by simulating the performance of actual systems of interest. As an outcome of the method, the impact of uncertainties related to context, stakeholder expectations, and system performance would be mitigated. Figure 3 below describes the proposed approach to formulate the generalized MPT+EEA method.

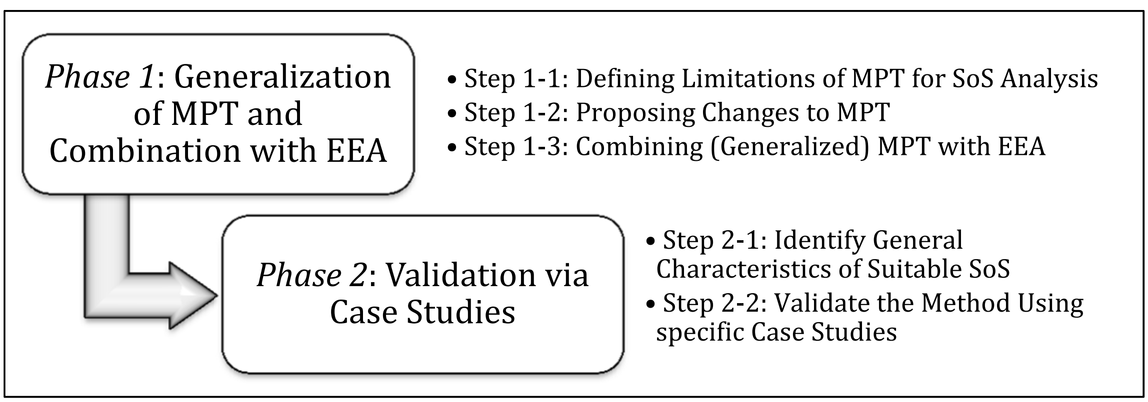

Figure 3. Proposed research approach for the generation of a prescriptive method for portfolio-based SoS composition.

The following sections describe the phases described in the proposed research approach.

Phase 1: Generalization of MPT and Combination with EEA

For the purpose of generating a method that enables decision makers during design to better manage the uncertainties associated with dynamic SoS, a systematic approach consisting of two main phases has been conceptualized. Phase 1 is aimed at generalizing MPT so to make it compatible for the analysis of SoS, and then combining it with EEA. As shown in Figure 3, there are three basic steps in Phase 1, which are described in the following subsections.

Step 1-1: Defining Limitations of MPT for SoS Analysis. In phase one, the first step is to define limitations and conditions for the applicability of MPT to the problem of SoS composition. More specifically, it is important to understand how viewing a *portfolio of systems* is different than a *portfolio of financial assets*. Ultimately, the objective is to conceive and formally theorize generalizations of the mechanisms behind MPT for selecting portfolios of constituent systems for SoS composition. What follows is a description of some of the important limitations and incompatibilities found so far.

An important difference between financial portfolios and SoS portfolios is that, whereas for the former risks and returns are typically extrapolated from past movements of stocks and other assets, in the case of SoS, simulation models may be needed in order to gather distributions of outcomes. The availability of historical data from which to draw distributions is significantly hampered for real systems, especially for unique or not-yet operating systems. Therefore, while it could be an arguably good approximation to model the return function of financial assets as *normally distributed*, that is not the case when considering constituent systems composing SoS. The distribution of the value (utility) of interest can in fact take a multitude of forms, and symmetric standard deviation around an expected value (characteristic of normal distributions) does not always accurately mirror the spread of the distribution.

A second notable difference is that MPT is based on an outcome function that aggregates the portfolio return as a weighted *linear* sum of the individual asset returns. In a SoS context, this linear relationship is often not the case. In fact, interactions and interdependencies among constituent systems, as well as saturation of possible performance and other factors, often yield non-linearity of the outcome function of interest. It is this nonlinearity, in fact, that is the lure of constructing a SoS in the first place: that emergence from combining the constituent systems together results in super-additivity of benefit. Some preliminary research has been done in framing the problem of how to combine contributions from constituent systems into an overall aggregated value function, but the work is still in its early stages (Chattopadhyay, Ross, and Rhodes 2009). Therefore, even in the unlikely case when normal distributions are good approximations, the expected value from the SoS cannot be aggregated as the sum of weighted expected values of individual systems (Jensen's inequality). Furthermore, the concept of covariance as intended in MPT does not hold both in the case systems' outcome distributions are not normal and for SoS that behave non-linearly.

Moreover, MPT relies on a constant availability of assets for all investors. This would indubitably be different when considering SoS constituent systems. It may be the case that particular systems are only available on a restricted basis, due to economic, technological, or political reasons, for instance. Also, some constituent systems may be initially available, but become unavailable at some point in future. For example, the production of a particular constituent system can stop, and only alternative systems with similar characteristics can be added or used to replace existing systems.

Finally, one last important difference is the fact that, unlike in finance, SoS portfolios are composed of assets whose growth and maintenance is driven by expenses and contributions by asset holders. Hence, there are costs associated with diversifying the portfolio and they must be taken into account in the analysis. Specifically, three types of costs that exist in SoS portfolios, but not in financial portfolios, can be identified: diversification cost, carrying cost and switching cost.

Diversification cost is the cost due to heterogeneity in the portfolio. For instance, having stocks, bonds, and foreign currencies in a financial portfolio, or having various types of aircraft in an airline's fleet. There is a cost associated with the system portfolio due to the need to maintain and operate diverse systems. For example, consider the airline that has a fleet of Boeing 737s, 757s, and Airbus A-340s. Due to the diversity, the airline must maintain training and parts diversity in order to maintain and operate the fleet. For financial portfolios, diversification costs are minimal.

Carrying cost is cost to maintain the existence of the portfolio. For financial portfolios this could amount to monthly maintenance fees paid to the financial managers; for system portfolios this could amount to the maintenance and operating costs for keeping the systems functional. Notice that diversification costs and carrying costs are distinct but related concepts in that the carrying costs are made "worse" by diversification for system portfolios (e.g., all things being equal a fleet of 50 aircraft where all are 737s has a different carrying cost than a mixed fleet).

Switching cost is the cost incurred when making a change to the portfolio, including changing the numbers or types of assets in the portfolio. For financial portfolios, this could amount to the transaction fee changed by the financial manager (e.g. $9.99 a trade). For system portfolios, switching costs can be substantial as acquisition and retirement of real assets can incur a nontrivial amount of cost, effort, and time.

The table below summarizes the significant differences that exist between financial portfolios and SoS portfolios.

Table 1: List of salient differences between financial and SoS portfolios

Financial Portfolios	SoS Portfolios
Often assumed normally distributed asset returns	Various types of distributions to be considered
Linear aggregation of asset return	Non-linear linear relationships in most cases
Covariance can express correlation of assets	Covariance cannot be used
Various types of assets are often generally available	Particular types may be limited based on economics, technology, politics
Availability of assets remains fairly constant	Assets can become available or unavailable over time
No portfolio diversification cost	Diversification cost
Low carrying costs	Possibly large carrying costs
Small switching costs	Possibly significant switching costs

Step 1-2: Proposing Changes to MPT. The second step of Phase 1 is to implement adequate generalizations to MPT in order to embrace the differences that arise during the analysis of SoS (listed in table 1). The two broadest and most critical differences to be tackled are the fact that distributions can be non-normal for SoS, and input-output relationships are non-linear. In particular, the concept of correlation of assets must be thought of in an alternative way than by using covariance matrices. The end goal is to develop and use a more general principle, analogous to the one of covariance.

It is also true that there can be instances in which some value (e.g. utility) functions (approximately) meet the requirements for application of MPT directly. This can be true for subsets of possible designs, for which changing the constituent systems or the numbers of each system (or even interactions) linearly increases or decreases the outcome of the utility function of interest (or approximately does). This is generally true when the outcome utility function is directly proportional to the number, type, or use of constituent systems; in this case, using variance can approximate outcome uncertainty.

Step 1-3: Combining (Generalized) MPT with EEA. The third important step in Phase 1 is to combine MPT, or the generalized version of it, with EEA. Epoch-Era Analysis is first used to gather performance and uncertainty information of many different SoS compositions operating through different epochs and eras (dynamic sequence of epochs). In particular, it provides information about the performance of constituent systems within the SoS. This is accomplished through enumeration of possible epochs (exogenous uncertainties), performance models (to evaluate the performance of alternative SoS within particular epochs), and related analyses ("multi-epoch analysis" and "era-level analysis"). Then, MPT makes use of this information to find which SoS compositions that yield maximum utility, given a specified risk level stakeholders are willing to accept, or, equivalently, minimum risk, given a certain utility of interest.

EEA provides an alternative to having only historical data on which to evaluate the performance assets in a portfolio. The two types of analyses within EEA each provide unique insights into the impact of uncertainty and dynamics on the value produced by systems. Multi-Epoch Analysis is an approach for identifying system robust to exogenous uncertainties involving contexts and expectations (Fitzgerald and Ross 2012a). This is accomplished through enumeration of a large set of possible epochs that might be encountered by a system. These epochs encapsulate a particular "point sampling" of uncertain futures. Analysis can be done looking across all of these point futures to identify alternatives that perform well (i.e. deliver high utility at low cost), that is, alternatives that are robust to changes in contexts and expectations (Ross, Rhodes, and Hastings 2009). In application of Multi-Epoch Analysis with MPT, one can consider the broad range of possible epochs as the equivalent of "market" uncertainty facing alternative SoS portfolios. Some portfolios will be impact more or less by these uncertainties and "difficult" and "easy" epochs can be identified. Those epochs in which all portfolios perform poorly are part of the "undiversifiable" risk faced by the SoS.

In contrast to Multi-Epoch Analysis, Era-level Analysis can be performed to identify evolution strategies for systems over time (Fitzgerald and Ross 2012b). This is accomplished through constructing alternative time-sequences of epochs, called eras, and analyzing the performance of systems that execute changes (i.e. "switches") in response to epoch shifts across the era. (Fitzgerald, Ross, and Rhodes 2011). In important consideration that can be accomplished through this type of analysis is the issue of "path-dependency," which is that the sequence of events and decisions experienced by a system matters. Of particular relevance in this application is the accumulation of costs, including diversification, carrying, and switching costs, over time may impact the ability to make decisions later in time. The trade-off of short term versus long term performance is not simply a matter of discounting future cash flows, as is often done in financial analysis, such as "net present value", but rather a more nuanced consideration of possible and achievable value at particular points in time (Ross *et al.* 2010). Since the availability of assets may change over time, "lock-in" through early decisions may preclude the availability of options at later decision points. For example, the airline that purchases new aircraft in 2005 may spend down its capital budget such that new acquisitions are not possible for over ten years, during which period competitors might change the market and therefore demand for alternative types of aircraft. The airline with the earlier purchase may not be able to effectively compete in this new market. Making the same purchase in 2000 or 2010 might have changed the picture. Era-level Analysis coupled with MPT will allow for the quantitative consideration of how one could evolve a portfolio over time, as well as the associated costs and benefits of alternative strategies for doing so.

Phase 2: Validation Using Case Studies

Phase 2 is concerned with testing the validity of the developed method (EEA+MPT) by using it for practical purposes. Phase 2 is aimed at exploring the common characteristics of SoS that could be eligible for the use of the method and directly applying the method to specific case studies. As shown in Figure 3 there are two basic steps in Phase 2 and they are described in the following headings.

Step 2-1: Identifying General Characteristics of Suitable SoS. The first step in Phase 2 is to delineate general features of SoS that can present themselves as candidates for the use of EEA+MPT. In general, it would be particularly relevant to consider SoS that are composed of a variety of different constituent systems, such that a multitude of compositions is possible. An eligible SoS shall have three basic variations that can be made. The first one is in regard to its *type*: different types of constituent systems that perform the same functions should be available for choice. The second possible variation is of *number*: the number of a particular type of constituent system should be able to vary and to be defined by the systems designer. The third possibility is to vary *interconnectedness* among systems: different types of connections among constituent systems should be possible. For example, alternative command and control architectures, such as distributed or central authorities. Variations in any of these three features of the portfolio should result in different SoS performance.

Step 2-2: Validating the Method Using Specific Case Studies. The second step of Phase 2 is to select SoS case studies that adheres to the characteristics listed in the first step, and explore the usefulness of the method developed by applying it to selected SoS. An important consideration is that before applying EEA+MPT, one must develop a simulation that can evaluate the performance (or at least benefit and cost) of the SoS in dynamic contexts to a desired level of fidelity. This need to simulate the performance of the SoS is one of the additional burdens of applying MPT to a SoS, rather than a set of financial assets with existing historical performance data.

An example candidate SoS that could be considered for analysis is a maritime security SoS. Although the tractability of this SoS as a case study is be investigated, this SoS is reasonable as an example for illustrative purposes. The purpose of this maritime security SoS is to monitor events happening over an area of interest, and keep the area safe form enemy attacks. The decision problem for the system architect is in regard to what (and how many) constituents systems to include in order to form a SoS that delivers a desired value, given fixed budget and a certain tolerable uncertainty. After the simulation is ready for use, EEA+MPT can be applied. EEA (more specifically multi-epoch analysis) would make it possible to analyze the performance of the SoS across different contexts and with regard to different desired capabilities (e.g. quantified in utility functions). Possible contexts include variations in the presence of weather, hostile pirates and smugglers, traffic level of passing ships, and availability of constituent systems and international partners. Possible functions of interest that provide value could include: detection, reconnaissance, coverage, effective communication, and attacking capabilities. For a selected desired value function, varying the types and proportions of constituent systems would yield different outcome distributions across alternative contexts. Information about these distributions and the role played by different constituent systems would then be used by generalized MPT in order to gain insights about what systems to include in the SoS.

As an example, if decision makers were interested in coverage for detection, the types and quantity of constituent systems can vary widely: it could be possible to use satellites, or radar towers, or low altitude UAVs (how many?), or high altitude UAVs (how many?). Obviously, the use of different constituent systems will lead to different performance, uncertainties and costs. This information can be used by generalized MPT at this point in order to make decisions on what systems to include. Eventually, after having applied the method for different utility functions, decision makers can identify what (and how many) constituent systems always stand out as contributors for the attainment of good results for any given utility measure.

Discussion

This paper introduced an approach for enabling decision makers to identify portfolios of constituent systems that are robust to uncertainties associated with SoS operating in uncertain and dynamic environments. A method was proposed that uses Modern Portfolio Theory in order to mitigate uncertainty, and Epoch-Era Analysis in order to analyze the impact of dynamic contexts on the SoS. This approach is comprised of two fundamental phases. The purpose of Phase 1 is to generalize MPT so to make it compatible for the analysis of SoS, and to combine it with EEA in order to form a method for identifying SoS that are more robust to uncertainties and dynamic environments. Phase 2 is concerned with testing the validity of the developed method by using it for practical purposes. First, common features of SoS eligible for the use of the method are delineated; then, the method is applied to specific case studies.

The underlying analogy between financial and SoS portfolios is also investigated in the paper. As an outcome, preliminary observations are made regarding violated assumptions in MPT when applied to SoS portfolios. Generalizing the concepts behind MPT to the analysis of SoS is a critical step to the success of the approach.

In general, the end goal of the proposed method is to facilitate the asset selection activity for SoS architects. It is important to recognize that the method is concerned with immediate (short-term) selection among available asset. Future considerations can take into account alternative types of investments. For example, medium-term investments would investigate the possibility of investing in asset development and modification; long-term investments would consider investing in technology development.

Furthermore, it is important to highlight the fact that the type of analysis carried out by the proposed approach would become notably useful when the composition of SoS is subject to fixed budgets. This is because one of the basic concepts behind MPT is can be used for minimizing the risks associated with a portfolio, given cost constraints. EEA can readily accommodate cost-constrained analysis and can be used to identify strategies for short term or long term value through evolving investment decisions.

While still in its exploratory phase, the proposed method development holds promise in leveraging a well-vetted approach for managing uncertainty from finance with a novel approach for managing the impact of dynamic contexts from engineering analysis. The synergy between MPT and EEA could potentially reveal new metrics, techniques, and principles for the development of robust and valuably changeable portfolios of systems for SoS composition in the face of uncertain and dynamic futures. In an interconnected and rapidly changing world, such a method might give leverage to help designers better compose their SoS and increase the likelihood of being able to sustain value in both the short and long run.

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Acknowledgement

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

Biography

Nicola Ricci. Nicola Ricci is a graduate student at MIT, pursuing an S.M. in Aeronautics and Astronautics. He is also a Research Assistant in the MIT Systems Engineering Advancement Research Initiative (SEAri), where his research focuses on the conceptualization and management of uncertainties present in Systems-of-Systems that operate in dynamic environments. His prior research experience includes developing an object-oriented simulation program in order to better understand the performance of System-of-Systems operating in highly stochastic environments.

Adam M. Ross is a Research Scientist in the MIT Engineering Systems Division (ESD) and a cofounder of the MIT Systems Engineering Advancement Research Initiative (SEAri). His research focuses on managing unarticulated value, designing for value robustness, and dynamic tradespace exploration for complex systems. Dr. Ross received his Ph.D. from MIT ESD and has published over 50 papers on changeability in system design and analysis. He has work experience with government, industry, and academia including NASA Goddard, JPL, the Smithsonian Astrophysical Observatory, Boeing Satellite Systems, MIT, Harvard, and Florida State Universities, performing both science and engineering research.