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Smart Model Based Systems Engineering

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ABSTRACT

Model Based Systems Engineering (MBSE) has been a dominant methodology for defining and developing complex systems; however, it has not yet been paired with cutting-edge digital engineering transformation. MBSE is constrained to represent a whole system, but lacks other capabilities, such as dynamic simulation and optimization, as well as integration of hardware and software functions.

This paper provides the key elements for developing a Smart MBSE (SMBSE) modeling approach that integrates Systems Engineering (SE) functionality with the full suite of other development tools utilized to create today's complex products. SMBSE connects hardware and software with a set of customer needs, design requirements, program targets, simulations and optimization functionalities.

The SMBSE modeling approach is still under development, with significant challenges for building bridges between conventional Systems Engineering methodology, with additional capabilities to reuse, automate, simulate and optimize the system model in order to generate solutions that do not require significant remodeling efforts for each subsequent new product. The proposed SMBSE framework provides the potential for product development teams to focus more of their efforts on the new subsystems and technologies and less time remodeling or updating legacy systems and components.

INTRODUCTION

A wide range of current Systems Engineering models were analyzed to identify opportunities for adding smart capabilities to current MBSE methodologies.

Model Based Systems Engineering (MBSE) can be defined as the formalized application of systems engineering modeling to support requirements compliance, identify interfaces, define verification and validation activities, and predict emergence[1] results, starting from a concept design stage and continuing throughout solution development and application during life cycle phases.[2] Sometimes MBSE is recognized as SysML, but it is not a proper concept since SysML is just the language tool for modeling systems architectures.

Current SysML software platforms are oriented towards the design of complex systems architecture by modeling without integrating dynamic simulation and visualization features. (Figure 1 – MBSE current visual simulation capabilities with static signals).

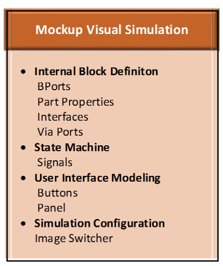

Figure 1: MBSE current visual simulation capabilities with static signals

Conventional MBSE is behind growing disruptive solutions for green energy, autonomy, full connectivity and mobility (Figure 2 - Gap between complex Engineering Systems and conventional MBSE evolution).

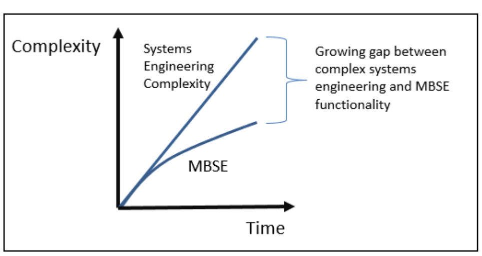

Figure 2: Gap between complex Engineering Systems and conventional MBSE evolution

Smart MBSE (SMBSE) will provide the required funcitonality in accordance with cyber-physical systems engineering requirements in terms of speed, robustness and anticipated results.

The new technologies have increased the complexity in the systems[3] being engineered thereby increasing the payoff of migrating to a SMBSE approach.

This research was oriented towards exploring the opportunity to develop a SMBSE in order to integrate features to the conventional MBSE in accordance with increasing systems engineering complexity, while taking full advantage of digital tools to automate, reutilize, simulate and optimize the development process for innovative solutions. (Figure 3 – SMBSE, four elements)

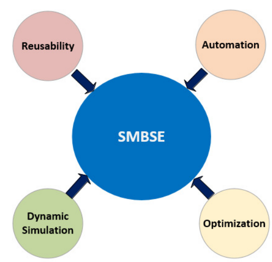

Figure 3: Smart Model Based Systems Engineering, four elements

The main benefit of SMBSE is to close the growing gap between complex systems engineering and conventional MBSE. An additional benefit is the design integration between software and physical components with multiple features, often with conflicting targets (Figure 4 - Proposed Multi-engineering full-integrated development system).

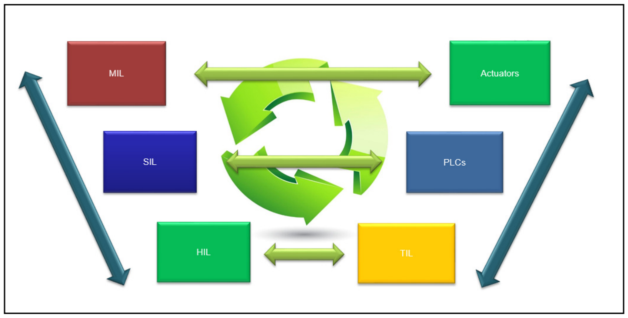

Figure 4: Proposed Multi-engineering full-integrated development system

An early interface integration between model in the loop (MIL), software in the loop (SIL) and hardware in the loop (HIL) provides the capability to validate model targets compliance before a full virtual product is available and without a costly physical prototype.

SMART MBSE

SMBSE´s distinctive features from conventional MBSE include reusability, automation, dynamic simulation and optimization. (Figure 5 - SMBSE Development Sequence).

Figure 5: SMBSE Development Sequence

The above sequence is the recommended path for developing a SMBSE leveraging the reusability of proven prior models while including an early step to focus on the unique elements required in the new model. The automation step receives the prior reusable subsystems and the new elements. The emergent model is used to conduct dynamic simulation analysis to provide a compliant solution, ready to be optimized.

SMBSE drives the subsequent or simultaneous design, control and validation steps, such as MIL, HIL, SIL, Quality Tools, CAD, CAE, CAM and optimization process to deliver a fully interconnected model with new functional capabilities (Figure 6 - Fully integrated SMBSE), that go from the representation and control of a set of entities and relationships, to a fully virtual validation and verification methodology.

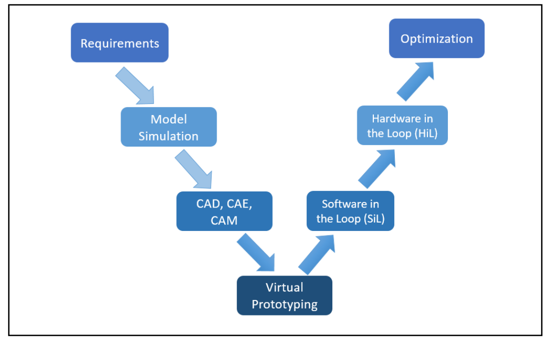

Figure 6: Fully integrated SMBSE

Reusability

The models developed using a SMBSE approach are able to reuse the requirements, signals and interfaces from the common subsystems, and apply them to the new systems.

The reusability of prior proven models provides opportunity to reduce the cost and timing for developing new complex models. The quality history, quality tools and lessons learned translated into design requirements and design rules, are key to preventing recurring or systemic issues in relation to the new models.

FMA Tools

Failure Mode Avoidance (FMA) methods and tools are the enablers for documenting and applying the lessons learned from previous programs to the architecture of new products. A common language and automated models enhance the opportunity to access information regarding previous issues so they can be prevented when working with new products or services by using structure, editable and standard processes to optimize the model.

Automation

SMBSE automation generates systems engineering models from parametric modeling algorithms that replicate the best structure and methodologies of existing robust models that can be built for the common architecture or subsystems that do not change on new products (Figure 7 - SMBSE Automation). In most ground vehicle applications, approximately 50% of the components are carryover from the prior product generation, even for products with revolutionary innovation.

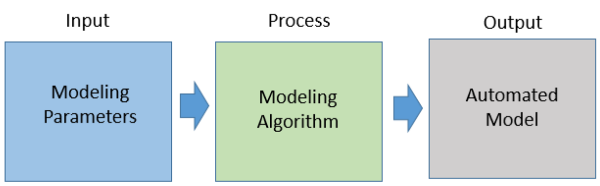

Figure 7: SMBSE Automation

Dynamic Simulation

An effective design of cyber physical systems requires the proper modeling representation, but fully integrated with simulation and the respective analysis. The current common practice is to conduct the modeling, simulation and analysis (Figure 8 – MBSE loops) on a separate base with ineffective interaction between these three central elements of systems engineering.

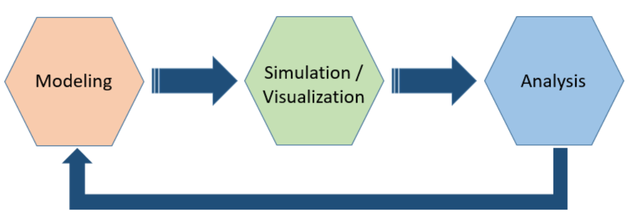

Figure 8: MBSE loops

A common constraint in the conventional MBSE is the limited simulation functionality with linear models, which are not representative of the real performance of complex and large systems.

The digital technology is available, but not used to integrate SysML platforms with iterative dynamic simulation software platforms.

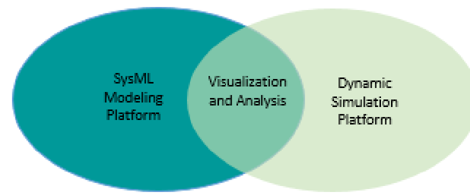

Figure 9: SMBSE with simulation and visualization capabilities

The increasing complexity of the disruptive technologies and resulting ultra large and complex systems[4] engineering, requires the development of fully integrated modeling and iterative analysis platforms (Figure 9 - SMBSE with simulation and visualization capabilities). The current practice is just a mechanic or manual interface between modeling and simulation platforms, which is not the most efficient tool for developing high tech products or services.

Optimization

The central benefit of SMBSE is to support the systems engineers identifying the simplest solution for complex and large systems, as well as to facilitate the decision-making process on the early architecture definition. The SMBSE optimization functionality is oriented towards identifying different systems architecture options before proceeding to develop a new subsystem or component. The wider the scope of architecture optimization, the simpler the solution at different levels of decomposition.

Once the model complies with the functional and interface requirements, the next step is to optimize the product or service solution in order to minimize unnecessary complexity, cost, weight or other variables that do not generate added value to comply the customer needs.[5]

Structural complexity and complexity elasticity metrics are useful to quantify the elegance of the overall system solution, before and after an optimization process.

$$\int_{to}^{tf} \text{Structural Complexity} = C_1 dt + C_2 C_3 dt$$

Equation 1: Structural Complexity[6]

Where:

- $C1$ = sum of the complexities of individual elements in the system
- $C2$ = complexity related to the interface
- $C3$ = complexity in the system topology
- to = initial time
- tf = final time

The resulting complexity elasticity metric from the above structural complexity equation (Equation 1 – Structural Complexity) compares input variables relative to output changes, that means, the ratio of change in structural complexity divided by the ratio of change in the number of system connections (Equation 2 – Complexity Elasticity, Figure 10 - Complexity Elasticity).

$$\text{Complexity elasticity} = \frac{\text{Ratio of change in structural complexity (\%)}}{\text{Ratio of change in number of system connections (\%)}}$$

Equation 2: Complexity Elasticity[2]

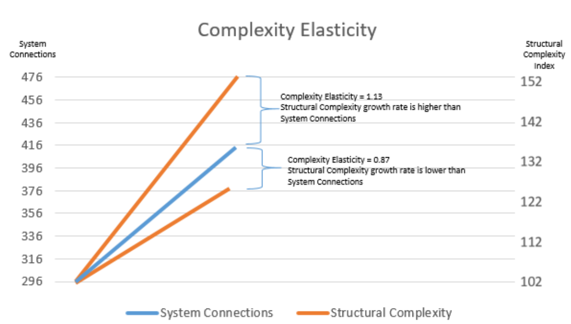

Figure 10: Complexity Elasticity

The SMBSE optimization includes the model evaluation with all the variables in a Model in the Loop (MIL), Software in the Loop (SIL) and Hardware in the Loop (HIL). The next step is to run a simulation platform with a range of parametrized design factors to find the optimal design results

The timing pressure for delivering products or services on a prescribed timeline often does not permit implementation of a final optimization phase before launching a product in the market. SMBSE allocates an optimization phase to deliver products or services that does not only comply with multiple requirements, but optimizes the variables to maximize user benefits and solution performance, while minimizing overall costs or preventing undesirable effects.

Instead of reworking a product already launched in the market with additional validation or retooling costs, an optimized product or service is the result of a lean product development process.

This final phase in the SMBSE is an integration between CAD, CAE, CAM and optimization platforms within a resulting Computer Aided Systems Engineering (CASE).

FURTHER DEVELOPMENT

Growing pressure to lower costs and shorten the product development cycle has forced high-tech industries to simulate engineering systems oriented towards the gradual replacement of physical prototyping testing. This trend has led to the development of virtual product development systems (VPD) by integrating modeling simulation and visualization tools.[7] Mathematical and CAE models software platforms support VPD with static and dynamic variables; however, MBSE software tools are constrained to handling dynamic variables, causing marginal integration with VPD. The solution is SMBSE by adding the missing dynamic simulation and visualization functionality and integrating the mathematical and CAE models in the systems engineering modeling tools.

The visualization functionality with dynamic variables enables the description of complex and large systems and transforms an abstract idea into a dynamic model representation.

High-tech industries are leading efforts to upgrade MBSE through isolated functionalities, but still lack the required efficient integration and have a long way to in terms of avoiding extensive and expensive adaptation to suit multiple systems engineering projects. This means there is a big opportunity to fully integrate the automation, reusability, simulation and optimization functionalities in MBSE in order to match increasing systems engineering complexity with designer tools able to expedite and optimize solutions.

CONCLUSIONS

Current MBSE methodologies are behind the industry´s digital engineering transformation challenges. The technologies required to develop the SMBSE methology are available, but a great effort is needed to develop efficient interfaces, not just between system entities, but with the virtual simulation platforms and optimization algorithms that deliver a fully integrated design solutions.

These research results are applicable to different kinds of industries with complex systems engineering development processes. The new disruptive techonologies require the development of smart and digital MBSE methodologies, otherwise the gap between cyber-physical systems and engineering design model tools will continue to grow. Available digital systems technology provides an opportunity to take the MBSE application further with a fully integrated framework from MIL, SIL, HIL, CAD, CAE, CAM, Artificial Intelligence, Quality and Optimization tools in order to evolve to SMBSE as the first step towards a disruptive evolution in Product Development disciplines.

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