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Reuse of SysML Model to Support Innovation in Mechatronic Systems Design

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***Abstract*—Mechatronic systems are inherently complex as they are multidisciplinary, integrating both hardware (electronical, mechanical) and software components. A huge effort is needed in the early design stages to take into account the requirements and constraints of the different stakeholders. A system model is needed to facilitate the communication between the collaborators from different domains. These efforts may be considered as a time loss by several companies. However, when a system model is available (i.e. electrical actuator for aircraft industry), it seems obvious that designing a new variant of the system with a modification of a set of requirements requires much less human effort, as it profits from the reuse and change of the already existing models of the previous system. In this paper, we propose to show the usefulness of the capitalization and reuse of system models by showing how a SysML model of an E-Taxiing (Electric Taxiing) aircraft system can be reused in order to design a new innovative HEPS (Hybrid Electric Propulsion System).**

I. Introduction

Designing new systems is getting more challenging due to their increasing complexity, the evolving customer and market needs, the rapid pace of new technologies and the sharp competitiveness. The integration of new functionality and new technologies requires collaborators from different domains such as mechanical, electrical and computer science designers, as well as multiphysics and safety experts to work together on the same system using different models with different tools at different levels of abstraction.

In order to ensure the consistency of all these models, system architects are key designers as their role is to share data, parameters, information and models with all the members of the design team. Model-Based Systems Engineering (MBSE) provides system architects with means to ensure the consistency of the whole model of a complex system where requirements, structure and functions of the system can be expressed with models instead of documents.

Usually, new products are obtained from progressive updates and changes of already existing ones. Indeed, companies usually integrate parts of their existing products to deliver new ones in order to save time and benefit from their previous design and testing efforts. This has the benefits of reducing risks and cost in the design of engineered products [1]. However, as the complexity of engineered systems is increasing, managing the changes needed for new variants or similar products is also increasingly challenging. Fricke et al. in [2] stated that the current system development shall face three key factors that are: a dynamic market, technological evolution and a variety of environments that imply design changes even at late stages of the design process. To cope with these factors, system design shall support design changes at any time of the design process or even during the operational phase of the system. Indeed, systems that have relatively long lifecycles, such as aeronautic systems, shall be designed with the ability to be changed during their operational phase to comply with evolving regulations and also include some new technologies either to stay ahead of competition or to enhance the efficiency and the operational cost of their products. For instance, several studies are conducted in order to replace conventional hydraulic actuators of the flight control surfaces such as ailerons, spoilers etc. with EMAs (Electromechanical Actuators) [3]. Recent electric technology development also gives innovative ideas of adding new functionality to the landing gear such as E-Taxiing (Electric Taxiing) and HEPS (Hybrid Electric Propulsion System) to reduce fuel consumption. E-Taxiing allows the aircraft to use only electric motors while switching off conventional main engines during taxiing [4], [5], [6], while HEPS upgrades E-Taxiing and allows hybrid Take-off and landing in addition to electric taxiing [7].

In this paper, we propose to demonstrate how a system model of the E-Taxiing system can be reused to save design effort and time while designing a new innovative HEPS. The design of both systems is performed using the SysML language based on the methodology proposed by Mhenni et al. [8]. We assume that the E-Taxiing system design model already exists and we will demonstrate how to reuse it to design the new HEPS system.

The paper is organized as follows. First an overview of related work is given in section II. Next, the proposed approach for model reuse is presented in section III. Section IV presents the case study applying the proposed approach to design the HEPS reusing the E-Taxiing model . Finally, the paper is concluded in section V.

II. Related Work

A. Integrated design of complex system and MBSE

Gotoh et al. proposed a model-driven development method for complex multidisciplinary systems design based on the

requirements modeling [9]. In this method, the requirements model has four layers: target product and context (L0), high level functions (domain) and cross-domain functions (application) (L1), system elements independently of the realization method (L2) and system composition elements taking into account the realization method (L3). Each layer has behavior, structure, constraint / technical specification and requirement qualification elements that are decomposed from the initial stakeholder requirements. Authors have examined the possibilities of the method by modeling an example of intelligent crane system using SysML. This study highlights how the understanding of the design intentions, the improvement of communication among different domains designers and the reuse of the model are facilitated. However, the link between the requirement model and the logical model is not discussed.

Eguchi et al. have also used a model-driven development method under the assumption of initial appropriate components structures, and decomposed and refined models by analyzing relationships between components and activities in relevant activity diagrams [10]. Starting with an appropriate structure may shave the number of design iterations, even if it may be quite difficult for designers to work with a predefined topological structure of the system.

A SysML based methodology for mechatronic systems design is proposed by Mhenni et al. [8]. This methodology is made up of two phases : a Black Box Analysis and a White Box Analysis. The Black Box Analysis phase is an external point of view dedicated to the requirements definition and analysis independently from the solution (i.e. the system is considered as a black box). The resulting set of requirements will be the baseline for the next design phase, the White Box Analysis. This phase is dedicated to modeling functional and components-based structure and behavior of the system, with respect to the previously defined requirements.

B. Methodology for engineering change

In the software development field, Hoda et al. in [11] proposed a method that facilitates to developers understanding and handling the impact of software modifications due to modified customer requirements and derived products development, in order to reuse an existing software. The proposed method visualizes the impact of modifications using Requirement-to-Component and Component-to-Component relationships on a duality chart to facilitate the understanding even to non-specialists. Therefore, developers can easily handle not only components that need modification but also test range and test policy that depend on the variety of “Add”, “Modify” and “Delete” modification in the test process.

The impact analysis of mechatronic system design change based on requirement model (respects the methodology of [9]) using SysML with TBD (Topdown-oriented Behavior Design system) framework and DSM (Design Structure Matrix) is studied by Eguchi et al. [10]. They tackle the extraction of affected model elements due to added or/and changed requirements from existing requirement models in order to clarify their impact and reuse. The impact analysis is performed to trace changed elements on DSM that is constructed from components, object flows, states, actions and values of requirement model element. However, relationships of DSM are limited to input / output and composition of components. Therefore more detailed relationship definition such as “refine”, “derive” and “satisfy” may give a better understanding.

Jeong et al. proposed a design method to support design change on long-life products such as vessels and plants [12]. Lifetime-scenario is described by technological and environmental changes that are expected during the design in order to build a model easily changeable in the future, on the product information model that is composed by Component-network and Constraint-network. The design change proposal is evaluated by risk of grown resource and ease of design adjustment. As their contribution, derivation and evaluation of design change proposal may be valid, however design support using suggestion of impact propagation is not valid enough.

III. Description of the Model-Reuse Approach

This section describes the reuse approach allowing to benefit from existing models in the design of new products sharing a set of requirements with the existing ones. By reusing existing models, the brainstorming, design efforts and rationale for previous choices are capitalized, thus, avoiding to designers to redo previous work. This approach only applies if the new system has several common points with the existing one, i.e. the new system is an enhanced version of the previous one with the purpose of adding new technologies or new functions. This approach is based on the top-down design methodology presented in [8]. The input point of this approach is an existing model built following the previously mentioned approach and a set of requirements of the new product to be designed. The requirements of the new product shall include some requirements in common with the initial system. In general, the new set of requirements RN can be divided into three subsets with respect to the requirements of the initial system:

- RN1: a subset of requirements that are identical to a subset of the initial system requirements.
- RN2: a subset of requirements that are a modified version of a subset of the initial system requirements.
- RN3: a subset of new requirements.

In the same way, the set of the initial requirements are divided into three subsets with respect to the new system requirements:

- RI1: a subset of requirements that are identical to a subset of the new system requirements RI1=RN1.
- RI2: a subset of requirements that are a modified version of a subset of the new system requirements.
- RI3: a subset of requirements suppressed in the new system.

The design of the new system follows the same top-down SysML-based approach as in the design of the initial system. However, the different processes of the design (i.e. Requirement definition, Functional specification etc.) will be fed with the corresponding models built during the design of

the initial system and these models will be updated according to the changes as shown in Figure 1.

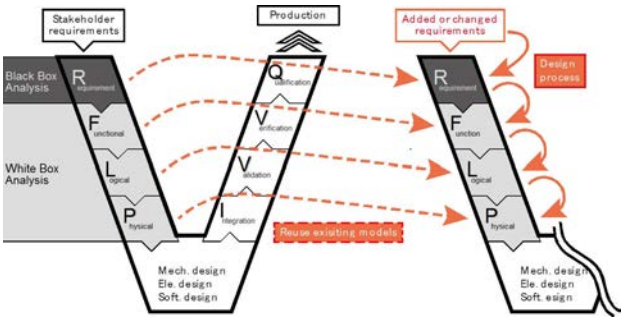

Fig. 1. Change Management Based on the V-Cycle Representation

The first step is then the update of the existing requirements model by adding the new requirements RN3, modifying RI2 into RN2 and discarding RI3. Thanks to the traceability links established in the initial model, it is easy to manage the impact of the requirements changes on the system model. Indeed, the system model elements (functions, components etc.) that are no longer linked to requirements shall be removed from the model and new model elements shall be added to satisfy the new requirements. Model elements linked to modified requirements shall be modified in turn to comply with the new requirements. At the functions level for instance, there will also be three subsets of functions in the initial and new system models. A subset of functions FN1 in the new system that are identical to a subset FI1 of the functions of the initial system, a subset FN2 of functions of the new system that are a modified version of a subset FI2 and a subset FN3 of the new functions in the new system that replace the subset FI3 of the initial system functions. The components shall be allocated to the new set of functions. Components allocated only to functions of the subset FI3 shall be deleted from the design of the new system. Then, the designers have the choice to either add new components to achieve the new functions or to modify the existing components to make them achieve more functions. The choice depends of different criteria such as the feasibility, cost, available volume etc.

IV. Reuse of System Model for New System with Modified Requirements

A. Description of the E-Taxiing system

Most of the on-ground operations (except the push-back) are performed using the main engines of the aircraft. While most aircraft are equipped with turbofan main engines optimized to minimize fuel consumption during airborne operations, the efficiency of the main engines is very low for on-ground operations. Therefore, the German Aerospace Center (DLR) has developed an E-Taxiing system in order to enable electric taxiing and push-back using in-wheel electric motors integrated in the Nose Landing Gear (NLG) of an Airbus A320 [13]. The E-Taxiing system allows the aircraft to move autonomously on the ground (during the taxiing phase) wile the main engines are stopped, electrical energy being provided by the on-board Auxiliary Power Unit (APU).

B. Procedure of reuse of SysML model of existing system

Hybrid Electric Propulsion System (HEPS) is used as a case study in this paper. The HEPS is intended to achieve new functions in addition to the electric Taxiing. The new SysML model of the HEPS is obtained by modifying the E-Taxiing SysML model according to the procedure described in the previous section.

The corresponding new stakeholder requirements are “Hybrid propulsion take-off” and “Hybrid brake landing with energy harvesting”. In the following, we will show how the HEPS system is designed starting from an already existing E-Taxiing system model by modifying it to comply with the new set of requirements. The different steps of the modification process are detailed here after with the new diagrams. On these diagrams, lime and green color elements show modified elements and aqua and blue color elements show the added elements.

- Global Mission and initial requirements of the E-Taxiing are reused to build the new requirements model for the HEPS, and modifications are considered with added and/or changed requirement. Figure 2 shows the new requirements diagram. To be adapted to the HEPS, some requirements need to be modified such as the on-board energy source that shall have additional electric storage for take-off and landing (for energy harvesting and storing), and the integrated HMI, etc. Other requirements are modified, such as the electric energy harvesting during landing.
- In the Context model, a new actor, “Thrust lever” is added and the association with the “Brake system” is modified to satisfy the new requirements. The actors of the HEPS are represented in Figure 3.
- External Interfaces are also updated and new external interfaces are added to the model to allow the system to interact with the added actors (in this case the “Thrust lever”). Some interfaces are also modified in consequence. Indeed, “Skid condition” and “Thrust level” are added and “Commands” and “Feedback ports are modified on the new diagram given in Figure 3.
- In addition to the services provided by the E-Taxiing system, the HEPS provides new services shown in the use case diagrams in Figure 4.
- Engineering requirements are given in a new requirement diagram and take into account all the requirements identified in the previous steps. New requirements are added such as “Capability of disengagement during rotating wheels”. The new diagram is shown in Figure 5.
- The functional breakdown has also been updated. New external pins are added in consistency with the external interfaces such as “Thrust-level, “Skid-condition, “User-cmd” and “User-Feedback” pins are modified. Some functions are also modified and other ones are added as shown in the activity diagram is given in Figure 6.

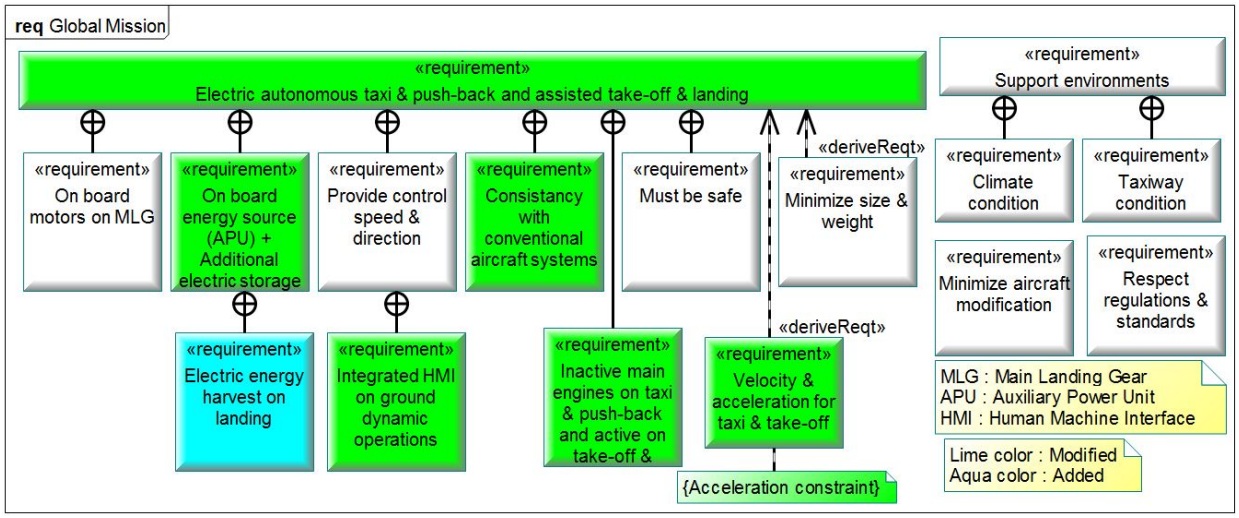

Fig. 2. Requirement Diagram: Global Mission and Initial Requirements

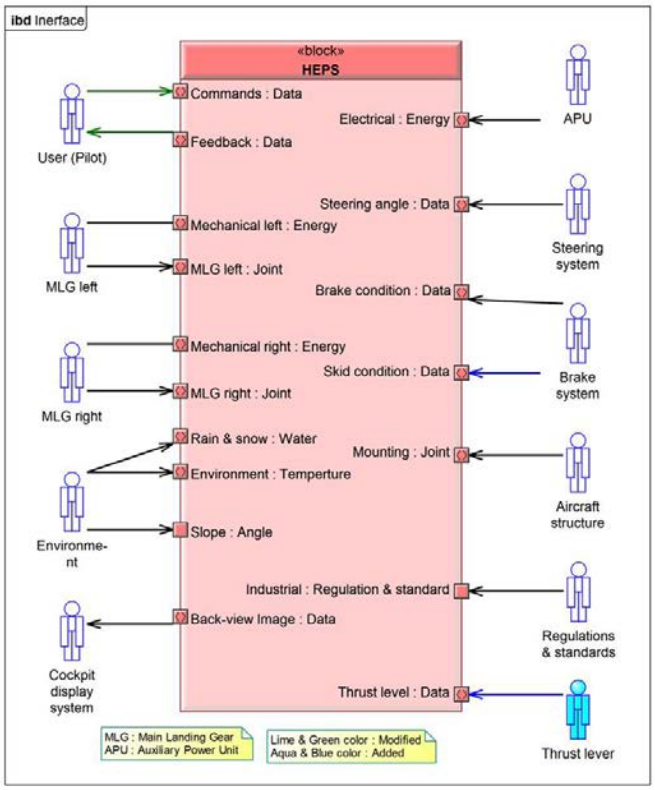

Fig. 3. External Interfaces

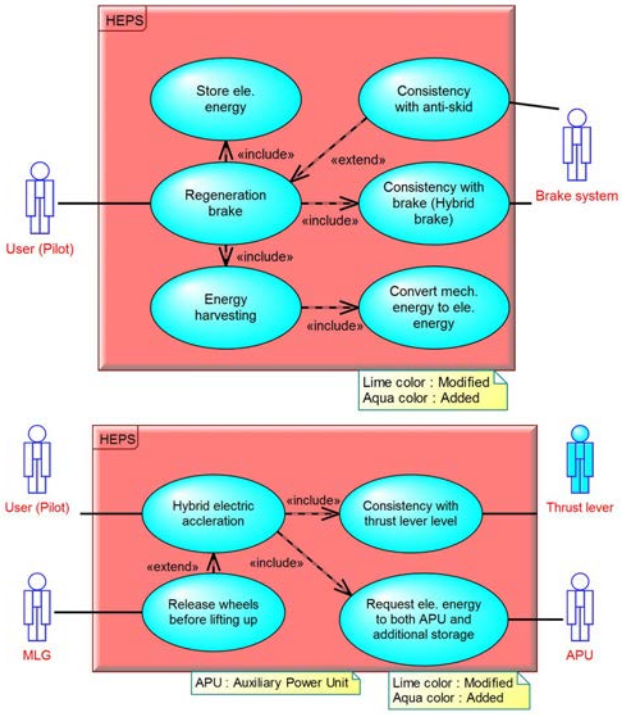

Fig. 4. New Provided Services for the HEPS

- As the HEPS is required to perform new functions compared to the E-Taxiing system, new components are added and are allocated to the new functions added to the functional breakdown. The IBD in Figure 7 gives the different components of the system and their interactions.

V. Conclusion

In order to explain how an existing SysML-based system model may be reused for a new innovative design, we have shown how to turn an electric taxiing system (EGTS) model into a hybrid-electric propulsion system (HEPS) model. Indeed, the reuse of an existing model for a new design project seems less time-consuming, provided the initial SysML model has been systematically built using an univocal and exhaustive system engineering methodology, e.g. with a black box and a white box analysis, encompassing a set of consistent

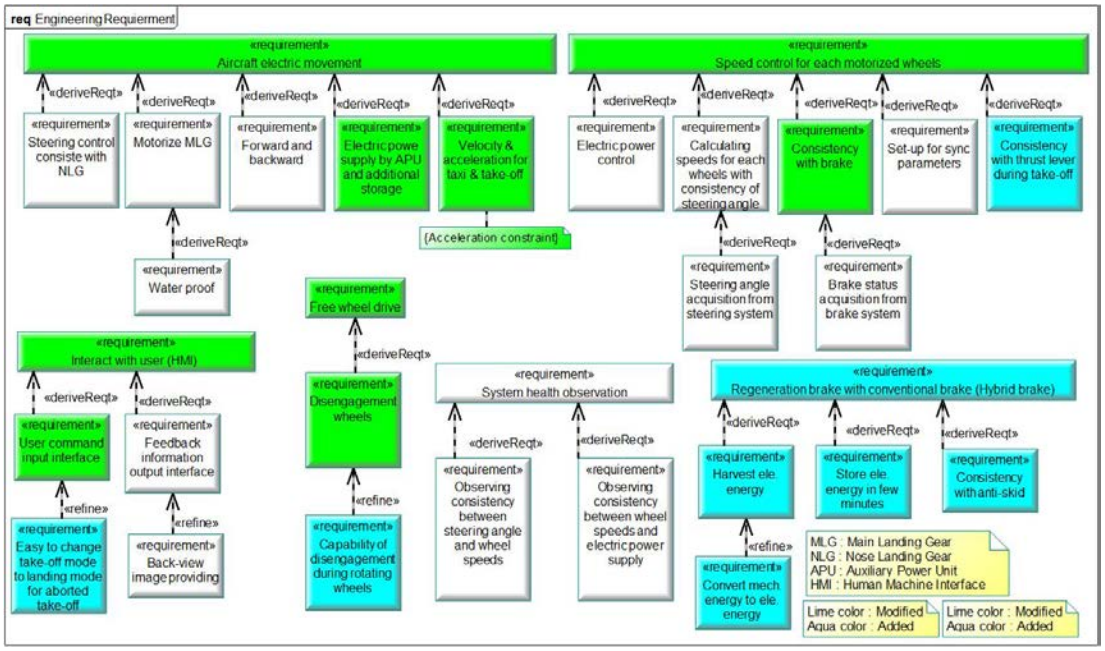

Fig. 5. Requirements Specification

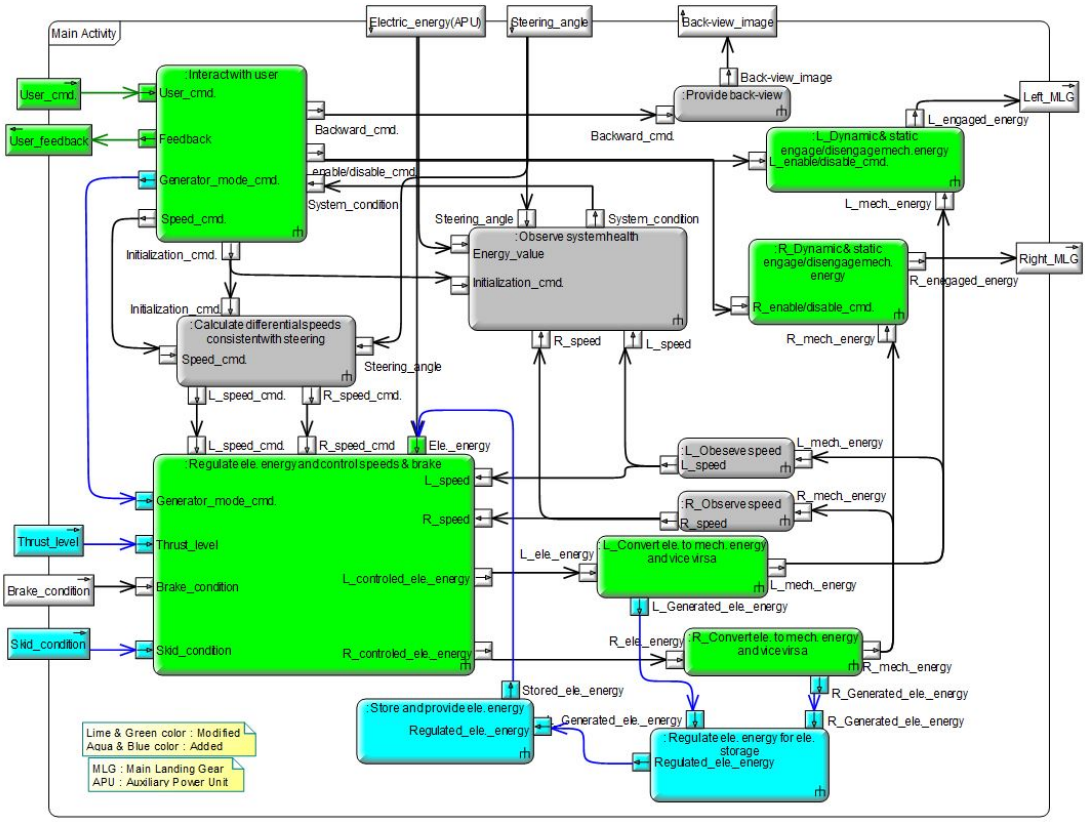

Fig. 6. Functional Architecture

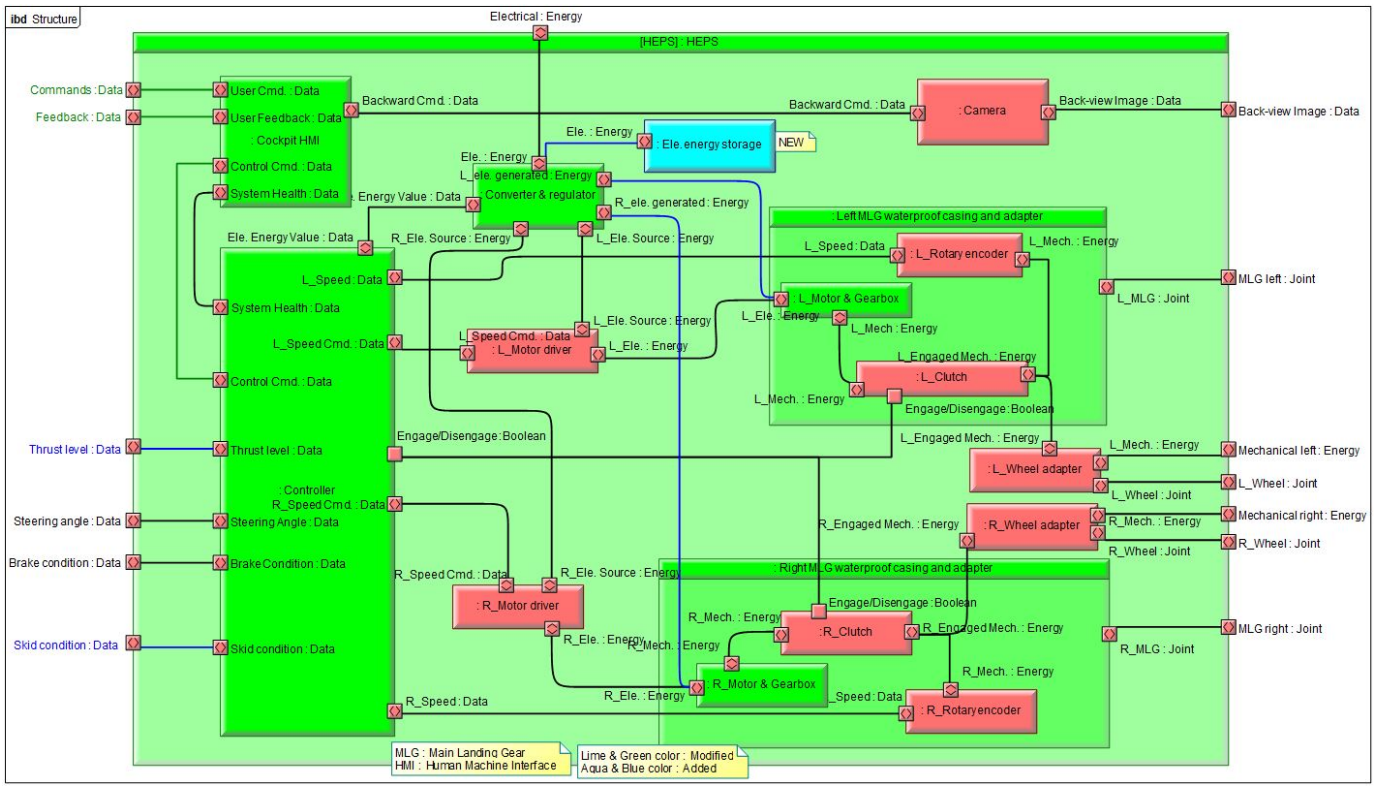

Fig. 7. Logical Architecture

viewpoint diagrams (requirements, structure, behavior, etc.) enriched with relevant essential traceability links. This paper highlights that both with a set of initial traceability links and a traceability matrix, it is much systematic and convenient to unveil the affected SysML objects that have to be modified, removed or added, depending on the requirements changes and the propagation of the change impact, when switching from an initial well-proven system to a new innovative one. Performing such an improvement process on initial SysML modeling allows capitalization of previous systems engineering studies, thus making SysML modeling more effective and acceptable to designers and experts. Since our study mainly focuses on the left side of the Vee-cycle with requirements, functional and components structures definition, future work will have to focus on verification that a similar reuse process can be applied to the right side of the Vee-cycle with integration, verification, validation, qualification and certification. Furthermore, safety considerations and geometrical aspects should be taken into account in these reuse processes to shave development time and cost of new innovative systems among an industrial domain.

References

[1] N. Cross, *Engineering Design Methods: Strategies for Product Design*, 1989.

[2] Fricke, Ernst, Schulz, and Armin, "Design for changeability (dfc): Principles to enable changes in systems throughout their entire lifecycle," *Systems Engineering*, vol. 8, no. 4, pp. 342–359, 2005. [Online]. Available: http://dx.doi.org/10.1002/sys.20039

[3] J.-C. Derrien, "Electromechanical actuator (EMA) advanced technologies for flight controls," in *28th International Congress of The Aeronautical Sciences, ICAS 2012*, 2012.

[4] Y. Nicolas, "etaxi: Taxiing aircraft with engines stopped," *FAST*, vol. 51, pp. 2–10, January 2013.

[5] (2015, November) http://www.greentaxiing.com/.

[6] (2015) http://www.wheeltug.gi/.

[7] M. C. Schwarze, *Operation and Performance Evaluation of Novel Electric-Wheel-Driven Hybrid-Electric Propulsion Systems on Standard Short Range Passenger Airplanes*, B. D. G. fur Luft-und Raumfahrt-Lilienthal-Oberth, Ed., 2013.

[8] F. Mhenni, J.-Y. Choley, O. Penas, R. Plateaux, and M. Hammadi, "A SysML-based methodology for mechatronic systems architectural design," *Advanced Engineering Informatics*, vol. 28, no. 3, pp. 218 – 231, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1474034614000342

[9] T. Gotoh, T. Eguchi, T. Koga, and K. Aoyama, "Model-driven development for electrical/mechanical/soft integrated products with sysml," in *Proceedings of the JSME D&S Conference, 2009*, 2009.

[10] T. Eguchi, T. Gotoh, T. Koga, and K. Aoyama, "Impact analysis of design change based on requirement model of mechatronics product," *Transactions on JSME*, pp. 26–35, 2010.

[11] K. Hoda, "Efficient improvement of software testing by visualizing the impact of software modifications," Union of Japanese Scientists and Engineers, Tech. Rep., 2004.

[12] D. Jeong, K. Oizumi, and K. Aoyama, "Design of changeable product structure with the consideration of change propagation," in *Proceedings of the JSME D&S Conference, 2014*, 2014.

[13] S. Michael, R. Frank, B. Andreas, and H. Heribert, "High integrated electric machine for aircraft autonomous taxiing," in *Proceedings of the 6th International Conference EVER, Monaco, 2011*, 2011.