Determining Parameter Objectives via Model-Based Engineering

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***Abstract*— The concept development of any system includes the definition of various parameters of interest and determination of the threshold (satisfactory) and goal (desired) value for each. These are classically organized into Measures of Effectiveness, Measures of Performance, and lower-level Technical Performance Measures. These form the basis of performance requirements, the means for evaluating design, and the measure by which systems are validated. They define the trade space within which to optimize the emerging solution. This is challenging in routine development and substantially complicated when the system of interest aims for unprecedented capabilities from emerging technologies, which is the situation for electric ship research.**

This paper presents a method for defining parameters and objectives which is being developed and used in the U.S. Department of Navy sponsored Power Electronic Power Distribution System (PEPDS) research initiative. The method then integrates the Model-Based Systems Engineering system model with genetic algorithm trade space exploration tools.

***Index Terms*—MBSE, Digital Engineering, Technical Performance Measures, Trade space**

I. Introduction

The concept development of any system includes the definition of various parameters of interest and the determination of the threshold (satisfactory) and goal (desired) value for each. These are classically organized into Measures of Effectiveness (MOEs), Measures of Performance (MOPs), and lower-level Technical Performance Measures (TPMs), along with a crosscutting subset of MOPs & TPMs identified as Key Performance Parameters (KPPs). These form the basis of performance requirements, the means for evaluating design, and the measure by which systems are validated. They define the trade space within which to optimize the emerging solution. This is challenging in routine development and substantially complicated when the system of interest aims for unprecedented capabilities from emerging technologies, which is the situation for electric ship research.

Electric ship research is motivated by the accelerating pace of change in the threat. Adversaries are gaining technological advances and expanding their ability to conduct combined operations. More powerful sensors and new warfighting capabilities will need to provide increased detection range, improved discrimination accuracy, and full spectrum dominance. High-energy laser weapons, such as the Solid-State Laser Technology Maturation (SSL-TM) system installed on the amphibious transport dock ship USS Portland (LPD 27), have demonstrated the value of incorporating directed energy engagement elements to augment close-in weapon systems with defensive capability to counter asymmetric threats and make the ship more survivable [1].

One of the ways the U.S. Navy is driving modernization and new construction toward the electric ship is by leveraging digital engineering advancements to introduce an agile Integrated Power and Energy System (IPES) that enables electrified ship war-fighting capabilities [2] and to realize new shipbuilding approaches that integrate modular building block-based systems realizations of IPES into the earliest stages of ship design [3]. The U.S. Department of Defense Digital Engineering Strategy (2018) defines digital engineering as an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal [4].

If digital engineering is to have value, it should provide better, cheaper, faster techniques for making engineering decisions and enable early design exploration capability at the system level even before the determination of final KPPs that drive the design of equipment comprising the (well ahead of

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the beginning of the design process). This latter need is particularly relevant to realization of the navy's vision for ship electrification. To elaborate further: Decisions need to be made by stakeholders, such as shipbuilders, navy procurement agencies, and other decision-makers, well ahead of the engineering decisions made after a procurement is in place. Progress towards the development of Rapid Ship Design Environment (RSDE) tools to help stakeholders determine the impacts of low-level procurement decisions on ship system feasibility and viability still lack the capability of connecting RSDE process outcomes to stakeholder needs [5], [6]. The definition and utilization of TPMs across engineering disciplines and activities offers an excellent opportunity to realize the benefits of early design space exploration to decision-makers, but doing so requires innovation. This paper discusses one such innovation, a method for defining parameters and objectives which is being developed and used in the U.S. Department of Navy sponsored Power Electronic Power Distribution System (PEPDS) research initiative. The method integrates the Model-Based Systems Engineering (MBSE) system model with genetic algorithm based trade space exploration Model Based Engineering (MBE) tools integrated with ship level SBD to achieve a RSDE with full traceability between hierarchical technical measures.

II. Literature Review

A. *Technical Measurement Organization*

The challenges tackled by warfighter systems today lead to systems of extraordinary complexity. This is reflected in the huge number of technical measures available for a development program. More technical measures are available than anyone could reasonably grasp but not all are equally important at all times or for all issues. Programs have traditionally employed the standard systems engineering technique of developing abstract hierarchies in order to manage this complexity. Higher levels, or *tiers*, in the hierarchy are more abstract (less detailed). Lower tiers are less abstract (more detailed). This vertical and horizonal separate of concerns can reduce the problem to one of manageable complexity, but as in any analysis technique in which a whole is broken down into parts, the synthesis of the whole can be lost in the process. This has been sometimes proposed as a fundamental fallacy for abstract hierarchies.

The classic abstract hierarchy for technical measures has three formal tiers and an orthogonal tier spanning set: MOEs, MOPs and TPMs. Some programs adopt an additional technical measure organization, Measures of Suitability, which this discussion does not address.

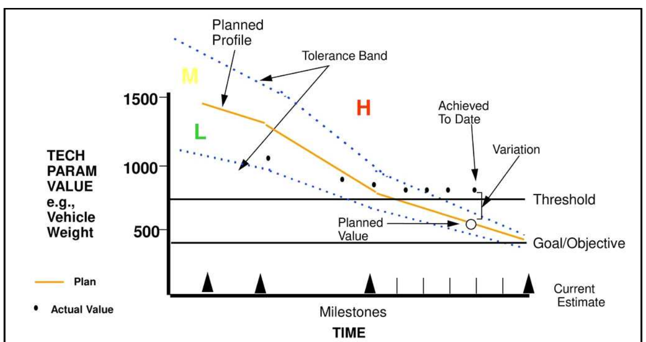


Fig. 1. Technical Measure Profile Illustration

The most abstract technical measure tier consists of MOEs which describe the requirements for the system's mission accomplishment. Programs typically identify MOEs during development of operational requirements and concepts. MOEs should provide insight into at least one operational objective or mission requirement. Despite the name "measure", MOEs often are n-tuples of related data and information as opposed to scalars.

The middle technical measure consists of MOPS, which derive from MOEs usually with several MOPS for each MOE. Programs typically identify MOPs during planning for test and evaluation. MOPs should be traceable to system level performance requirements, goals, risk, or issues.

Under the classical definition, the most detailed (least abstract) technical measure tier consists of (general) TPMs which derive from the system's MOPs usually with several TPMs per MOP. Programs typically identify TPMs early in the project, often during the proposal. MOPs support trade studies, feasibility evaluations, quality, and risk management. However, the MOPs themselves may not reveal the features that stakeholders really care about. Also, MOPs will fall within a range of threshold and goal values (as suggested by Fig. 1) and specific MOPs may be competitive, resulting in multiple feasible solutions. The TPMs are associated with the application environment or during integration of a System of Systems (SoS) to isolate the most viable sub-set of solutions—those that ultimately meet the program needs.

The final classic technical measure organization are the KPPs, sometimes also referred to as Key Performance Indicators (KPIs), a subset of MOPs and TPMs which are essential to developing a required capability. KPPs establish threshold values for mission accomplishment, performance, and operational factors. If not met, they have a great impact on the system's overall effectiveness and suitability. The US Department of Defense (DoD) requires specific KPPs for certain acquisitions. Often KPPs are experiential. For new development programs, KPPs may emerge through a correlation between MOPs and TPMs only after multiple successive system integration studies with the Integration Framework.

The result of all these is a cascading hierarchy of technical measures that are distilled into Technical Performance Measures. Reference [7] discusses the results of a study of actual practice technical measure organization on real acquisition programs, which Table 1 summarizes.

Table 1. Program Survey of Technical Measures[7]

Tier	Per Higher Tier		Program Total	
	Range	**Average**	**Range**	**Average**
MOEs	n/a	n/a	2-12	6
MOPs	1-10	5	5-50	30
TPMs	1-7	4	5-350	54

This data shows that programs invest in substantial technical measure programs but, given the intrinsic complexities of the systems involved, this kind of program can hardly be judged as comprehensive. The programs in question incorporate dozens of significant capabilities through the integration of hundreds of thousands of parts, millions of lines of software, in multiple force structures, with worldwide operation. Even 350 TPMs can provide only a glimpse into how well the system development is doing in achieving required capabilities. Enabling an expanded scope of inquiry is a key area in which digital engineering can achieve significant valuable innovation.

Identification of technical measures is just the beginning. In order to have any effect on managing the technical work, programs must determine the value that the program needs to achieve for each measure, and actually measure the value. Fig. 1 shows a generic technical measure profile. The profile defines a threshold (here as a maximum but could be a minimum or range) which is the value the program believes must be obtained in this measure for success. If the threshold value is not achieved, it could result in the acquisition program being terminated. It defines a goal/objective, a value that would provide additional benefit but is not strictly required. It defines a planned profile, here in the typical expectation that initial work does not meet the threshold (much less the goal) but that engineering will over the life of the program "do better". Since such plans always involve substantial uncertainty, the profile shows tolerance bands so the program can realize when their plan for success has gone awry. Finally, it includes "actuals", what has really been achieved-to-date.

Determining what has been achieved-to-date is a remarkable challenge in its own right. At the end of a development program, when first articles exist, actual measurements are conceptually easy through Test and Evaluation (T&E) – although in the real world, T&E often proves prohibitively resource intensive, impractical, or even impossible. Early in a development program, "actuals' are not actuals at all but "guesstimates" often done by projection from analogous systems. This is where modeling & simulation has become so important over the past four decades in moving from "wags" to estimates grounded in at least explicit, grounded models. This movement began with the adoption of disparate computer-based modeling & simulation methods in 1960's, improved as Moore's law fulfilled its promise of ever increasing computational power, a leap forward with the introduction of networked simulation, and is becoming fully integrated into engineering process through today's state of practice MBSE, state of the art Model-Based Engineering (MBE), and the leading edge work in Digital Engineering, as mentioned.

Thus actuals, the complement to measuring the achieved-to-date performance however is actually driven by determining what can be done, what must be done, and what may be done—or thresholds, goals, & objectives. The process of determining the goals, objectives, and thresholds of a system's MOPs, TPMs, and KPPs is a crucial aspect of systems engineering. To determine the goals, objectives, and thresholds of a system's MOPs, TPMs, and KPPs, a combination of methodologies, tools, and techniques are used.

Technical management, especially via technical measurement, is a key focus of systems engineering so other systems engineering techniques, such as functional analysis, trade studies, and risk analysis, provide some insights toward determining the system's performance objectives, and threshold values, and tolerance bands for the TPMs [8]. These insights however simply frame the technical measure issues, they do not determine thresholds, goals, or actuals.

A typical approach is top-down performance requirement allocation, where system performance requirements are allocated to its components [9]. Such approaches amount to a kind of top-down budgeting, where the program first estimates the technical measure value needed for the overall system, and then budgets a portion of that down the abstract hierarchy of functions and/or structures according to often unstated assumptions about what those lower components may achieve. The hope of accuracy in such an approach is heavily grounded in the central limit theorem, such that the error of lots of smaller guesses produces a sampling distribution that is unbiased with respect to truth. In actual practice, such budgets amount to a first approximation guess, useful mostly as a place to start, and components negotiate from there as facts emerge. This is not an approach which encourages an overall systems approach because it divides the interests of components.

The first approximation is more often than not based on "expert opinion". Forecasting for technical performance has included eliciting expert opinion. In many real-world forecasting exercises, statistical techniques may not be viable or practical, and expert judgment may provide the only basis for a forecast [10].

TPM Risk Index (TRI) is a method that describes "how individual TPMs may be combined to measure and monitor the overall performance risk of a system or SoS. The TRI methodology advocates a method to measure TPM risk, normalize it into a dimensionless value, and then aggregate it into the overall system risk [9].

A number of sources suggest various techniques grounded in statistical analyses. Reference [13] has presented a stochastic approach that can be used to determine MOP metrics estimates, bands of uncertainty, and to conduct sensitivity analysis, with the objective of improving performance prediction during the development of systems. Although those methods are reliant on specific metrics, basic forecasting for time series methods has been developed. These statistical methods can be used to forecast values in the future, given past performance [11].

Technical Readiness Levels (TRLs) are often discussed in the context of technical measures, however achieved-to-date (actuals) may not be best suited for measuring progress toward a TRL. At the early stages of the technology, the technical aspects of the system may not be readily measurable as they are yet to be proven. Technology maturation remains difficult to quantify [7].

Thus, thresholds and goals, as unto actuals, remain significant challenges although at least partially addressed within the scope of extant techniques. Digital engineering may provide improvement over these but is unlikely to be a fundamental paradigm shift.

However, beneath the problem of determining thresholds, goals, and actuals lurks a much more insidious problem buried in the assumptions of an abstract hierarchy of technical measures. We mentioned earlier that such an approach is subject to internal fallacies such as the loss of the whole.

The technical measure abstract hierarchy contains within itself a fallacy. Each component of a higher tier has a one-to-many relationship with the lower tier's components –with no interaction between measures that derive from different higher tier components. This, however, is self-evidently wrong. The problem can be likened to trying to pop a balloon bigger than one's hand– squeezing just makes the balloon bulge elsewhere. Likewise, focusing on a branch of the technical measure abstract hierarchy inevitably has repercussions in other measures out of focus. There is interaction between measures and the behaviors/structure that they measure. One can not simply partition the technical measures into neat never intersecting compartments. Everything can change any time and everything affects everything.

It is in addressing this last problem that the method explored in this paper offers a true innovation.

III. Method

A. Overview

While technical measurement is a key focus of systems engineering, systems engineering obviously does not define measures, determine thresholds and goals, or measure achieved-to-date in absentia from other technical disciplines. A major benefit of systems engineering is to break the stovepipes that naturally separate different kinds of work – to stovepipe systems engineering would be to make the solution part of the problem. MBSE, MBE, and Digital Engineering all point to models as the way to inform and integrate technical work as illustrated in Fig. 2. These model-based approaches depend on the use of a system model which integrates specialty models of all sources through the data they produce and consume.

Therefore, the system model instead of being a governor or allocator of responsibility is instead a broker which creates a "market" for data – literally a trade space. Within this trade space, contributing disciplines can explore the full range of values possible via their contribution, just as buyers and sellers do in a stock market. Instead of thresholds and goals being handed down from above, they can emerge from actual costs and benefits determined by the people who have the expertise and knowledge to determine the best fit. And more importantly, just as no one in a stock market buys and sells only one stock, individual disciplines will be able to trade thresholds and goals against all other measures.

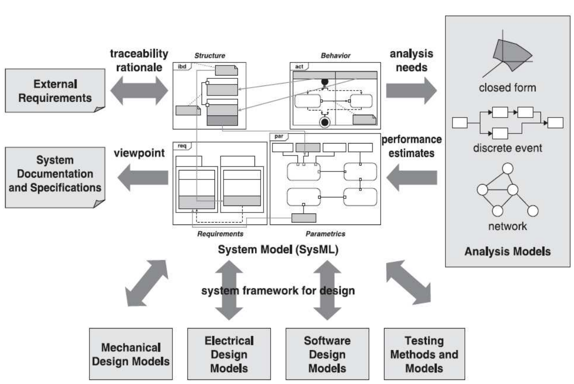


Fig. 2. The system model as an Integration Framework [27]

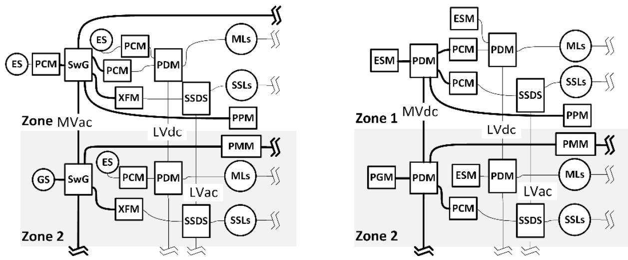
Perhaps this is an inspiring vision, but how can it be made a practical reality? One promising approach is to define the trade space as a solution space whose dimensions are the various measures, and the thresholds and goals as points along those dimensions. A specific "solution" is the vector with thresholds, goals, and actuals for each measure, fed to and arising from discipline specific models. Defined this way, the trade space has very high dimensionality but is very sparsely populated. To search this trade space is to search for the vector that provides the best overall value. This is precisely how a genetic algorithm works, with the vector's point addresses serving as genes and the optimal value defining the objective function.

Tying back to the stock market analogy, the "bid" price is the threshold, the "ask" price is the goal, the actual cost at sale is achieved, the buyers are the genetic algorithm's objective function, and the sellers are the discipline-specific models.

B. Motivation

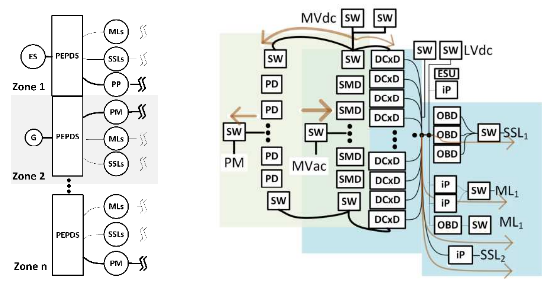
Realization of the U.S. navy's vision for IPES presents an important demonstration use case for the development of a suitable Integration Framework for MBSE, MBE, and Digital Engineering. IPES is the means by which the navy can achieve competing objectives of smaller ships, increased war-fighting capability, and reduced manning through electrification. Ship loads include installed Mission Loads (MLs) of a significant power level, electric propulsion, and pulsed power loads, in addition to requisite Ship Service Loads (SSLs). In aggregate, installed loads will far exceed the installed generation capacity. The IPES is an SoS responsible for the dependable delivery of electrical power and energy when and where it is needed. In the present taxonomy of the electric ship design community, the sub-systems of IPES are referred to as Modules to which specific functionality has been assigned. These Modules with their designations and descriptions are shown in Table 2.

Various realizations of IPES have been proposed as shown in Fig. 3, comprised of the IPES sub-systems listed in Table 2. Table 2 also describes the components and sub-components of each IPES sub-system. The IPES is a zonal electrical distribution system, where electrical and physical zones of protection align with the ship layout to ensure survivability. Also, MLs and critical SSLs are dual-fed from port and starboard-side feeds from PDMs and through the Ship Service Distribution System (SSDS) respectively. Fig. 3(a) shows integration of IPES into a conventional MVac distribution system where the PCMs, PDMs, PMMs and PPMs (of Table 2) are overlaid on top of conventional MVac switchgear, circuit breaker-based SSDS. The fact that this additional equipment is added to existing electrical infrastructure seems, contrary to the goals of enabling smaller ships with increased war-fighting capability.



(a) MVac-based system (b) MVdc-based system

Fig. 3. Variations on IPES (port-side half-zones shown)



(a) NiPEC (b) PEPDS Power Trains

Fig. 4. NiPEC-based PEPDS

TABLE 2. IPES SUB-SYSTEMS

Designations		Description
Transformer	XFM	MVac to LVac transformer plus switchgear
LVac Distribution	SSDS	The Ship Service Distribution System, including Load Centers and Power Panels
Switchgear	SWG	MVac Multi-Circuit Breaker switchgear
Power Conversion Module	PCM	General isolated or non-isolated ac-dc, dc-dc or dc-ac power conversion
Power Distribution Module	PDM	Multi- MVdc or LVdc Disconnect Switch Cabinet for MVdc or LVdc Distribution
Generator System	GS	Prime Mover plus Generator
Power Generation Module	PGM	Prime Mover, Generator, Switchgear, PCM and Disconnect Switch feeders
Energy Storage	ES	Bulk Energy Storage
Energy Storage Module	ESM	ES plus PCM including and Disconnect Switch feeders
Propulsion Motor	PM	Propulsion Motor
Propulsion Motor Module	PMM	MVdc or MVac to Variable Frequency MVac PCM plus PM
Pulsed Power Module	PPM	High Energy Pulsed Loads plus PCMs, short-term energy storage and Disconnect Switch feeders

TABLE 3. NIPEC-BASED PEPDS BUILDING BLOCKS

Designations		Descriptions
PEBB Drawer	PD	PEBB, dielectric stand-off & inductor
iPEBB	iP	Integrated multi-stage PEBB Drawer w/ transformer isolation
OB Drawer	OBD	Outer Bridge part of iPEBB with passives and dielectric stand-off (as required by interface)
Sub-Module Drawer	SMD	FB-MMC Sub-Module Drawer with PEBB and sub-model inductance and capacitance
DCx Drawer	DCxD	Isolated DC-DC Converter (DCx) part of iPEBB with dielectric stand-off (as required by interface)
ES Unit	ESU	Discrete Energy Storage Unit
Disconnect	SW	Galvanic Disconnect Switch

The MVdc-based IPES, shown in Fig. 3(b), attempts to reduce space consumed by eliminating cabling overhead and by assuming increased voltage and consequential reduced current ratings will reduce equipment size overall. MVdc-based IPES forces integration of common functionalities to the IPES Modules (PGM, PMM, etc.) to enforce space claim and other performance constraints through design and procurement. This approach carries two principal risks: (1.) Impacts of insulation, creepage and clearance on power density versus reliability (aging) are not well understood for MVdc systems mixed with switching power conversion. (2.) Each Module is a self-contained system, carrying the inefficiencies of thermal, busing, cabling and structural overhead, and space claim impacts are not well understood.

Successful IPES implementations require simultaneous exploration of all variables being considered—from components comprising IPES to the electrical distribution framework. Furthermore, IPES is only a sub-system within the larger ship system—which must accommodate physical space required for IPES sub-systems, constrained by hull displacement and impacts to ship level thermal management systems. These impacts to ship design are TPMs that determine overall feasibility of an IPES approach.

A PEPDS version of IPES separates out the power conversion and distribution functionalities of IPES into a single ship-wide Naval Integrated Power Electronic Corridor (NiPEC). Here, there are no physical IPES sub-systems, only building blocks listed in Table 3 that implement functionalities of the power conversion and distribution aspects of the IPES Modules. These building blocks include multi-use Line Replaceable Units (LRUs), such as Power Electronic Building Block (PEBB). NiPEC is built into the ship system bulkheads and decks thereby eliminating overhead inefficiencies associated with the systems of Fig. 3 through shared usage of common thermal, busing and cabling interconnections between the building blocks. NiPEC eliminates the enclosure and structural overhead associated "gray-box" cabinets of typical procured equipment. The PEPDS enables truly flexible and autonomously re-configurable delivery of electrical power and energy; and can extend the life of ships by enabling plug and play mission and technology upgrades.

Regardless of the approach, the IPES takes up a significant portion of the overall ship space and, as a result, will be integral to new ship design and build activities that require sign-off from a range of stakeholders. These include DoD decision-makers, procurement agencies, shipbuilders, and naval architects. Once enabling capabilities of IPES are sold to stakeholders at the highest level, subsequent design and procurement decisions must be made *concurrently* with the host of design decisions made by naval architects in the early stages of design. Critical MOEs of the IPES, such as operability, reliability, maintainability and availability (RMA), and safety, must be assessed during early-stage design exploration. MBSE is the best approach to deriving the host of MOPS against which IPES sub-system components will be assessed. At the same time, the correlation between MOPs and system-level TPMs and KPPs must be understood early on through an MBE approach.

Fig. 5 shows a generalized MBE-based Integration Framework for early-stage design exploration of IPES-based ships. As proposed in [15], IPES sub-system design space exploration occurs within an evolutionary environment to enable multi-disciplinary optimization—so that the trade space of competing MOPs is exhaustive and transparent (i.e. decisions can be reconstructed after the fact). Because it is integral to the whole ship design, design exploration of IPES sub-systems must connect the total ship Concurrent Engineering environment that will be utilized by naval architects to execute Set-Based Design (SBD) of the ship system [16]. SBD identifies sets of feasible and viable solutions for the overall ship. The novelty of Fig. 5 is that it maintains traceability to IPES sub-system level decisions through design space variables, $\mathbf{x}_V$, that are a sub-set of the ship system level design space variables, $\mathbf{x}_S$, and thereby enforce transparency. These design space variables, $\mathbf{x}_V$, feed analytical electro-physical models forming a fitness function constrained by $\mathbf{r}_V$, i.e., sets of IPES sub-system requirements and constraints that are sub-sets of the ship system level requirements and constraints, $\mathbf{r}_S$. The fitness function is executed within the evolutionary optimization environment to produce a performance space of competing MOPs, such as such as power density (ρ, MW/m3) or specific power (γ, kW/kg) versus efficiency (η, %). These MOPs are meaningful at the individual IPES sub-system level. Fig. 5 is only a MBE approach and does not include the MBSE connection to stakeholder needs. In many programs, the MBSE aspect is often put off until after design exploration begins, resulting in built-in inefficiencies and risks. MBSE should precede MBE to avoid re-work and misleading results.

IPES design exploration outcomes must formulate sets of solutions for the ship system level. Model-based solutions that are functions of $\mathbf{x}_V$ are made possible by extraction of a metamodel for each IPES sub-system. The integration of IPES sub-system design exploration with scalable metamodels of components for system-level exploration is based on the principles described in [17] and [18]. Solution metamodels are extracted from designs aligned with the MOP space Pareto front. They are represented as models to the total ship CE environment in sufficient detail in the form of *parameters* that are functions of input design space variables, $\mathbf{k}_V(\mathbf{x}_V)$, and *performance functions*, $\mathbf{\Psi}_V(\mathbf{x}_V)$, which are subject to the IPES sub-system constraints, $\mathbf{r}_V$. The total ship CE environment can then produce TPMs that can be assessed against stakeholder needs. Ultimately, MBSE will connect those MOPs to the system level MOEs through identified and weighted TPMs and KPPs, according to stakeholder needs.

The total ship CE environment may be realized through Smart Systems Design (S3D) [19], [20], which is a digital engineering environment developed for the modeling and analysis of Navy shipboard distribution systems. An S3D model can be thought of as a *digital twin* for the total ship system to be utilized by naval architects in the execution of Set-Based Design (SBD) [16] to identify feasible solution sets. These solution sets link to a MBSE process when they are based upon stakeholder identified, acceptable TPM limits and system level requirements, $\mathbf{r}_S$. SBD feasible solutions that are functions of sets of system level design space variables, $\mathbf{x}_S$, which can then be reduced down to much smaller viable

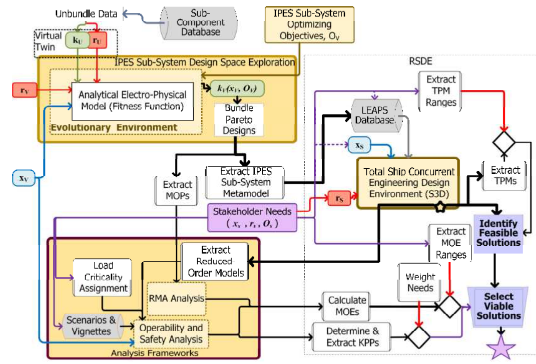


Fig. 5. Generalized MBE-based early-stage design exploration

solution sets through performance of additional analysis that enable the assessment of total ship-level MOEs against sets of stakeholder derived and weighted MOEs. In this way $\mathbf{x}_S$ represents the range of alternatives in the total ship design being considered.

S3D combines use of *physical twins* and *virtual twins* of ship system components, component interconnects and ship-space structures, according to the digital twin definition [21]. These elements of digital twin are part of the execution of SBD in the RSDE. S3D is integrated with the Leading Edge Architecture for Prototyping Ships (LEAPS) [22], which is the Navy's data repository for ship information.

LEAPS contains properties that can be utilized to model ship components, interconnects (i.e. shafts, piping and cables) and structures (i.e. hulls and bulkheads). These properties are unique identifiers for the mathematical model of components, interconnects and structures modeled within S3D. If the data stored in LEAPS is compliant with the Formal Object Classification for Understanding Ships (FOCUS) then it applies across programs. FOCUS is the product metamodel that defines how to store and use LEAPS properties within S3D [23].

FOCUS-compliant properties can be traceable to physical realizations of Program of Record (PoR) components, interconnects, and structures across multiple programs. S3D models the electrical and performance, physical space claim and mass of PoR elements in corresponding domains in order to construct the total ship CE environment. FOCUS-compliant PoR components may also connect to the IPES design space exploration for more conventional implementations, such as Fig. 3(a) by utilizing components of the IPES sub-systems that are traceable to originating physical twins through properties stored in LEAPS. The same goes for the population of the total ship model with components of other sub-systems, including the MLs and SSLs. These are not part of the IPES design space exploration, which is responsible only for producing those IPES sub-systems that connect to the MLs and SSLs.

Metamodels are constructed in S3D utilizing derived performance properties stored in LEAPS. The result is the construction of virtual twin models of components in S3D. PoR components are represented generally by parameters, $\mathbf{k}_U$ and constraints, $\mathbf{r}_U$. In the three-dimensional layout space of S3D $\mathbf{k}_U$'s are used to construct physical models with dimensions and mass. TPMs of an IPES implementation, such as total space claim of the arrangement of components and interconnects, within the total allowable ship space, and associated hull displacement, can then be extracted. In other domains of the S3D CE environment, electrical and thermal KPPs can be extracted by post-processing results for these models, built from $\mathbf{k}_U$'s associated with these environments and, constrained by intersection of respective $\mathbf{r}_U$'s, with $\mathbf{r}_S$'s. Examples include component versus system voltage ratings, installed power capabilities (intrinsic power ratings, P_{oi}) versus load demand and component pressure drop versus thermal management system supply.

The RSDE of Fig. 5 does not model the dynamic performance necessary to extract system-level KPPs, such as metrics of survivability, operability and resiliency. Ultimately, the combinations of IPES sub-system level MOPs and IPES system and ship level KPPs must trace back to MOEs as one means to down-select of viable solution sets from larger feasible solution sets. Therefore, an additional Analysis Framework is added that incorporates emulation of reduced-order, detailed time-domain ship system models with the IPES (derived from the S3D ship model of feasible solutions) into a real-time or accelerated-time simulation platform, such as OPAL-RT or RTDS. The operability and safety analyses can then be explored as a function of $\mathbf{x}_S$, which, combined with RMA analysis, to produce the necessary KPPs.

C. *Scalability of IPES Sub-Systems*

Consider the MVdc-based IPES of Fig. 3(b) where IPES Modules, PGM, ESM, PPM and PMM, have integrated into them all of the nominative functionalities (listed Table 2). Referring to Fig. 5, $\mathbf{x}_V$ dependent metamodels of IPES sub-systems should be extracted and then incorporated into LEAPs. Three-dimensional models of these Modules should be represented as cuboids within S3D ship arrangements environment that are scalable with $\mathbf{x}_S$ and dimensionally constrained by the maximum allowable deck height (y-direction) and spaces in front, back and sides for accessibility and maintainability (included in $\mathbf{r}_S$).

If scalable models cannot be produced, then the RSDE can only rely upon PoR or commercial off the shelf (COTS) equipment, that has been incorporated into performance data within LEAPS. Even if a sufficient catalog of PoR and COTS components existed within LEAPS, their associated virtual twins represent single set-point designs. This approach limits the validity of the solution sets that can be explored by executing SBD within the RSDE. Decisions are made based upon sub-optimal inputs to the process, resulting in significant risks to programs.

The beginning of a solution to this quandary are Office of Naval Research (ONR) Science and Technology (S&T) investments in multi-use PEBB development programs and subsequent integrated PEBB (iPEBB) programs. PEBB and iPEBB can enable both maintainable, scalable, and flexible IPES sub-systems and, more significantly, the NiPEC-based PEPDS approach to IPES. A common PEBB enables a wide range of power conversion functionality that can be allocated to and spread among multiple IPES modules, there y reducing specific cost (σ, MW/USD) through economies of scale. Also, recent programs utilize the PEBB as a convenient means for new technology insertion. Examples include ONR's investment in 6kV PEBBs (PEBB6000), utilizing 10kV rated Silicon Carbide (SiC) MOSFETs, and a 1kV iPEBB that integrates four H-bridges, a high frequency transformer, dc-link capacitors and associated control interface hardware into a single common substrate structure. Development efforts over the past decade have brought the PEBB6000 to TRL 4, with efforts underway to bring PEBB6000 to TRL 6 through system-level demonstration programs. The iPEBB is progressing towards TRL 3, while addressing many multi-disciplinary innovations.

The PEBB/iPEBB enables ship level SBD that has traceability by incorporating the PEBB type usage into the design space variables, $\mathbf{x}_V$. Assuming that data can be extracted to enable virtual twins of PEBB/iPEBB building blocks to be utilized for design space explorations of IPES sub-systems and PEPDS within S3D, and assuming that associated data includes unique identifiers traceable to PEBB/iPEBB TRL, then early-stage ship level design exploration can be done concurrent with PEBB/iPEBB development efforts and new ONR S&T investments. This will allow RSDE to be refreshed as TRLs increase or, conversely, RSDE outcomes to inform PEBB/iPEBB development or better focus impacts of PEBB/iPEBB MOPs on the system level MOEs.

Constructing a system-compatible PEBB/iPEBB based solution for IPES is not a simple matter given a number of practical considerations. With only a PEBB6000 as a building block, the PCM-level capability is insufficient. For example, breakerless IPES architectures are enabled by fault current limiting of the PGM during MVdc bus short circuit faults. The full-bridge version PEBB6000 enables this capability when configured as a Full-Bridge Modular Multilevel Converter (FB-MMC) based active rectifier for MVac-MVdc non-isolated conversion. The FB-MMC current arresting functionality cannot be achieved without addition of dc-link and sub-model arm inductance passive components to the PEBB6000 to form one sub-module of the FB-MMC. A new building block for FB-MMC can be realized by incorporating the PEBB and required passives into a stackable Sub-Module Drawers (SMDs) [17], [18], [25]. Also, since the FB-MMC requires series connection of lower voltage rated PEBBs to enable a higher MVac/MVdc PCM-level voltage rating, the SMD provides a location for addition of dielectric stand-off distances between floating PEBB chasses and the ship hull ground (at the potential as Module cabinet or NiPEC chasse) to meet system-level creepage and clearance requirements. Similar approaches to power conversion are realized with Drawers containing iPEBB and sub-components of iPEBB, described in Fig. 4(b) and Table 3

The authors have proposed a Virtual Prototyping Process (VPP) to produce scalable PEBB-based solutions to PCMs and PDMs within IPES sub-systems *and* PEPDS [25]. The VPP accounts for many practicalities needed to correctly quantify dimensional and mass impacts to ship spaces and hull displacement. These allocations are organized into cuboid representations (xyz space) within and around Drawers assigned to the following functionalities: (1.) maintainability, $\boldsymbol{\alpha}_{\mathbf{a}}$, (2.) insulation stand-off derived from an insulation coordination process, $\boldsymbol{\alpha}_{\mathbf{d}}$, (3.) thermal management, $\boldsymbol{\alpha}_{\boldsymbol{\eth}}$, frame structure and enclosures α_f, and busses and bus-interconnects α_c. These allocations apply not only at the Drawer level but are formed around the stacked arrangement of Drawers into vertical compartments. The α-space will define additional compartments that provide bus interconnections, accessibility support and thermal management to these Drawer compartments. IPES Sub-systems and PEPDS can be built by compiling together all of these compartments into Bays. In this way, MOPs such as power density and specific power are correctly represented in the system and the associated system-level TPMs can be derived.

D. *MBSE Approach*

Ship builders and DoD agencies responsible for acquisitions have little experiential basis for MOPs that drive specifications for and qualifications of procured sub-systems of IPES. This will be especially true for an NiPEC-based PEPDS realization of the IPES, which will require that qualified procured building blocks are seamlessly integrated into the ship system. Traceability of MOPs to MOEs can be accomplished by building a System Model following an MBSE process. For the IPES, at the ship system level, all MOPs (at various levels of service within the IPES) are derived from three MOEs: Operability, RMA and Safety. Table 4 shows MOPs that can be derived for the point of service function for all Module types.

IV. Results

A. *System Model*

The PEPDS Architecture Team has successfully baselined a System Model defining functional architecture described in terms of needs, functions, structures, and measures transformed into a baselined set of functional requirements. The functional architecture baseline enables design exploration in the solution space. Fig. 7 shows an example of outcomes from the System Model. The full set representing the functional architecture is defined in several extension System Modeling Language (SysML) diagrams which are available via Reference [27].

The next ordinary steps would be to allocate the thresholds and goals to each defined MOE, MOP, and TPM. Instead, because of the many unknowns of the NiPEC-based PEPDS, we intend to proceed according to the process shown in Fig. 6, as will be described in the next section.

B. *Framework for MBSE and MBE of PEPDS*

Fig. 6 describes an MBE-based Integration Framework for NiPEC-based PEPDS and every aspect of achieving successful outcomes from the RSDE discussed in this paper, including the connection to the System Model. Comparing this with Fig. 5, the design exploration of IPES sub-systems block is replaced by VPP of PEPDS power trains. The concept of a power train highlights a key distinction between conventional IPES sub-systems and PEPDS. Referring to Table 2 and Fig. 5, PCM and PDM sub-components Modules are the scalable models that would be extracted from multi-disciplinary optimizations within the evolutionary environment over the design exploration space, $\mathbf{x_V}$. These metamodels will typically represent only a single power conversion stage (that is part of the Module) and, for any distinct set of variables within $\mathbf{x_V}$, multiple solutions are produced along a Pareto surface, from which a metamodel for that power conversion stage (the PCM within the Module) can be derived having an intrinsic power rating, P_{oi}, that is a function of the specific inlet water temperature, T_A and its mass flow rate, $\dot{q}$. These, in turn are variables within the $\mathbf{x_V}$ that are bounded by upper and lower limits imposed by the external thermal management system at the ship level. A range of dimensional cuboid volumes, in a Cartesian (or *xyz*) reference frame, are produced for each design space variable set of combinations that lie somewhere along Pareto surfaces that are defined by the starred MOPs listed in Table 4: σ, ρ, γ, η and λ^{-1}.

Table 4. IPES Sub-System or PEPDS Technical Measures
(*indicates MOP used as an optimizing objective)

MOEs	MOP Categories	Module (Fig. 3) or Power Train (Fig. 4) MOPs
Operability	Adaptability	Robustness
		Application Adaptability
		Scalability
	Affordability	*Recurring Specific Cost (σ)
		Non-recurring Specific Cost
	Logistics	LRU Repair Time
		LRU Repair Cost
	Power Distribution	*Power Density (ρ)
		*Specific Power (γ)
		*Conversion Efficiency (η)
		Nominal Step Load Voltage Response
		Nominal Bus Stability
		Voltage Ramp Rate
		Charge / Discharge Rates
		Nominal Step Load Voltage Response
		Nominal Bus Stability
RMA	Reliability	*Rate of Failure (λ^{-1})
		MTBF
	Maintainability	MTTR
		Maintenance Burden
		Percent BIT Fault Detection
		Percent BIT Fault Isolation
	Availability	Inherent Availability
		Operational Availability
		Achieved Availability
Safety	Personnel Safety	LRU Transportability
		LRU Liftability
		Galvanic Isolatability

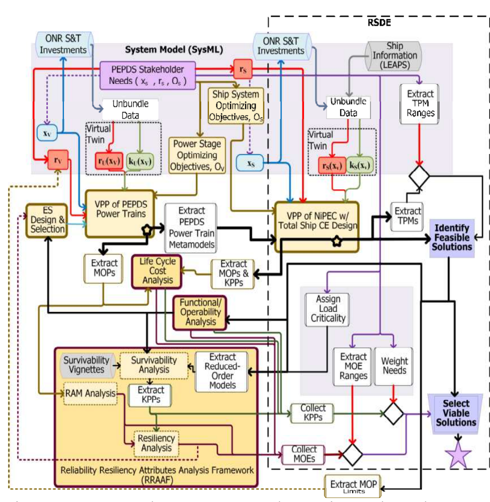


Fig. 6. MBSE and MBE approach to NiPEC-based PEPDS

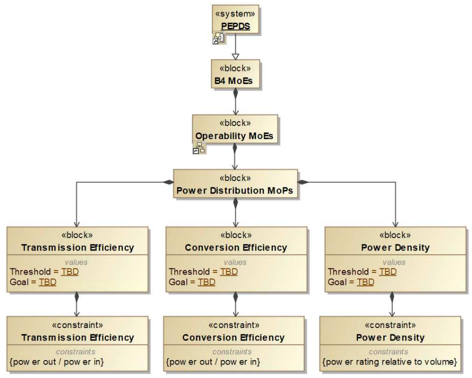


Fig. 7. Example of SysML outcomes defining the traceability between MOEs and MOPs of the NiPEC-based PEPDS

Consider power density MOP (ρ). A single point solution on the Pareto front, maps to a ρ value, for that power conversion stage, defined as the ratio of its distinct installed $P_{oi}(T_A,q^{\cdot})$ to its dimensional volume. For a PEPDS solution, meaningful MOPs are technical measures between points of input source to output load. These are defined as *power trains*. So, for example, Fig. 4(b) shows multiple power trains associated with a grouping of PEPDS building blocks installed in a section of NiPEC. One power train is from an MVac input to an MVac output, which includes two power stages and two sets of three disconnect switches at each interface. There will be a an intrinsic power capability, $P_{oi}(T_A,q^{\cdot})$, of the combined path through the building blocks in that power train and a volume occupied by the power train. The volume is calculated from sum of the cuboid volumes, bounded by the front and backs of NiPEC, of all of the NiPEC building blocks (refer to Table 3 for definitions of designations in Fig. 4(b)). The volume calculation includes the α-space within SMDs and PEBB Drawers (P), as well as the α-space of the shared bus and thermal interconnections between them and volume of the manifold and accessibility interfaces for each vertical section of the power train (including those that may be only partially populated) to the shared interface to ship level thermal management. This approach accurately represents the total space claim within NiPEC of the power train and the ratio of $P_{oi}(T_A,q^{\cdot})$ to space claim within NiPEC defines the power train power density, ρ. A second power train shown in Fig. 4(b) is from the MVac input to the combined outputs feeding the low voltage MLs and SSLs in a zone.

As shown in Fig. 6, metamodels must be extracted from the VPP applied to each power train that are functions of $\mathbf{x}_\mathrm{V}\supseteq\mathbf{x}_\mathrm{S}$.and $\mathbf{r}_\mathrm{V}\supseteq\mathbf{r}_\mathrm{S}$. The outcome of the VPP of a power train are Pareto optimized SMD(s), P(s), iP(s) and smd(s) comprising that power train. Considering the PEBB6000 example for a FB-MMC power stage, the SMD passive LRUs are first optimized by searching through pre-defined templates for SMD arrangements and executing NGSAII on the passive LRUs that constraints their heights to the height of the PEBB. The compilation of the SMD incorporates all allocations, including, those for dielectric stand-off distances, α_d, accessibility space, α_a, and thermal management space, α_∂, around the PEBB and passive LRUs. An underlying optimizing object is to minimize any dead space within the SMD not occupied by an LRU or by α-space. VPP is executed within MATLAB and utilizes an external toolset, GOSET, for NSGAII, developed by Purdue University. Fig. 8 shows the results of the VPP of MVac to MVac PEPDS power train SMDs against two optimizing objectives, ρ and η, as a function of supplied inlet water temperature, T_A, assuming that all LRUs producing heat are coldplate cooled by deionized water. The remaining design space variables are at one set point and include MVdc bus voltage (12kV), generator frequency (60Hz), inlet water mass flow rate, FB-MMC MVac-MVdc circuit topology, PEBB/iPEBB=PEBB6000, and Half-Bridge MMC MVdc-MVac circuit topology utilizing one-cycle PWM control. The surface contours from which the metamodels are derived are also shown in Fig. 8.

Properties of the SMD(s), P(s), iP(s) and smd(s), including parameters, $\mathbf{k}_\mathrm{V}(\mathbf{x}_\mathrm{V})$, and performance functions associated with the distinct functional features of the power train, $\mathbf{\Psi}_\mathrm{V}(\mathbf{x}_\mathrm{V})$, formulatea distinct metamodel for the power train. Within the S3D total ship CE design environment, all of the possible power trains that can be produced by an NiPEC-based PEPDS installation of the IPES will be incorporated into the LEAPS database, so that VPP of NiPEC can continue in that environment to optimize the arrangements and surrounding structures within the NiPEC according the same MOPs into order produce sets of NiPEC designs concurrent with sets of overall ship designs using the SBD. This is the vision for PEPDS-based RSDE. Under the current paradigm for VPP execution, it will be enabled if the models for PEPDS power trains built in S3D can embed MATLAB functions within them.

Fig. 6 also shows the connections between the VPP of PEPDS power train, NiPEC VPP, ship system SBD and the System Model. All of this shows the complete connections between MSBE and MBE for NiPEC early-stage design exploration. The System Model is currently executed in CAMEO and produces, through functional model analysis, the PEPDS power train level MOPs, a portion of which are intended to inform the goal/objective values for those MOPs that are used for PEPDS power train optimizing objectives. Since there is no experiential bases for what these goal/objective values should be, the intention is to inform those goal/objective values as constraints, $\mathbf{r}_\mathrm{V}$, based on iterative execution of the VPP on multiple possible power trains (shown by the dashed connections between extracted MOPs from sets of feasible solutions. Currently, the System Model can can inform some MOPs (such as those associated with RMA MOEs) with logistics analysis and inform other MOPs with results from models other than the system model. Finally, system level KPPs will be derived from the Analysis Frameworks that are also shown in Fig. 8.

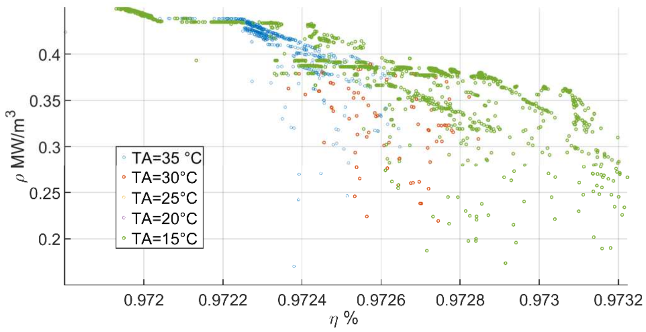


Fig. 8. MOPs produced by VPP of the PEPDS power train from MVac (generator input) to MVac (variable frequency propulsion motor output)

V. CONCLUSIONS

This paper reviewed the challenge that MBSE, MBE, and Digital Engineering faces in defining various measures of "goodness", establishing thresholds and goals for them, and creating a coherent chain of evidence from the system and other models used in a program. It presented a method for defining parameters and objectives which is being developed and used in the U.S. Department of Navy sponsored PEPDS research initiative. The method then integrates the MBSE System Model with genetic algorithm trade space exploration tools. The proposal has high "face" credibility, which further research aims to confirm as a practical general approach.

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