Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 11 (2013) 425 – 430

www.elsevier.com/locate/procedia

2nd International Through-life Engineering Services Conference

Through-Life Systems Engineering Design & Support with SysML

Stuart R. Chandler[a] & Peter C. Matthews[b]

[a]*Durham University, Stockton Road, Durham, DH1 3LE, UK.*
[b]*Durham University, Stockton Road, Durham, DH1 3LE, UK.*

* Corresponding author. Tel.: +44 (0)191-334-2000. *E-mail address:* s.r.chandler@durham.ac.uk

---

Abstract

New system capability needs have been evaluated based primarily on the product design characteristics. This process neglects the other areas of the system design such as operational availability. The proposed solution takes a more holistic view of system capability identification and trade-off analysis. . This solution will consider the combination of both operations and support environments with through-life predictions of the key performance indicators of the various options, while using the systems modelling language (SysML) integrated with SimuLink. This involves using SysML to provide engineering templates, modular assembly of simulation scenarios and a matrix trade-off method using stochastic information.

Selection and peer-review under responsibility of the International Scientific Committee of the "2nd International Through-life Engineering Services Conference" and the Programme Chair – Ashutosh Tiwari

Keywords: Through-Life; Holistic Design; MBSE; SysML; Simulation Systems; Matrix trade-off

---

1. Introduction

1.1. Aims

The aims of this research is to investigate, develop and apply a holistic Model Based Systems Engineering (MBSE) approach for the design of Renewable Energy systems with the use of SysML (System Modelling Language), simulation modelling and efficient techniques in the area of design trade-off analysis. For Example, due to the level of uncertainty that exists within the operational environment of renewable energy systems a Bayesian type method is applied, which draws information from a probabilistic concepts matrix that is generated by the simulations. The approach of using SysML to replace the standard methods of deriving information like FMECA (Failure Modes Effect & Criticality Analysis) is something that has already started within the research community and will aid the integration of engineering domain analyses and the systems engineering environment. This comparison will illustrate the savings that can be achieved through the reuse of model diagram artifacts and a more effective form of design trade-off analysis. After this basic comparison the holistic approach to SysML for these Engineering analyses will be tested with two case studies: one will be in the form of a wind farm, that will be compared with a stochastic MATLAB simulation model and the other will be applied to the assessment of marine vessel energy efficiency studies.

1.2. Objectives

The objectives of this research is to investigate how: SysML can integrate Engineering information, like parametric algorithms and tabular text (i.e., FMECA & RCM (Reliability Centred Maintenance) worksheets) to cover those disciplines that contribute towards the creation and improvement of operation and support systems through life; the relevant parametric algorithms that represent the Key Performance Indicators (KPIs) of the system of interest can be applied within the developed System Engineering solution; this information once organized and integrated can be used within simulation modeling to investigate the dynamics and interactions of both operation and support systems within the context of its operating environment; a number of design

Selection and peer-review under responsibility of the International Scientific Committee of the "2nd International Through-life Engineering Services Conference" and the Programme Chair – Ashutosh Tiwari
doi:10.1016/j.procir.2013.07.002

trade-off methods can accept a matrix set of inputs from the simulation results to determine the best mix of system options for each life cycle phase, which will lead to a method that can deal with uncertainty being developed and its application justified; Test and validate the results within the context of two practical case studies: a wind farm and a marine vessel energy efficiency boat study. The source information for these studies will come from industry.

1.3. Scope

The scope of this research covers holistic design analysis within the context of MBSE and adopts the use of SysML. This organizes engineering source data that is required to enable the parametric algorithms to derive output values in a manner that promotes simulation and results collection methods. These methods lead onto how those results are used through design trade-off processes to derive a justified decision choice. Fig 1 illustrates the scope of the work and the flow of information, which follows an iterative process at key decision points within the complete system life cycle phases:

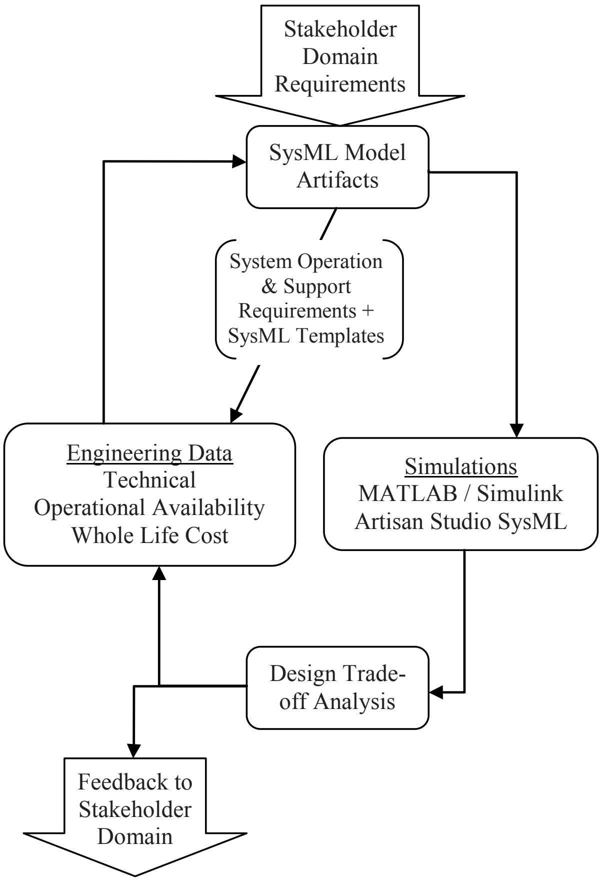

Fig. 1. Research Scope & Information Flow

2. Holistic Systems Engineering Basis

2.1. Motivation

The motivation for this research comes in part from the UK MoD Defence Science and Technology (Dstl) [1] calling for a Proof of Concept (PoC) competition for the development of a more holistic approach to High Level Operational Analysis (HLOA) that considers all eight Defence Lines of Development (DLOD). The UK MoD [2] has defined what the DLODs are. The other part of the motivation comes from practical experience in the defence industry.

Considering the MoD tends to be ahead of commercial industry in the application of this kind of technology, it is reasonable to hypothesize that the renewable energy industry has the same need to be more efficient in the creation of new system designs. This will be verified in later studies via a survey involving businesses involved in renewable energy based systems.

2.2. A System, Systems Engineering, MBSE & SysML

There are many types of Systems Engineering processes, which are normally based upon the industry in which they are being applied and SysML has been designed to operate within any industry that applies Systems Engineering. It is important however to define a “System” and “Systems Engineering to assist in the identification of relevant processes and scope. The International Council on Systems Engineering (INCOSE) [3] defines these. A system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents, that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behavior and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts, that is, how they are interconnected. Systems Engineering is defined as an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder’s needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system’s entire life cycle.

The Johns Hopkins Applied Physics Laboratory [4] provides a view of systems engineering as illustrated in their MBSE with SysML Tutorial, which can be accessed via the Object Management Group (OMG) System Modelling Language (SysML) website [5] and is reproduced in fig 2 below:

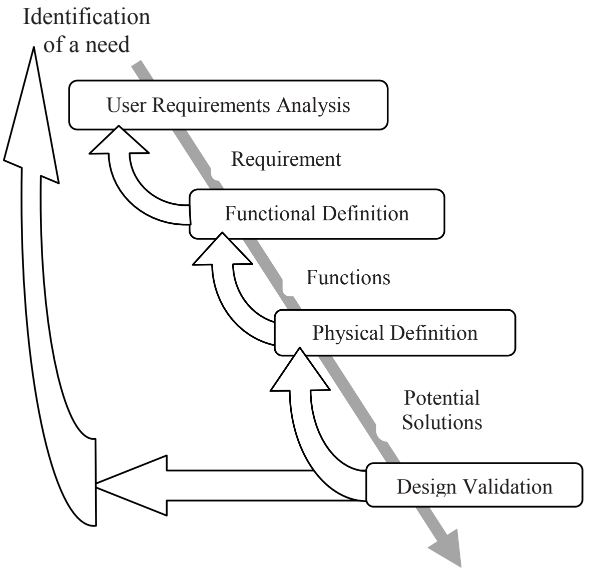

Fig. 2. Systems Engineering, adapted from [4]

Friedenthal et al [6] describes MBSE and SysML as MBSE applies systems modeling as part of the systems engineering process to support system requirements specifications, design, analysis, verification and validation activities of the system being developed from the conceptual design phase and continuing throughout development and later life cycle phases. A primary artifact of MBSE is a coherent model of the system being developed. This approach enhances communications, specification and design precision, design integration and reuse of system specification and design artifacts. The description for SysML is that it provides a means to capture the system modeling information as part of an MBSE approach without imposing a specific method on how this is performed. The selected method determines which activities are performed, the ordering of the activities, and which modeling artifacts are created to represent the system. For example, a use case driven approach that derives functionality based on scenario analysis and associated interactions among the parts. SysML is a general-purpose graphical modeling language that supports the analysis, specification, design, verification and validation of complex systems. These systems may include hardware, software, data, personnel, procedures, facilities and other elements of man-made and natural systems.

OMG [7] provides a SysML specification which identifies and defines nine diagrams: requirement, activity, sequence, state machine, use case, package, block, internal block and parametric.

3. Holistic Systems Engineering Technology Development

The type of engineering data being integrated through the SysML based approach is limited to: Product design engineering data (consisting of operational, functional and physical descriptions), Operational availability data (consisting of reliability, maintainability and supportability predictions and collected data) and whole life cost (organized into individual life cycle phases).

Before looking into the integration of this engineering information, a connection between the systems engineering method in figure 2 and the use of the SysML diagrams identified in OMG [7] needs to be provided. In support of this unique viewpoint, information has been drawn from the John Hopkins University Applied Physics Laboratory's tutorial on MBSE with SysML [8] and information from the German SYSMOD [9] Systems Modelling Process, which helped to derive the following systems engineering process:

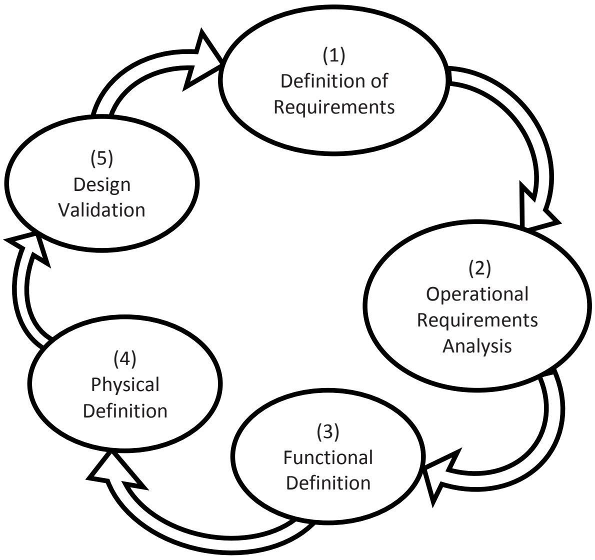

Fig. 3. A Derived Systems Engineering Process

The definition of requirements takes or receives information on the stakeholder and market demands to derive a basic level of system objectives, which in turn provides the basis for the system requirements text. Such text can be recorded in requirements management tools like DOORS.

The operational requirements analysis will start with deriving a system context definition using the SysML block definition diagram. To ensure verification and validation can be conducted within the system model, the system requirements will be described using the requirements diagram. The operational behavior of the system within the context is described with use case diagrams.

The functional definition elaborates the behaviour of the system as described in the use cases with sequence, state machine and activity diagrams.

The physical definition uses the block definition diagram to define the system structure, which is further detailed using the internal block diagram. This structure provides the basis for the definition of the system performance characteristics using the parametric diagram.

The design validation is done by comparing system requirements with potential system solution using the requirement and parametric diagrams.

This basic process is iterative and will progressively produce more detail as the design solutions mature. When looking at the early project phases Bernard [10] addresses the integration of requirements engineering into a MBSE method using SysML.

Addressing the product design engineering data area Wolkl and Shea [11] propose an integrated product model constructed using SysML that moves beyond geometry to integrate all necessary aspects for conceptual design. These include requirements, functions and function structures, working principles and their structures as well as physical effects. This proposal involves a design case study to illustrate how SysML diagram types are used in this engineering area. The integrated product models provide an accumulation of all information describing a product from different viewpoints throughout the product life cycle from concept development to product disposal. There are other research that addresses an integrated view on product design, but like this one it falls short of including operational availability and WLC data as part of the design process.

Machida et al [12] have addressed availability modeling for cloud service providers using SysML during the in-service phase. They present a component-based availability modelling framework, named “Candy”, which constructs a comprehensive availability model semi-automatically from system specifications described by SysML. The construction of the availability model is based on a translation of the SysML model into a series of Stochastic Reward Nets. The approach describes an existing system and does not deal with the system design phases. System failure and scheduled maintenance are addressed, but only in relation to the fact that these events are dictated to the Cloud service providers by the manufacturers. Consequently there is no link between the proposed availability modelling and the system design trade-off studies.

With the aim of applying the SysML approach within the engineering domains David et al [13] describe an approach to use SysML to conduct FMEA (Failure Modes Effect Analysis). The approach describes an engineering framework aimed at integrating the reliability analysis practices within the functional design process. The method is structured into a SysML context and proposes the execution of varied safety and reliability analyses based on the SysML based FMEA. This involved applying techniques of data translation from SysML to FMEA using files exploiting XML (eXtensible Markup Language). The application of the idea required the use of four separate languages in order to generate the FMEA.

When dealing with maintainability engineering in support of the engineering design process no research could be found. However, some research has mentioned maintainability, but this only deals with the maintainability of the SysML model artifacts and the software code that drives the simulations.

The application of SysML to assist Supportability engineering has received interest within the research world, but mainly from China. Li et al [14] present a process using SysML that designs a military aircraft support system. The investigation involved simulation technologies to validate the SysML model. Aspects of the support to maintain the aircraft support system were identified, but only cover a few of the topics that exist within supportability engineering.

Staying within the area of supportability engineering, Thiers and McGinnis [15] have addressed logistic systems and identified that the supply chain can be a key consideration in product design, with its design and operations influenced by concerns about uncertain energy costs, sustainability, economic security, and other complex issues. However, the proposed approach is centered on Global Supply Chains (GSC) and does not address the link with design in terms of design trade-off studies.

When integrating WLC domain into a SysML based approach Smartt and Ferreira [16] have identified a connection with systems engineering using SysML and WLC domain specific tools. It also suggests a statistical based approach to identify WLC values.

With the hope that all the relevant engineering information can be integrated using the SysML approach and various research have investigated the integration of the SysML environment with simulation modelling technologies. The most popular appears to be linking SysML with Modelica and in light of this interest the OMG [17] produced a Modelica Transformation specification. It describes Modelica as a standardized general purpose systems modelling language for analyzing the continuous and discrete time dynamics of complex systems based on solving differential algebraic equations. An alternative approach is provided by Qamar et al [18] where an integrated environment is proposed to link SysML to MATLAB / Simulink models and highlights the need for communication between SysML and other domain tools. The purpose behind this environment is the system engineering models represent multiple domain information, which is used by the different engineering design teams.

Lastly addressing the last link in the chain, which is design trade-off analysis, Biltgen et al [19] propose a methodology for technology evaluation, which incorporates several best-in-class practices and identifies a technique that uses surrogate models and intelligent agents to reduce the burden on human analysts while alleviating the confounding effects of technologies and tactics. This approach addresses the complexities in developing systems-of-systems which are often dominated not by the attributes of individual systems, but rather, the complex interactions of multiple systems that combine to provide a capability.

4. Research Shortfall Readdress

It is clear that SysML is starting to find its way into engineering domains other than systems engineering, but there are still gaps in trying to use SysML as a mean to integrate these engineering domains with the systems engineering process, which in turn is directly linked to the simulation modelling environments.

A key aspect to this integration is the adoption of SysML within the engineering domains. Applications are being developed and refined, for example within the reliability engineering domain a SysML approach to reliability block diagram models and a unique template to produce FMECA worksheets, which extends to the maintainability engineering domain for RCM worksheets and the supportability engineering domain for maintenance task analysis worksheets.

The proposed method here is to take the SysML approach and introduce it into the other engineering domains in the form of SysML model artifact templates. It will require some training for the domain specific engineers to get use to using SysML, but the gains in efficiency due to better coordination, model reuse and the reduction of the duplication of deriving similar information is worth it.

The solution in applying SysML is done through the Artisan Studio software [20] which is being used to describe a range of relevant data within a proper context of both operations and support activities. SysML has the potential to support a good level of integration between disciplines and between software, hardware and human elements of systems operations during design analysis. While SysML is good it is nevertheless a static model, but dynamics can be added to the SysML modelling approach via the parametric diagram. The dynamics are provided in the form of a simulation model using MATLAB/SIMULINK with the Key Performance Indicators (KPI) being collected during the course of the simulation process, which will be used within the design trade-off activity to compare the design options being investigated. The manner in which these trade-off analyses will be conducted is based on a stochastic results matrix produced by the simulations. It will be necessary to design a range of tests covering the characteristics of each life cycle phase to illustrate the through life potential of this modelling approach. Two case studies will be conducted which will each follow a different set of life cycle phases. Source data will come from industry and if no practical data is available then CAD simulations with other virtual analyses will be used. A list of Key Performance Indicators will be identified which is dependent on the system and its operations and it will be these KPIs that will be measured for each design option. This measurement will be used to compare the performances of each option to aid the decision making process. Based on the simulations, which will derive a set of results and the value of these results will be compared with the performances of real operating systems to establish how close and realistic the simulations were in order to provide some sort of validation.

A simple example to briefly explain the application of this approach is provided in the form of a marine vessel battery charging system using a basic wind turbine. The systems engineering process defined in section three will be used, which starts with the definition of a need and doesn't involve SysML. Just a schematic and a basic text is all that is required initially, see Fig 1 and Fig 3 for the scope of the process:

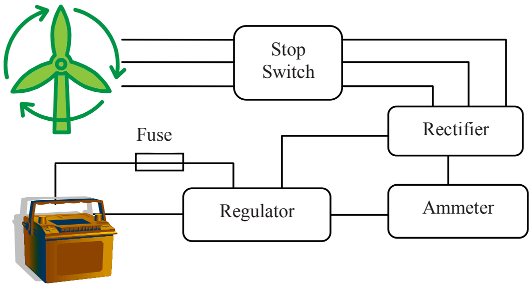

Fig. 4. Basic Block Diagram of Boat Battery Charging adapted from Ampair [21]

Taking the process defined in Fig 3 and applying it to the system scope as defined by Fig 4 the definition of requirements for this system is to allow weekend use of the stored electrical energy in the battery bank without having to rely upon shore line supply. This will require knowledge of the average wind speed in the moored area and the weekend operational use intensity to size both the wind turbine and the battery bank.

The operational requirements of this battery charging system starts with deriving the system context, which could be similar to fig 4, but it includes details of the potential wind energy and the battery bank discharge rate. This insures the system of interest is analysed within the context of its operating and support environment. The system requirements definition using the requirement diagram takes the requirements text and attaches certain constraints to define KPIs. This will show what the energy collection, energy storage and energy utilization levels are required and how the system options will be compared with one another during the design trade-off process. Use cases can be included depending on whether the system is a known existing system or a new design requiring new development.

The functional definition is still within the systems engineering domain and will use sequence, state machine and activities diagrams

The physical definition is the point where the component requirements are defined which needs to cover both operation and support systems. These requirements with SysML templates will be provided to the engineering domains to supply relevant information in a coordinated manner. They will return a range of information for various potential solutions being considered. The information derived by the engineering domains is then used to link into the simulation environment, such as Simulink to produce a matrix of KPI results for all the options. These results are then assessed by the design trade-off process, which will yield recommendations.

Design validation will require the use of the results, parametric diagram and the requirements diagram to perform this activity in support of the design decision direction. Further iterations of this then follow.

The SysML model for this basic example converts the wind force, which can be represented in a matrix covering a 24 hour period and specific to locations, to the corresponding current that can be charged into the battery bank. Since the model allows instances of the design then several solutions can be considered. What is taken into account is the not just the wind force but also the system operational availability state. When this is scaled up it becomes clear that availability will affect the design decision process to ensure the best system through life is created with respect to performance, availability and cost of ownership.

5. Conclusion

The present research reviewed has specialized in one domain and there is nothing that addresses the primary engineering domains integration with each other or with the systems engineering domain collectively. However, if SysML was to be expanded to include the missing engineering domains and linked to some of the present research and the systems engineering process then it will be possible to integrate the key engineering design activities. This will have the benefit of allowing the systems engineering function to coordinate those activities and collect key engineering data to support the simulation and project management processes.

The impact that SysML can have on the decision making process is through its ability to define system interconnections in a structured and consistent manner. The defined interconnections will allow the simulations to derive more realistic results which are then assessed through the trade-off analysis to provide a ranked list with risks identified for the decision making process. By not using SysML to assist the simulation design and build there are risks that some real-life interconnections could be missed and the results would not be as realistic and the resulting decision to select one option over another could be wrong.

The areas considered unique to this research are expanding the use of SysML into other engineering domains not covered to date (i.e., RCM, MTA, whole life cost, combined operation and support system design, etc.), the creation of a combined SysML with simulation code, to support modularization and model reuse and the design of an evolving 3D simulation results matrix to support design trade-off sampling methods.

The main point here is to create systems that can work within the intended environment given the variability's of wind resource (in this example) and the system's ability to continue functioning at the most cost effective level. This will require the system modelling technology to consider many different potential system configurations, which provides the added bonus to tailor system designs to particular environments and situations.

Acknowledgements

This research is part of the "Through Life Engineering Services" project (EPSRC funded: EP/I033246/1).

References

[1] United Kingdom (UK) Ministry of Defence (MoD) Defence Science and Technology, "Operational Research and Analysis: Providing the Evidence for Evidence-Based Decision Making", 15th November 2011.

[2] United Kingdom (UK) Ministry of Defence (MoD), AOF strategic guide DLOD.

[3] International Committee on Systems Engineering (INCOSE) fellows consesus. http://www.incose.org/practice/fellowsconsensus.aspx.

[4] The Johns Hopkins University Applied Physics Laboratory, Training Material – Model-Based Systems Engineering with SysML, Section 1b – SE Overview.pdf, p. 9, copyright 2009.

[5] Object Management Group (OMG) System Modelling Language (SysML) Publications Tutorial section, "MBSE with SysML Tutorial.

[6] Friedenthal, S., Moore A., and Steiner, R., 2008. A Practical Guide to SysML, The Systems Modelling Language, a book published by Elsevier, section 2 and section 3.3.

[7] Object Management Group (OMG) System Modelling Language (SysML)., 2012. Specification SysML version 1.3, p. 167.

[8] The Johns Hopkins University Applied Physics Laboratory, Training Material – Model-Based Systems Engineering with SysML, Section 1d – SysML Overview.pdf, p. 29, copyright 2009.

[9] SYSMOD – Systems Modelling Process, copyright 2010 oose Innovative Informatik GmbH, based on the book Systems Engineering with SysML/UML by Tim Weilkiens.

[10] Bernard, Y., 2012. Requirements Management within a Full Model-Based Engineering Approach, Journal Systems Engineering, Vol 15, No. 2, Wiley Periodicals.

[11] Wolkl, S., and Shea, K., 2009. A Computational Product Model for Conceptual Design Using SysML. Proceedings of Computers and Information in Engineering Conference, ASME.

[12] Machida, F., Andrade, E., Kim, D.S., and Trivedi, K.S., 2011. Candy: Component-based Availability Framework for Cloud Service Management Using SysML. 30th IEEE International Symposium on Reliable Distributed Systems by IEEE Computer Society.

[13] David, P., Idasiak, V., and Kratz, F., 2010. Automating the Synthesis of AltaRica Data-Flow models from SysML. Reliability, Risk and Safety: Theory and Applications by Taylor & Francis Group.

[14] Li, L., Ma, L., Wang, N., and Yang, Q., 2011. Modelling Method of Military Aircraft Support Process Based SysML. IEEE.

[15] Thiers, G., and McGinnis, L., 2011. Logistics Systems Modelling and Simulation. Winter Simulation Conference by IEEE.

[16] Smartt, C., and Ferreira, S., 2011. Advancing Systems Engineering in Support of the Bid and Proposal Process, Vol. 14, No. 3, Wiley Periodicals.

[17] OMG, 2012. SysML – Modelica Transformation. OMG SE DSIG SysML – Modelica Working Group.

[18] Qamar, A., During, C., and Wikander, J., 2009. Designing Mechatronic Systems, a Model-based Perspective, an Attempt to Achieve SysML-MATLAB/Simulink Model Integration. IEEE/ASME International Conference on Advanced Intelligent Mechatronics.

[19] Biltgen, P.T., and Mavris, D.N., 2006. A Methodology for Technology Evaluation and Capability Trade-off for Complex System Architectures. 25th International Congress of the Aeronautical Sciences.

[20] Artisan Studio software by Atego, 2013 .

[21] Ampair Energy Limited, 2nd February 2011. Ampair 300 Wind Turbine Operation and Maintenance Manual, page 17.