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Exploration and Investigation of Appropriate Tools to Facilitate Set-Based Design

Abstract

A conscious effort is underway to explore the paradigm of Set-Based Design (SBD) for development of next generation US Navy ships. The Electric Ships Research and Development Consortium (ESRDC) funded through the Office of Naval Research (ONR) is responsible for developing a state-of-the-art design environment namely, Smart Ships Systems Design (S3D) wherein one focus area is to incorporate SBD functionalities. Impetus and efforts to develop SBD enablers, to be used within a concurrent and collaborative environment like S3D are in its infancy. The first step, is to explore viable well-established tools that are most suitable to perform the fundamental SBD task of feasible-design space reduction subject to user driven requirements and constraints. Once potential tools have been identified, the next step is to investigate their suitability for integration with S3D, with further studies into extent of necessity of modifications. This paper illustrates the use of full-factorial design analysis as one potential tool to facilitate SBD and discusses relevant aspects and future work. The benchmark medium voltage DC (MVDC) equipment considered for this study is the modular multilevel converter (MMC).

Index Terms – Design methodology, full factorial design, set reduction tools, SBD, S3D.

INTRODUCTION

Development of S3D [1] has been an ongoing effort within the ESRDC and remains a major area of focus. Recent work done by authors highlight some potential tools which informs background work to better understand the design domain, impact factors and pertinent metrics [2]-[5]. Well-established techniques used in the product development arena, identified by authors as potential candidates to facilitate SBD are:

1. Quality function deployment, particularly the House of Quality (HOQ) [6].
2. Robust design using reduced factorial Taguchi method (TM) [7].

Leveraging these efforts, the next step is to make detailed and rigorous analyses to better understand the applicability of the identified tools. A reduced factorial representation via the TM was detailed in [4] which uses outcomes of HOQ that lead to extracting expert knowledge and guiding further work are reported in [5]. Understanding the fact that S3D is an early-stage ship design environment, some important aspects to be mindful of are as follows:

1. Sufficient level of design detail across the system and sub-system
2. Capturing expert knowledge to inform the user to make better decisions
3. Integration with S3D of functionalities and tools developed

Prior work evaluated the usefulness of the TM to perform set-reduction and showed promising results. This paper expands on the work previously done by analyzing designs through a full-factorial array. This supplements the TM based effort by adding detail to the set of feasible designs and enables evaluation across an expanded space. MATLAB and MS Excel were mainly used to develop functions, analyze results and visualize the design arrays. As in previous work, this paper uses the MMC topology as a benchmark system available for study at the authors' facility [8] which forms an important design assessment reference.

MMC DESIGN STEPS FOR SHIPBOARD SYSTEM

The basic aspects of the procedure to design an MMC system have been sufficiently explained in the works [2]-[5] and [9]. An important metric to evaluate MMC system designs is its power density expressed in MW/m^3. To understand which of the MMC constituents that impact this metric the most, a component level decomposition study was reported in [2] and [3] outcomes of which are summarized as follows:

1. Cooling scheme – The heat sink (HS) of the each MMC submodule (SM) is the most significant contributor to the volume (≈50% [2]). Hence the

choice of the HS plays a key role in obtaining the best power density.

2. SM capacitors – While the capacitors within each SM do not contribute much to the volume (< 10% [10])
3. Cabinets – These house the individual SM and the arm inductors. In most cases, the two cabinets are separate and could be cooled using different schemes for example liquid cooling for the SM and forced cooling for the arm inductors. The key factor for designing the enclosure is to account for maintenance which includes spacing and clearances that lower the overall power density. Another important factor is the restriction on the cabinet height for ease of replacing equipment. These aspects have been elaborated upon in [4].

The analysis shown in this paper is conducted for the SM cabinet. Studies including the arm inductor cabinet are planned for future work, which will then encompass the whole MMC system and enable derivation of scaling relations.

ESTABLISHING DESIGN RULES AND GUIDELINES

Design rules form an important part of the process. Two distinct categories of design rules are elaborated here which tie in the previously explained component-level aspects.

1. **Mathematical** – These design rules are equations that enable calculating values for components after which relevant manufacturer catalogs are referenced to select components. The component values required change with varying parameters and dictate the task of selection from catalogs. In relation to the MMC SM, the following components require such mathematical design rules:
   a. *SM capacitor (C_{SM})* – Sizing equation utilized in [3].
   b. *IGBT thermal resistance (R_{th})* – IGBT selection is relatively straightforward and based on the SM voltage (V_{SM}). The R_{th} computation follows fundamental heat transfer equations and is elaborated in [2]. This in turn dictates the selection of the HS that determines the baseplate area.
2. **Physical** – These are practical constants which mainly aid maintenance activities. Some important physical rules governing these constants are [2]:
   a. *Cabinet height* – This is restricted to be under 2 m that corresponds to the average height of a person and is inclusive of 50 cm ground clearance for shock mounts. Therefore effectively the cabinet space is restricted to be at most 1.5 m.
   b. *Cabinet depth* – Restricted to 0.75 m which corresponds to the average length of a human arm so that crew could reach at the back if needed.
   c. *Interior clearance* – This is the space surrounding each SM and is considered approximately 10 cm (average width of palm).
   d. *C_{SM} arrangement* – This is simplified to be in a square irrespective of the whether the total number of individual capacitors needed for a particular design is a perfect square. As an example, if a total of 12 capacitors are needed, then the space required is in a 4×4 square related to the length or width dimension.
   e. *General component arrangements* – This pertains to the placement of IGBTs and capacitors of a SM on the baseplate of the HS. The two basic arrangements are shown in fig.1 that depicts placement of individual components either mainly along the length or width leading to the computation of the baseplate area to select the HS. Here, two IGBTs are shown (if half-bridge switches are used) however a single full-bridge device could also be selected. The important criteria is to find the most compact arrangement such that a suitable HS from catalogs could be found subject to limitations of length (L), width (W) and the overall R_{th}.

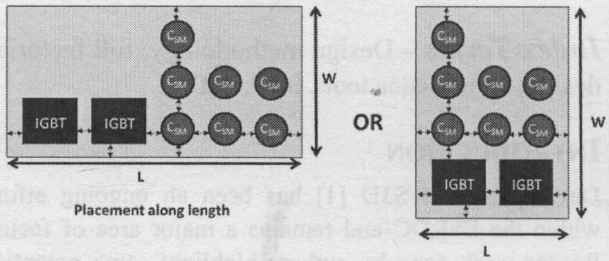

Fig. 1. Two basic arrangements to compute baseplate dimensions of a MMC SM to select an appropriate HS

It is vital to understand that a designer may change the considered physical rules in particular depending on specific rationale. For example, the perfect square arrangement for capacitors could be changed to an "equilateral triangle" arrangement, or rectangular. Similarly the spacing and clearances could be altered. The rules defined in this work are mainly to illustrate the various design aspects that govern the overall process.

Full Factorial Design Analysis

The first step to conduct the full-factorial analysis is the definition of system level design factors (SLDF) and equipment level design factors (ELDF). The SLDF as the name suggests, are the overarching parameters common to all parts of the shipboard power system. These factors are normally unchangeable for individual equipment designers who must use SLDF as a basis. Some important SLDF that are considered for the MMC SM study in this paper are:

1. DC bus voltage (V_{dc}) – 6 kV, 12 kV and 18 kV
2. System current (I_s) – 200 A, 500 A and 1000 A.
3. Fundamental generation frequency (f0) – 60 Hz, 180 Hz and 300 Hz.
4. Power factor (k) – 0.8, 0.9 and 0.95

The ELDF considered are:

1. SM voltage (VSM) – 0.5 kV, 1 kV and 2 kV.
2. Voltage ripple (ε) – 1%, 2% and 5%.
3. HS type – Natural convection (NC), forced convection (FC) or liquid cooled (LC).

With these SLDF and ELDF at their various distinct levels, a full factorial matrix is generated using the TM approach of inner and outer arrays [7]. The SLDF array is 4×81 and the ELDF array is 3×27 and are arranged as shown in fig 2 by flipping (or transposing) the ELDF array. This generates a 27×81 design space representing every combination of the ELDF and SLDF. The signal to noise ratio (SNR) for each row can be calculated based on the measured metric, which in this case is power density in MW/m^3.

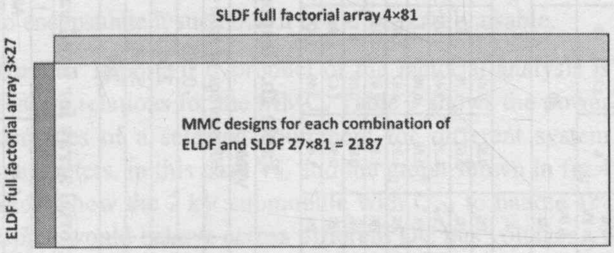

Fig. 2. Full factorial design space

Systematic Design Space Reduction

Once the full factorial arrays have been generated and arranged, the next step is to begin reducing this large design space and narrow it down to the best few. The initial design matrix theoretically contains 27×81 = 2187 individual MMC designs that fit combinations of ELDF and SLDF. For preserving the conciseness of this paper, this initial matrix is not shown here, however it must be noted that the studies yielded 2172 complete designs as for certain combinations, the design did not meet specified physical restrictions (15). All of these 15 out of bound designs occurred for I_s = 1000 A.

With every successive step, the design space could be reduced by selecting and fixing one or more of the factors. In this paper, an example is shown where after generating the initial full factorial matrix yielding 2172 designs, the HS type is fixed by selecting LC type and the power factor k is fixed at 0.9. This yields the subsequent full factorial matrix of 9×27=243 total designs. In the results presented, 1 design exceeds limitations, thus yielding 242 designs as shown in table 1a. Table 1b is the response matrix for table 1a, where the SNR values per ELDF are isolated and their averages computed. The larger the better (LTB) SNR equation is used here since the objective is to find high values of MW/m^3. Conversely, if the design quantity studied would be volume, the smaller the better SNR should be used since ideally the lowest volume is desirable. Equations used to find capacitance values and other physical aspects have been taken from previous work by authors [2]-[5].

After this first reduction, at the next pass a further design space reduction could be made by fixing one (or more) of either the SLDF or ELDF or both. In the example for this paper, the SLDF I_s is now fixed at 500 A to produce the next full factorial array shown in table 2a, with its response matrix in table 2b. Table 2a shows 81 designs with fixed attributes of MMC SM with LC HS type at system parameters of 500 A current and 0.9 power factor.

At this juncture, the next step could fix the ELDF V_{SM} (at 2 kV) and ε (at 1%) along with the SLDF f_0 (at 60 Hz) leading to three designs spanning the V_{dc} values of 6, 12 and 18 kV for k = 0.9, Is = 500 A. This final pass now enables the designers to select the appropriate system DC bus voltage and readily know the respective MMC power density.

Discussion

Interpreting Results

The values from the response matrices indicate the designs where the SNR is maximized. In other words, such a design is likely to fit a wider combination of system parameters. Along with the response matrix, a designer must also assess the means (μ) and standard deviation (σ) values for the equipment which in turn indicate the most robust designs that have the least variation in the metric measured i.e. MW/m^3 in this case.

Table 1. MW/m³ full factorial array for fixed value of k=0.9 and LC as HS type

12	18	6	12	18	6	12	18	6	12	18	6	12	18	6	12	18	6	12	18	6	12	18	6	12	18			
60		180			300			60			180			300			60			180			300					
200								500									1000									Mean (μ)	Std. dev. (σ)	SNR LTB
MW/m³ values																												
0.35	0.4	0.35	0.35	0.4	0.35	0.35	0.4	0.9	0.9	1.1	0.9	0.9	1.1	0.9	0.9	1.1	1.7	1.8	2.2	1.6	1.7	2.2	1.7	1.8	2.2	1.07	0.65	-4.58
0.7	0.8	0.6	0.7	0.8	0.6	0.7	0.8	1.6	1.8	1.6	1.4	1.6	1.6	0.9	1.6	1.6	1.7	2.9	3.2	2.2	2.9	3.2	2.2	2.9	3.2	1.64	0.91	0.06
1.0	1.0	0.6	1.0	1.0	0.6	1.0	1.0	1.3	2.5	2.5	1.4	2.5	2.5	1.4	2.5	2.5	x	2.7	3.0	1.6	3.0	3.0	1.6	3.0	3.0	1.81	0.93	1.13
0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	1.1	0.9	0.9	1.1	0.9	0.9	1.1	1.7	1.7	2.2	1.7	1.8	2.2	1.7	1.8	2.2	1.08	0.65	-4.58
0.7	0.8	0.6	0.7	0.8	0.6	0.7	0.8	1.4	1.6	1.6	0.9	1.6	1.6	0.9	1.6	2.0	2.2	2.9	3.2	2.2	2.9	3.2	2.2	2.9	3.2	1.63	0.93	-0.61
1.0	1.0	0.6	1.0	1.0	0.6	1.0	1.0	1.3	2.5	2.5	1.4	2.5	2.5	1.4	2.5	2.5	1.5	3.0	3.0	1.6	3.0	3.0	1.7	3.0	3.3	1.83	0.89	1.35
0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	1.1	0.9	0.9	1.1	0.9	0.9	1.1	1.7	1.8	2.2	1.8	1.8	2.2	1.8	1.8	2.2	1.08	0.65	-4.51
0.7	0.8	0.6	0.7	0.7	0.6	0.7	0.7	0.9	1.6	1.6	0.9	1.6	2.0	0.9	1.8	2.0	2.2	2.9	3.2	2.2	2.9	3.2	2.2	2.9	3.2	1.63	0.95	-0.29
1.0	1.0	0.6	1.0	1.0	0.6	1.0	1.0	1.4	2.5	2.5	1.4	2.5	2.5	1.4	2.5	2.5	1.6	3.0	3.0	1.7	3.3	3.3	1.7	3.3	3.3	1.88	0.94	1.45

Table 1b. Response matrix for ELDF from table 1a.

VSM		ε	
Values or levels	*SNR average at each value*	*Values or levels*	*SNR average at each value*
0.5 kV	$\frac{-4.58-4.58-4.51}{3}$= -4.56	***1%***	-1.13
1 kV	-0.28	***2%***	$\frac{-4.58-0.61-1.35}{3}$= -1.28
2 kV	1.31	***5%***	-1.12
Maximum occurs at	2kV	***Maximum occurs at***	5%

Table 2a. MW/m³ full factorial array for fixed value of k=0.9, I_s = 500 A and LC as HS type

	V_{dc} in kV	6	12	18	6	12	18	6	12	18			
	f_0 in Hz	60			180			300			Mean (μ)	Std. dev. (σ)	SNR LTB
V_{SM} in kV	ε	MW/m³ values											
0.5	1%	0.87	0.87	1.1	0.87	0.88	1.1	0.87	0.88	1.1	0.95	0.11	-0.61
1	1%	1.63	1.76	1.62	1.36	1.62	1.62	0.94	1.62	1.62	1.53	0.25	3.23
2	1%	1.29	2.45	2.45	1.43	2.45	2.45	1.43	2.45	2.47	2.10	0.54	5.43
0.5	2%	0.88	0.88	1.1	0.87	0.88	1.1	0.88	0.88	1.1	0.95	0.11	-0.57
1	2%	1.35	1.62	1.62	0.94	1.62	1.62	0.94	1.62	1.96	1.48	0.34	2.57
2	2%	1.32	2.45	2.45	1.43	2.45	2.47	1.43	2.46	2.47	2.10	0.53	5.49
0.5	5%	0.87	0.88	1.1	0.88	0.88	1.1	0.88	0.88	1.08	0.95	0.11	-0.58
1	5%	0.94	1.62	1.62	0.94	1.62	1.96	0.94	1.76	1.96	1.48	0.43	2.23
2	5%	1.43	2.45	2.47	1.43	2.46	2.47	1.43	2.46	2.47	2.12	0.52	5.64

Table 2b. Response matrix for ELDF from table 2a.

VSM		ε	
Values or levels	*SNR average at each value*	*Values or levels*	*SNR average at each value*
0.5 kV	-0.585	***1%***	2.69
1 kV	2.68	***2%***	2.5
2 kV	5.52	***5%***	2.43
Maximum occurs at	2kV	***Maximum occurs at***	1%

Table 2a. MW/m³ full factorial array for fixed value of k=0.9, I_s = 500 A, and LC as HS type, V_{SM} = 2 kV and ε = 1%

	V_{dc} in kV	6	12	18			
V_{SM} in kV	ε	MW/m³ values			Mean (μ)	Std. dev. (σ)	SNR LTB
2	1%	1.29	2.45	2.45	2.06	0.67	5.07

STEP-WISE DESIGN SPACE REDUCTION

The example shown in this paper is on the backdrop of facilitating design-space reduction within a concurrent and collaborative design environment such as S3D. This implies that a host of SLDF and ELDF are available for conducting trade-off studies and therefore, the step by step elimination (or fixing) of design factors enables evaluations to be made from both the system as well as sub-system (or equipment) points of view.

AUTOMATED FUNCTIONALITY

As mentioned earlier, MATLAB code was developed to generate full factorial arrays and move through the design equations. MS Excel was used to better visualize the arrays. This combination is by far semi-automatic. It is desirable that an automated functionality within S3D or standalone tool which S3D could call be developed that enables both, design computations as well as visualization while also enabling cross-talk and collaboration between the system and sub-system designers. However, development along these lines is out of the scope of the work currently presented in the paper, but is indeed an important aspect for future research.

OUTCOMES OF APPROACH

The first learning derived from this study is the basic differences in the design of power conversion systems for land and naval applications. It is important that practical and traceable design guidelines be inputted into the S3D database which enable users to have expert-validated rules of thumb as well as industry practices. Authors have proposed the use of product development tools [5] to gather relevant knowledge and there is further necessity to encapsulate it such that it could be readily usable.

Another important byproduct of the factorial analysis is scaling relations for the MMC. Table 3 shows the power densities of a selected equipment for different system parameters, in this case V_{dc} and the graph shown in fig.4 shows how the 2 kV submodule with C_{SM} to handle 1% ripple would behave across different DC bus voltages. A similar approach could be used to produce scaling relations across fundamental generation frequencies for a fixed DC bus voltage.

UNDERSTANDING IMPACT OF COMPONENTS

The study of designs forces research into individual components thereby building knowledge from bottom up. A component level decomposition analysis reported in [3] helped in shedding light on the various components that have the most impact on the overall MMC volume. Fig 4 depicts the importance of "box" volume and the essential notion that each SM component contributes a proportion within a range toward the overall SM and hence the cabinet size (represented in fig. 4).

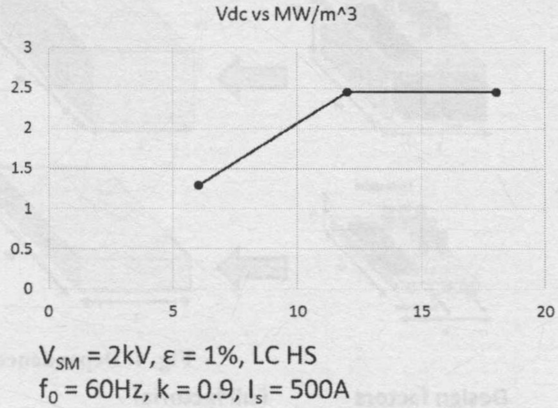

Fig. 3. Dependence of MW/m³ for different V_{dc}

CONCLUDING REMARKS

The work in this paper shows an effective, rigorous and systematic methodology to enable design space reduction that facilitates the fundamental attribute of SBD (depicted in fig. 5 and derived from [11]). The example shown in the paper provides the designer with a complete picture of the design space and reduces it from 2187 to 3 candidate designs in an efficient, detailed and transparent manner. The MMC design approach can be traced back to the benchmark system reported in [8]. The power density at 6 kV bus voltage, 200 A current for 1 kV SM ranges from 0.37 MW/m³ to 0.55 MW/m³ (shown in table 1a) which is close to the estimated power density ≈ 0.4MW/m³ of an equivalent compact system derived from the benchmark as explained in [10].

An important outcome is scaling relations as explained in the previous section. Such relations are vital inputs to the S3D design database and are expected to enable better informed guidance and decision support to the user. The authors believe that developing automated tools based on the proposed full-factorial approach is a feasible technique to derive scaling relations that are independent of power conversion topology.

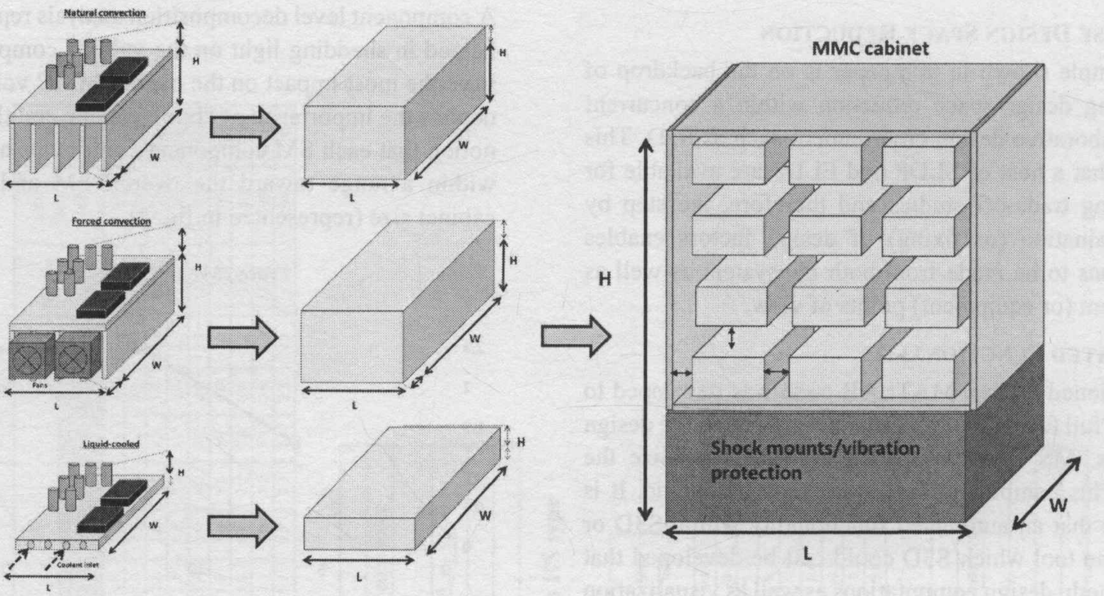

Fig. 4. Dependence of MW/m³ for different V_{dc}

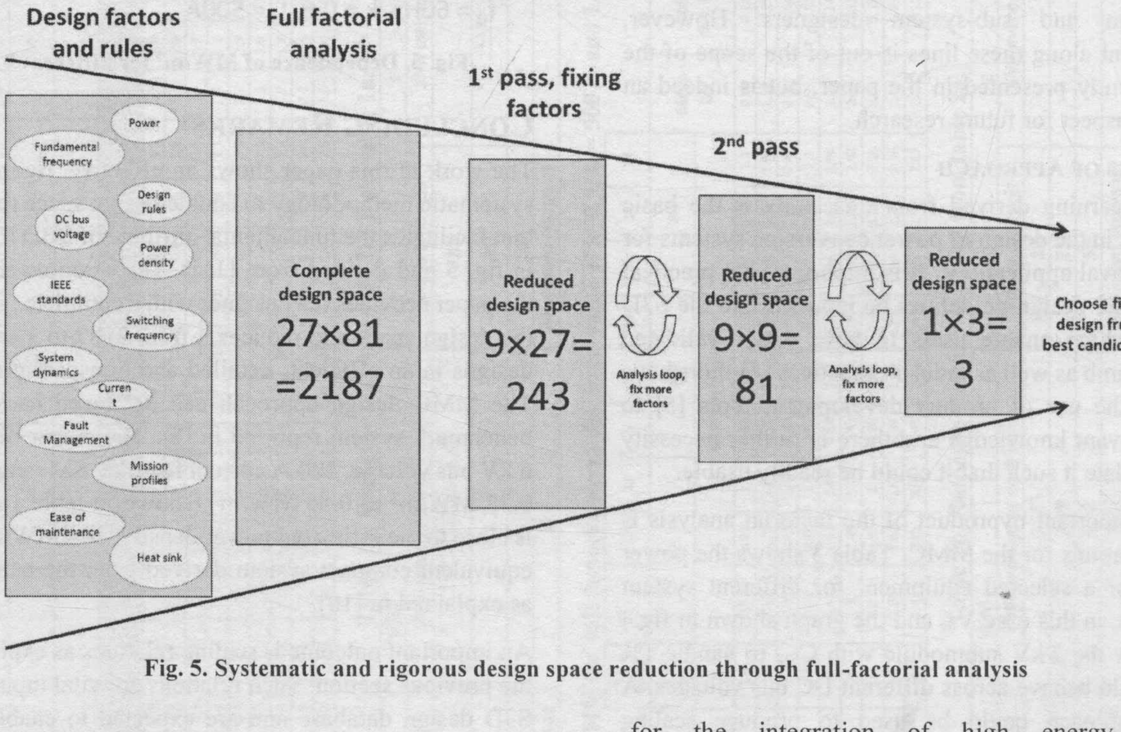

Fig. 5. Systematic and rigorous design space reduction through full-factorial analysis

Future Work

Further work in this research will focus on expanding the proposed approach to other competing power conversion topologies. This will form a similarly detailed development of design rules and thereby enable comparison and evaluation between different converter topologies which could be done through a full-factorial analysis scheme. Another important portion of future work is to extend efforts toward other vital components of the MVDC breaker-less architecture, one example being energy storage technologies to meet the demands for the integration of high energy weapons. Simultaneously, efforts will be directed toward extracting meaningful design guidelines and rules that adhere to shipboard system compatibility which will supplement the derivation of scaling relations.

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Industrialization of Early Stage Design via Simulation Data Science, Platform and the Cloud

ABSTRACT

Today, it is clear that some of the Navy's new surface combatant designs will largely be driven by the much more power-hungry weapons and sensors of the future. The ship platform solution must be an optimized combination of power generation, conversion, control and another new variable: energy storage. At the same time, the Navy needs to engineer, model, and simulate in accordance with real-world scenarios to ensure power is available for the ultimate combat effectiveness. Interoperability with the fleet and new fleet assets such as unmanned vehicles present both an opportunity and a challenge. The scale of the problem is intractable as HM&E architecture and topology options in the thousands, combined with operational load cases can potentially produce billions of design and mission scenarios to evaluate for a single platform.

This paper will explore the implications of the advent of recent technologies that can help to drive even greater innovation and collaboration across the Navy R&D community including: Simulation Data Science, Cloud and platform-based computing.

Simulation Data Science is an enabler for innovation. It is a family of applications and technologies to capture and manage information, standardize simulation processes, leverage data analytics, & integrate the practice of simulation into the enterprise.

INTRODUCTION

Across many industries, wherever products are comprised of highly automated systems of systems for improved performance, there is an increasing challenge that can only be solved through advanced system engineering processes. The Navy's Future Surface combatant design challenge is a prime example. There are three major elements to the design:

- The platform (Hull, Mechanical, Electrical)
- The Integrated Electric Power Plant
- The Integrated Warfare System

Then, there are wild cards that can contribute to the ship's value over its service life:

- The potential for Modularization that brings Flexibility during the ship's service life.
- The ability to interoperate with the fleet and other assets in order to accomplish missions and take defensive measures.

As an example, Georgia Tech's Aerospace Systems Design Laboratory (ASDL) computed the potential of over 90 billion architecture and load combinations facing the next generation hybrid-electric power system (1). Add that computation to the challenges of the Hull/Mechanical and Combat System communities.

The US Navy already has a strong culture of modeling and simulation. The need to architect, model, and simulate in accordance with real-world scenarios to ensure the ultimate combat effectiveness of future systems is understood.

At the same time, R&D organizations across the ecosystem are still working in silos. Non-integrated file-based tools and file-based management systems are still the norm. The integration found within the Leading Edge Architecture for Prototyping Systems (LEAPS) is an exception. Beyond the community using LEAPS, the disconnected tools and processes are inefficient. Our success in developing the highly-automated systems of the future requires that we make development processes faster, more transactional and more integrated. Technical solutions developed in online digital environments must also be able to feed Certification, Contract and Program execution as well as the digital manufacturing and lifecycle support of complex systems.

PLATFORMS

On a larger scale and across communities, platform architectures are needed to accelerate engineering development and downstream processes. Platforms enable the digitalization of simulation and development processes along the value chain, providing real time access to all stakeholders in a transparent, but secure and auditable manner.

A platform can be a framework to digitalize sustainable innovation. It unites engineers, suppliers, consumers and regulators, across the globe, and provides capabilities to model and simulate meaningful use case scenarios. With a platform, information flow and full traceability can be maintained across the system engineering process: from Requirements to Functional Architecture, to Logical Definition, to Physical Design. Related modeling and simulation I/O can also be associated with the correct version of the product/system as it develops for Validation and Verification. At the same time, the platform allows businesses to leverage their legacy data by indexing information in their existing systems to become more data-driven in their internal processes.

A platform and its applications can be purpose built to digitalize end-to-end processes, with capabilities to analyze, design, simulate, engineer and deliver new ideas. A platform can enable innovators to develop a deep understanding of the effects of their end product's operating environment through the analysis of the results of simulation addressing multiple states, dynamic conditions and potential scenarios. During the operating lifecycle, the baseline models continue to be enriched with valuable insights gleaned from the usage data, setting the stage for the next cycle of innovation.

Innovation efficiency is often impeded by multiple hand-offs due to discontinuity in processes and systems across disciplines and functions, resulting in elongating time-lines and wasted effort due to rework. The older generation electronic Product Lifecycle Management (PLM) systems connected the silos together, whereas in a digital platform, the silos are eliminated. A Platform needs to have architecture to define a common data model across design, simulation, manufacturing and governance applications with intelligence, dashboard visualization and social collaboration capabilities. This would provide users the ability to connect online to a single digital definition and collaborate in real-time.

An RFLP-MSR-PPR framework can cut across different disciplines, functions and establishes a true model-based platform for innovation. The entire innovation process can be digitalized by connecting views of the model across the lifecycle. The operational model, requirements model, functional and logical model, physical model, all form the basis for product definition (RFLP). Model-Scenario-Results (MSR) extends the framework for simulation. MSR defines the scenarios for simulation and relates the models, inputs and the results under various usage scenarios. Product-Process-Resources (PPR) extends the framework to the manufacturing domain and relates the product to the process and resources required to execute the process.

A platform also needs to provide the underpinning applications and services that enable the transformation to a digital, data-driven, model-based environment. This includes the framework to establish the Single Source of Truth (SSoT) concept so everyone in the organization is working from the same product structure and current definition. Communication and computational channels have to exist to allow collaboration and execution of many different computations during a program's design phase. Visualization is vital so that the SSoT model has a context that is appropriate to the designer, analyst, manufacturing engineer, product engineer, etc.

Adopting a data-driven, model-based digital platform across all functions involved in the innovation process is the foundation for an effective model-based approach. Adopting this model-based approach across the value chain makes experience thinking a reality. This involves a cultural and behavioral paradigm shift that is embraced at all levels of corporate, government, and program management.

The Cloud

The preceding discussion of the Platform-based, digitalized approach implies the use of the Cloud, but it is not an absolute requirement. Many companies today implement on-premises environments due to concerns about cloud security. Digital technology trends such as the idea of the Digital twin, advanced simulation and business analytics are changing R&D processes and disrupting business models. An equally transformative force and prime enabler for all will eventually be the Cloud.

Investments are being made to ensure that the Cloud delivers what businesses require to make a digital transformation: high flexibility, secure, on-demand access anytime, anywhere. It gives immediate availability to advanced software. At the same time, it will greatly simplify and accelerate implementation – reducing both the time required and the cost.

The importance of the Cloud in business transformation is reflected in CIO surveys that continually rank the Cloud as a top company priority, and in double-digit adoption rates that show no signs of slowing. Specific business advantages that are driving this high cloud adoption include:

- **Innovation**

The Cloud is promoting experimentation and collaboration across organizations and communities. It frees people and organizations to focus on core work activities and have the most current and correct version of the data available to all who need it on a controlled basis.

- **Scalability**

The Cloud offers ready-to-use resources for instant project and/or support services ramp-up. Users can add new applications and services on-the-fly, whenever needed. In addition, advanced and innovative new features can be downloaded, installed and fully configured in minutes.

- **Reactivity**

Cloud computing delivers benefits from increased IT department reactivity, where the power of computers is utilized more efficiently through scalable hardware and software resources.

- **Security**

Large, established cloud Internet Service providers have technical expertise and dedicated security resources that are typically beyond those of in-house IT teams. According to the Cloud Security Alliance, the cloud is inspiring new solutions to old security problems: "a focus on greater automation, disposable infrastructure, agility among other concepts are changing how we deal with problems such as malware, forensics, denial of service attacks and compliance." (2) The visible evolution of Cloud security may in part explain why businesses are increasingly identifying the desire to improve information security as their primary reason for adopting cloud services.

While it is not an absolute requirement to use the Cloud, the potential savings and enhanced performance that it brings will make it a key enabling technology for Simulation Data Science.

Multiscale / Multiphysics

A ship is a system made up of millions of components. These components are reviewed individually to meet certain specifications and performance criteria, but the assessment doesn't stop at the component level. Groups of components are reviewed as either systems or sub-systems and the range of specifications and requirements grow as the individual component is consumed ultimately by the final product, which in the Navy's case can be an operational ship.

In simulating the behavior of something as complex as a naval vessel, one has to consider the behaviors and interactions of a component, assembly, sub-system, or the entire vessel to the environment it is subjected to and what duty cycles are expected for its performance. This requires a two-pronged approach in regards to the physical scale being addressed and the physics disciplines involved at that level of scale as shown below:

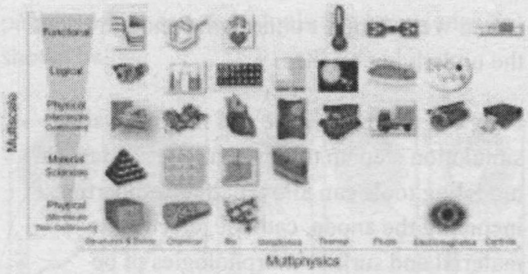

Figure 1: Multiscale v. Multiphysics Simulation Breadth and Depth

This is commonly referred to as a Multiscale / Multiphysics simulation. The scale at which something, such as a material, responds to physics such as continuum mechanics, chemical reactions, thermal environments (e.g., Multiphysics) needs to be assessed along with interactions at increasing and decreasing scales (e.g., Multiscale).

Lest you think this a bridge too far for naval ship design, consider the case of the hybrid-electric drive system. Today, serious research is being dedicated to adding energy storage capabilities to ships with integrated electric power systems. Though battery technology is pervasive, research is needed to improve performance and match it to the needs of the larger system. To quote Dr. Peter Bruce of Oxford University (3): "The major part of developing advances in Lithium Ion batteries comes down to discovering new materials with different properties and combinations of properties. That is all about controlling at the atomistic level, producing new compounds, putting atoms together in different combinations, producing different structures at the atomic level and then realizing by doing that, materials that bind properties that we perhaps didn't have before. In a lot of these storage challenges for electric vehicles and the electricity grid in the future, we don't really have energy storage technologies including batteries that are fit for purpose. And, the reason that we don't have these technologies is that we still don't understand enough about the underlying science. "

How can the multi-scale and multi-physics simulation step up to this challenge? Material modeling tools can allow battery properties including the anode, cathode, electrolyte material and surface morphologies to be optimized to maximize the final performance of the battery for its projected operating profiles. Simplified electrochemical models of battery cells can then be used to optimize the packaging. Performance of the entire battery system can be performed to assess the aging in the cells. 3D thermal and cooling systems simulations can be performed at the cell and pack level to assess the potential for thermal runaway which is a key safety consideration and to ensure the safety of the battery pack system. Trade-off studies of the KPI's using results analytics can be performed to identify the best design options. Finally, a complete system simulation with all component behaviors including models of a drive train and other electric loads can ensure the most optimum battery integration by taking into account anticipated use cases.

The scale of a component may not simply be its outer 3-Dimensional representation. A representation of a certain scale, such as at the material level, can be addressed anywhere from a molecular scale to a macroscopic level which may only involve gross section property values that define its behavior. Some of these microscopic to macroscopic/logical/functional levels have assessments conducted on the order of 1, 2, or 3-Dimensional geometry, with or without consideration of steady-state or transient time behavior. Additionally, consideration may be required for non-structural components like phase change (solid, amorphous, liquid), fluid flow via air, liquid or thermals and electromagnetics.

One of the many benefits of a Single Source of Truth (SSoT) Platform is the ability to overlay multiple representations of a system, assembly or component, as appropriate to the physical scale being addressed. Simulations are performed at a given level which can span the spectrum of individual physics involved with a certain set of operating conditions. Traceability is established by tying requirements, specifications, inputs, methods and outputs to each representation and operating condition simulated. This provides a mechanism to review what was used in a given simulation to determine what changes, if any, have occurred upstream that could impact the simulation and its results. This is critical in the design phase of a project and helps establish pedigree in the work performed that can be used as a basis for best practice or method development later on in the project or for future projects. Ultimately, this SSoT Platform helps define, establish and validate Multiscale and Multiphysics aspects that comprise real world product behavior before producing a single component.

In addition to the potential coupling of certain levels of scale with certain physics behavior, there are realistic scenarios occurring on a ship that involve the simultaneous co-mingling of multiple physics disciples. Examples of this can include structural impacts to a piping system subjected to turbulent fluid flow, controls interactions with kinematic, electrical, thermal and mechanical systems, and electromagnetic interference with rotating machinery.
Technology has provided a way to look at these simultaneously occurring phenomena and co-simulate their interactions without building and testing the product. This becomes even more critical today when creating next generation design methods for U.S. Naval vessels in a non-siloed environment. The complexity in technology, specifications and requirements

makes it imperative to break out of a siloed mentality.

Simulation Data Science

To understand the discipline called Simulation Data Science, one has to take a step back to understand how data plays such an important role in everything designed, manufactured and operated today. Data science, also known as data-driven science, is an interdisciplinary field about scientific processes and systems to extract knowledge or insights from data in various forms. This may present itself in either a structured or unstructured manner as a continuation of some of the data analysis fields such as statistics, machine learning, data mining, and predictive analytics. Turing award winner Jim Gray imagined data science as a "fourth paradigm" of science (empirical, theoretical, computational and now data-driven) and asserted that "everything about science is changing because of the impact of information technology" and the data deluge.

As industry continues to grapple with ways to create products in a "better, faster and cheaper" manner, innovation is considered a critical enabler. Respected companies, such as Accenture and the Boston Consulting Group, have surveyed executives in various industries about this challenge. (5, 6) Over and over again it has been stated that innovation is a high priority to help address this challenge. An ingredient to enabling and enhancing innovation is digitalization which is routinely cited as a critical path on many executive's priority lists. Simulation has clearly been identified as one of the top priorities to deliver on innovation and digitalization strategies.

Simulation Data Science is an innovation thread with an organization. It involves a grouping of people, processes, data, tools and knowledge as shown below:

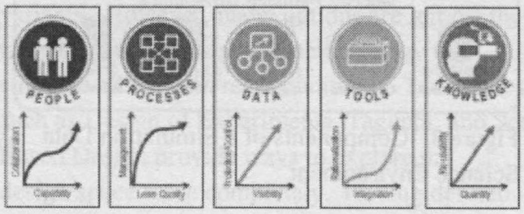

Figure 2: Simulation Data Science Innovation Thread within an Organization

Another way to look at this can be seen in the following two analogies. When innovating, research along with previous experience and knowledge generates Data. Data is studied and assembled to form Information which educates people, and when put into practice develops into Knowledge. As that knowledge is disseminated and utilized, Experiences are formed. It can be seen that this becomes a recurring loop growing though each pass. An analogy of this is seen in the testing world. Hypotheses are posed for a given experiment. The execution of those hypotheses is done via one or multiple Tests. Once the results are produced from testing, there is an Observation of what was produced. Connecting the results through the testing via methods such as correlation and analysis provides a mechanism to Learn. This is a form of experience which can then be cycled and grown through this loop moving forward through new hypotheses and experiments.

The discipline of Simulation Data Science builds upon the field of Data Science with a focus on the aspect of Simulation. Simulation Data Science is conceptually a family of applications and infrastructure that allows organizations to capture & manage their simulation data, standardize simulation processes, leverage data analytics, & integrate the practice of simulation into the enterprise.