Smart Mobile Factory Design Decomposition Using Model-based Systems Engineering

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Abstract. Nowadays, providing an automatic agile process in the design processes relying on Model-Based Systems Engineering (MBSE) to speed up innovation creation as possible is a progress key as well as a survival factor in the competitive industrial environment. Therefore, companies should make a cultural shift from traditional document-based information exchange and iterative time-consuming serial design procedures, to communicate the information based on visual modeling in a common language such as SysML, which is easier to follow. In this respect, although the capability of Axiomatic Design (AD) in product work breakdown structure has been proven, from stakeholders' needs to functional requirements and physical solutions, it seems that now is the time to automate and speed up this critical process in the product life cycle practically using developed MBSE tools. That means, when changes occur, updating a model is more straightforward than documents that require manual revisions of tables, glossaries, requirements, etc. To show the application of such a work, this paper proposes the AD of a smart mobile Hyperloop transportation factory through requirements modeling and analysis in the Cameo System Modeler software. As the main goal of the project is the decentralization of producing tube elements, and easily disassembling and building up again along the planned track/construction side, the AD is focused on the mobile factory than the Hyperloop system. Results illustrate how MBSE could alleviate difficulties in dealing with AD problems in real-world complex applications with lots of requirements.

Keywords: Model-Based Systems Engineering, Cameo System Modeler, Axiomatic Design, Smart Mobile Factory, Hyperloop Transport System.

1 Introduction

The main idea of Smart Mobile Factories (SMFs) relied on industries that can operate in remote areas with limited logistical capabilities. Using SMFs and operating locally can gain competitive advantages by reducing logistics efforts and costs while improving operational efficiency. As SMFs can install, implement, and disassemble in nearby operational platforms, parts can be produced directly wherever the need arises without having to wait for them to arrive from a supplier or central storage. Overall, a wealth of potential applications considering sustainability factors can be provided through the SMFs. A systematic literature review on modular and mobile facility location problems is done by Eduardo and Udo in [1]. According to [1], to provide a more efficient response to today's markets, more-flexible networks have to be proposed by addressing the inclusion of modular units to considering fully mobile units. As the situation of flexibility in factories' planning horizon shows (see Fig. 1), flexibility directly depends on the degree of mobility [2]. After the idea of "factory in a box" as a solution to move toward SMFs (i.e., manufacturing small-scale components in a container, see Fig. 2), now it is time for emerging concepts for the additive manufacturing of prefabricated parts made of concrete or other materials for real-world industrial applications [3, 4].

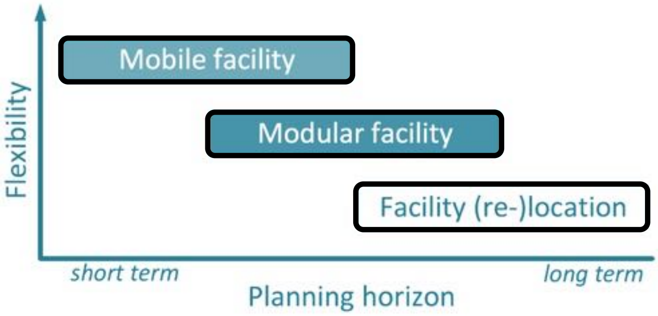


Fig. 1. Flexibility in factories' planning horizon [1]

Fig. 2. Factory in a box as a solution for SMFs [4]

In recent years, pandemic problems such as the COVID-19 crisis remarkably revealed supply chain vulnerabilities. The manufacturing industry strongly persists to promote the expectations of previous years and a strong trend toward intelligent reindustrialization and local production can be seen these days. More and more companies are striving to alleviate supply chain difficulties due to geographically distant suppliers through SMFs [4]. At the same time, significant attention to the systems engineering field relying on a system thinking mindset will speed up systems design in a product lifecycle and it is expected to increase productivity through efficiency gains and thus gradually reduce the gap between design and manufacturing.

This research aims to illustrate how Model-Based Systems Engineering (MBSE) tools like Catia Magic can be used to decompose the functional requirements of complex systems. Therefore, producing infrastructure elements of the Hyperloop Transportation System (HTS) as an SMF is proposed.

In the following, first, a brief overview of the SMF of the HTS project at the Free University of Bozen-Bolzano is presented. Then, the problem definition and formulation as an Axiomatic Design (AD) are introduced in the next section. After that, the application of the Cameo Systems Modeler as part of Catia Magic in the automation of the AD process and related results are highlighted and proposed. The final section provides the conclusions of this research.

2 Mobile Smart Factory for Hyperloop Construction

The Hyperloop concept was born in 2013 when tech entrepreneur Elon Musk published a white paper on the subject [5] that focused on environmentally friendly goods and passenger transport. The Hyperloop's propulsion system is generated by a linear electric motor powered by renewable energy sources. Magnetic levitation is eco-friendly, consumes less energy, and causes no emissions. Eurotube Foundation [6] a non-profit research institution from Switzerland has developed a patent that envisages building the tube infrastructure using concrete instead of metal alloys. Within the joint research project Smart Mobile Factory for Infrastructure Projects (SMF4INFRA) between the Eidgenössische Technische Hochschule Zürich (ETH Zürich) and the Free University of Bozen-Bolzano, a prototype for a smart mobile factory to deliver material for the construction of hyperloop infrastructure is developed. Using a mobile factory in a linear construction site, with wide-ranging routes, allows for erecting the infrastructure sustainably. Moving the production factory of the individual pipe components while remaining close to the construction site's progression helps guarantee economic and ecological sustainability. Within the SMF4INFRA project, the physical mobile factory will be designed (Fig. 3) and its Digital Twin will be developed to ensure environmental sustainability during the construction of the hyperloop infrastructure project.

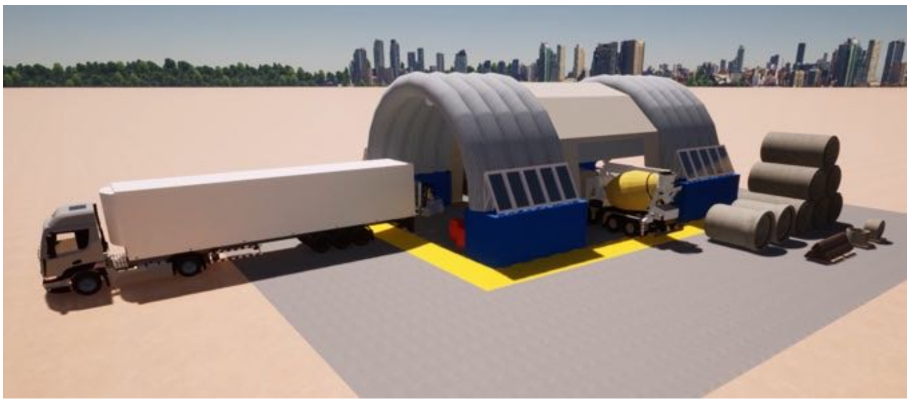


Fig. 3. First concept of the Smart Mobile Factory for hyperloop construction

3 Axiomatic Design Decomposition

Axiomatic Design (AD) was developed by Nam P. Suh in the mid-1970s in the pursuit of developing a scientific, generalized, codified, and systematic procedure for design. AD uses the following four domains:

1) the customer domain where the customer wishes are described as so-called customer needs (CNs);
2) the functional domain where CNs are translated into functional requirements (FRs) as well as design constraints (Cs);
3) the physical domain where design parameters (DPs) are derived that meet the previously defined functional requirements and
4) the process domain, where the DPs are transformed into real process variables (PVs).

The scientific theory gets its name from two axioms in AD that must be respected [7].

- The first is the Independence Axiom: Maintain the independence of the functional elements, i.e., avoid coupling in the system (e.g., avoiding dependencies between the DPs and other FRs).
- The second is the Information Axiom: Minimize the information content: select the solution with the least information content, i.e., that has the highest probability of success.

To apply these axioms, parallel functional and physical hierarchies are constructed, the latter containing the physical design solutions. The benefit of AD is that the designer learns how to construct large design hierarchies quickly that are more structured, thus freeing more time for mastering applications [8].
In the initial workshop on AD at Smart Mini Factory Lab. at Unibz, requirements and so-called CAs of the SMF4INFRA project were collected. Based on these inputs, FRs and Cs are defined and design parameters for a redesign were derived in an AD top-down decomposition and mapping process. The AD steps that have been carried out are as follows:

Step 1: Problem Formulation
Step 2: Elaborate use cases into steps
Step 3: Identify customer needs
Step 4: Translate Needs and Use Case Steps to FRs and FRms
Step 5: Generate Physical Solutions alternatives
Step 6: Design decomposition – chose PS to achieve FR.

Figure 4 presents the result of these six steps for decomposing the design of a smart mobile factory for hyperloop infrastructure into 4 levels (Level 0 to Level 3). The design team has checked the independence axiom using the design matrix for each level to achieve an uncoupled or at least decoupled design.

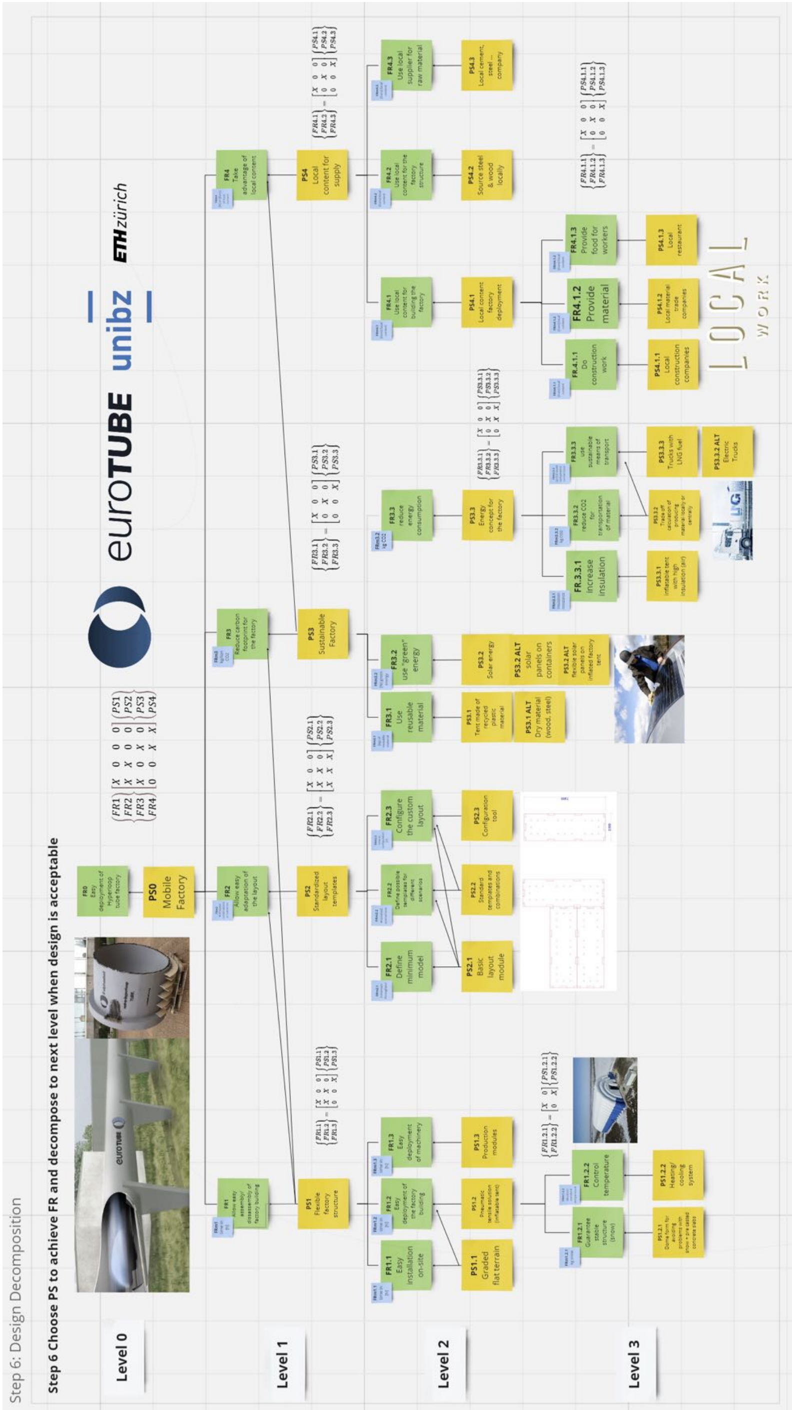


Fig. 3. Overview of the Axiomatic Design based decomposition of FR and PS

4 Model-based Systems Engineering (MBSE) using Catia Magic

Model-based systems engineering tools like Cameo System Modeler (developed by No Magic Inc. which was purchased by Dassault Systems company in 2018 and is now part of Catia Magic) are suitable solutions for software architectures and operational processes. Requirement management is one of the features of this tool which provides capabilities as follows for users (see Fig. 5) [9]:

- Creating requirements
- Importing text-based requirements
- Requirements decomposition
- Requirements numbering
- Requirements gap and coverage analysis
- Tracing requirement changes in Teamwork Cloud
- Requirements verification
- Visualize and analyze.

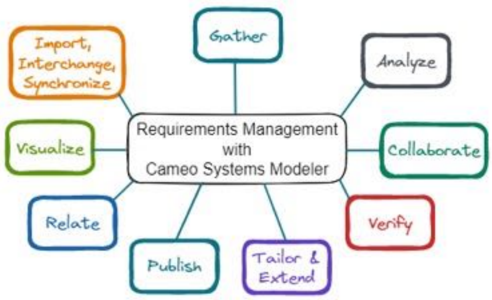


Fig. 5. The main features of Cameo Requirements Management [9]

Requirements can easily be visualized through the Requirement Diagram and Requirements Table by creating and importing them into the modeling tool. But before diving into the requirements, the structure of the problem can be modeled with blocks which here SysML Block Definition Diagram (BDD) plays an important role in this software. Using this part, you can see the problem's overall work breakdown structure and decide on decomposition and interaction between different blocks. In another word, system hierarchy from system to sub-systems and the specification of software, hardware, or human elements can be represented by blocks [9]. Figure 6 illustrates the SMF structure of the Hyperloop system in the BDD.

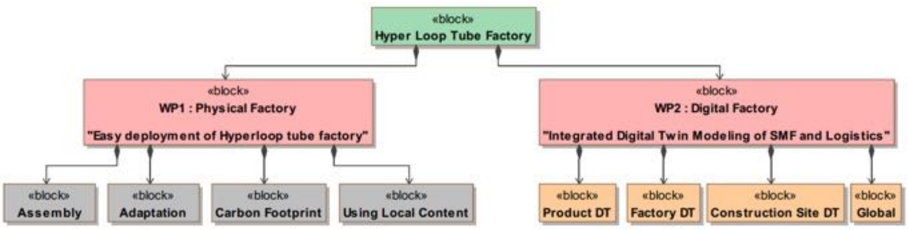
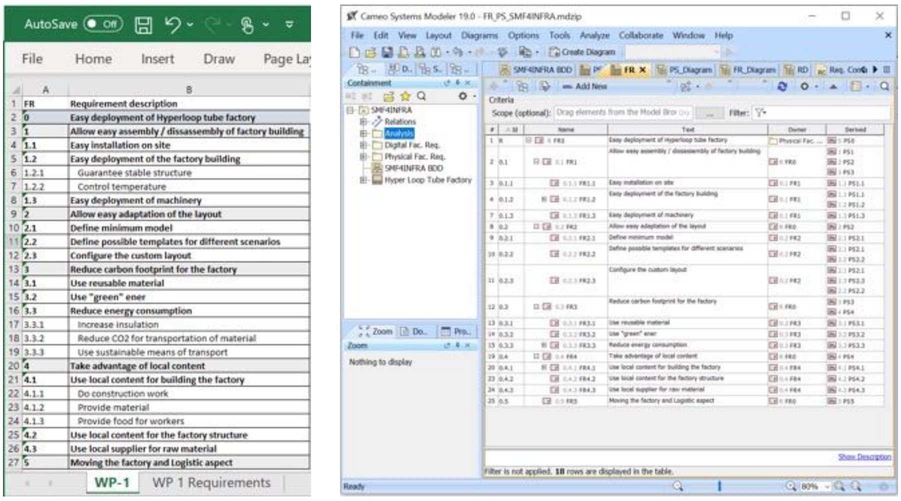


Fig. 6. The structure of the SMF of the Hyperloop project in the BDD

After creating the work breakdown structure of the problem from the system to the subsystem level, it is time to import predetermined FRs and PSs from excel sheets to the Cameo software. This process can be done from the beginning in the software. But importing and exporting requirements with different text-related software using Cameo is an advantage. All requirements can be easily updated in tables and diagrams just by copying and pasting them into the requirements table by a predetermined template. Figure 7 illustrates the FRs table based on related excel sheet requirements. The requirement Diagrams are a valuable tool to provide a bridge between traditional requirement management tools and other SysML models. They are for demonstrating traceability from the requirements to the elements that are dependent on them. The FRs and PSs diagrams are represented in Fig. 8.

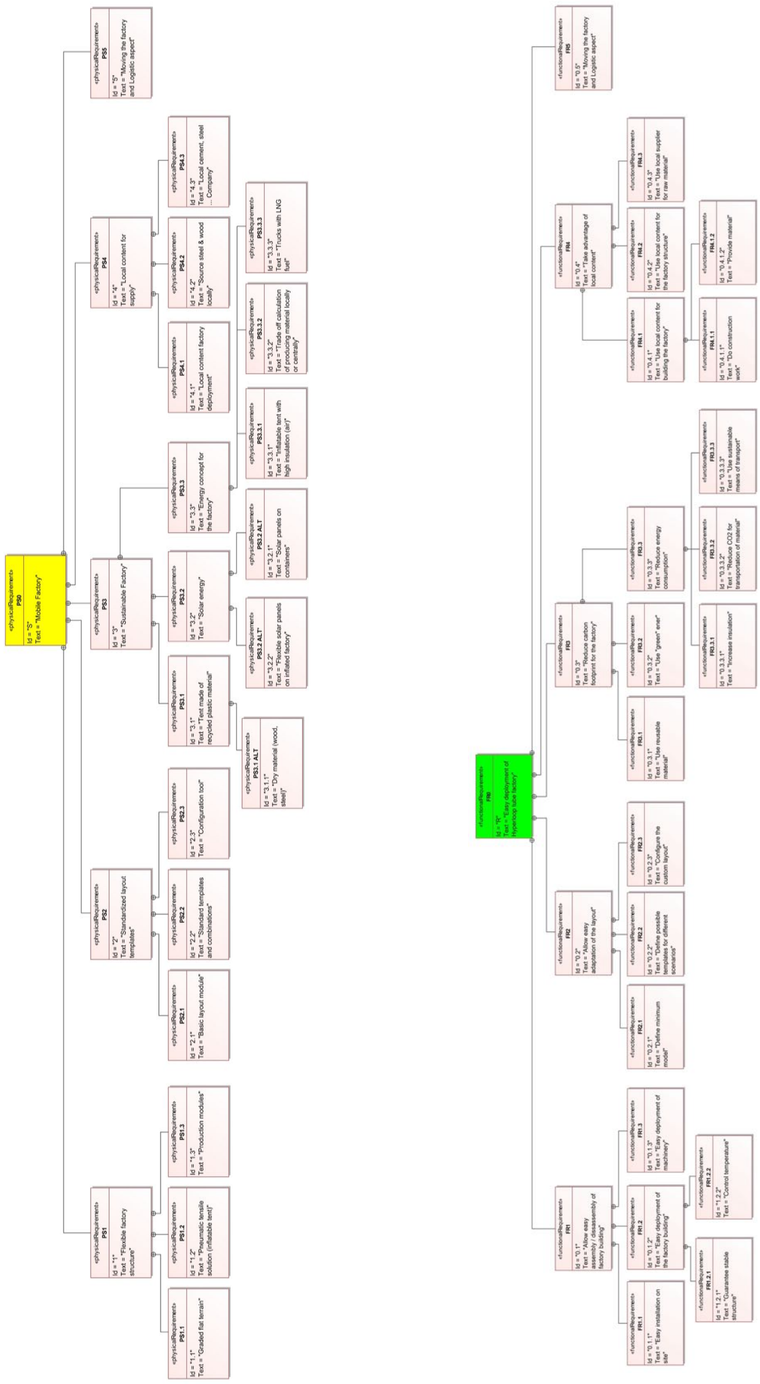
Such modeling can be done for PSs and finally, the relation between FRs and PSs can be shown and checked by providing a diagram including both (Fig. 9). One of the advantages of a requirements diagram like Fig. 9 is that the user can create any FRs and PSs and just link them together and by updating the software, the changes can be saved in other tables that could be exported for other usages.

We can use the Requirement Containment Map (RCM) and Requirement Derivation Map (RDM) to review, analyze, and decompose the Requirements. In these decompositions as trees, the RDM displays the decomposition of requirements related to the Derive relationship. Figures 10 and 11 show the RDM and RCM of the SMF of the Hyperloop infrastructure project respectively. The user can determine the level/depth of decomposition to display results.



Requirements Excel Sheet *Cameo Requirements Table*

Fig. 7. The FRs table in Cameo



PSs *FRs*

Fig. 8. The FRs and PSs diagrams in Cameo

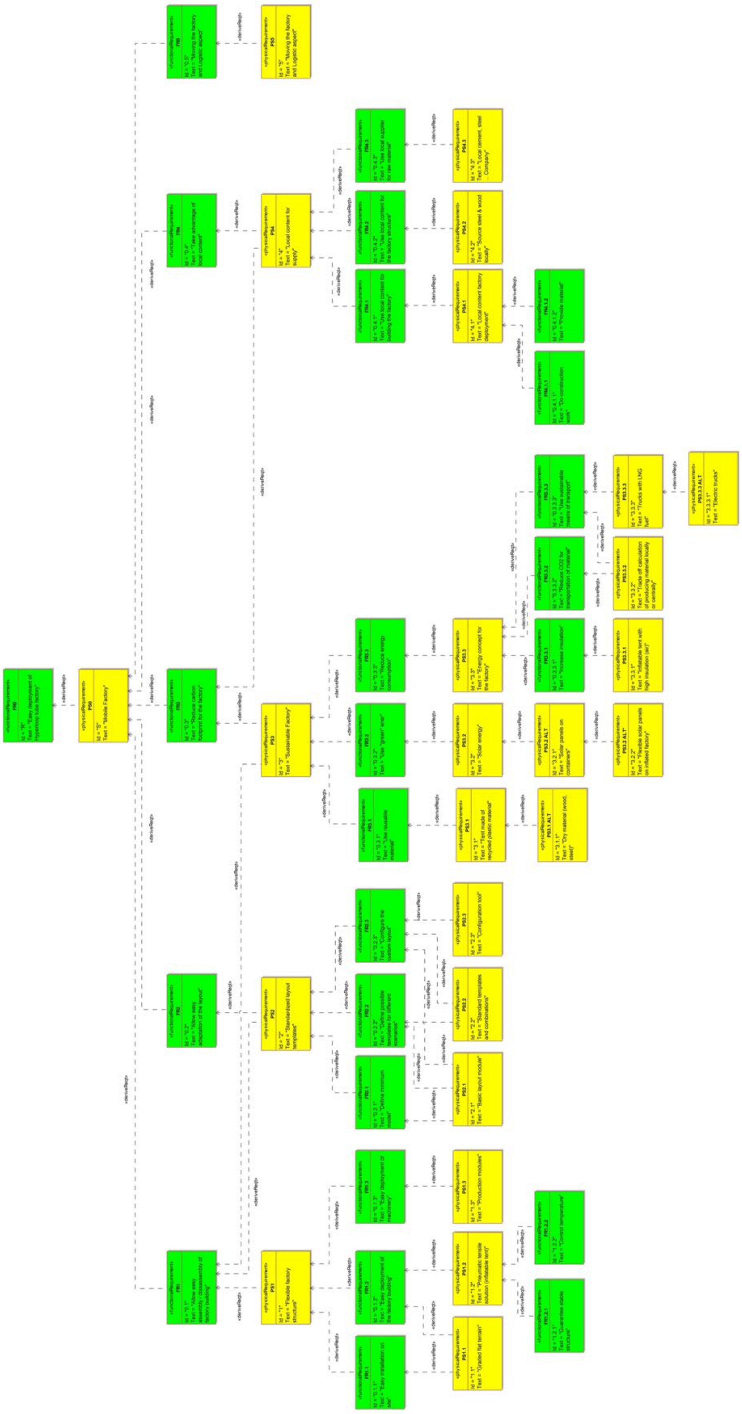
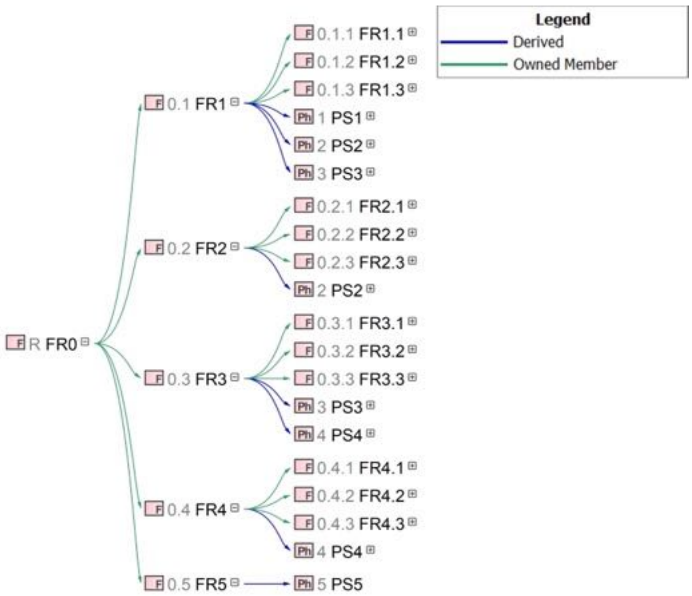
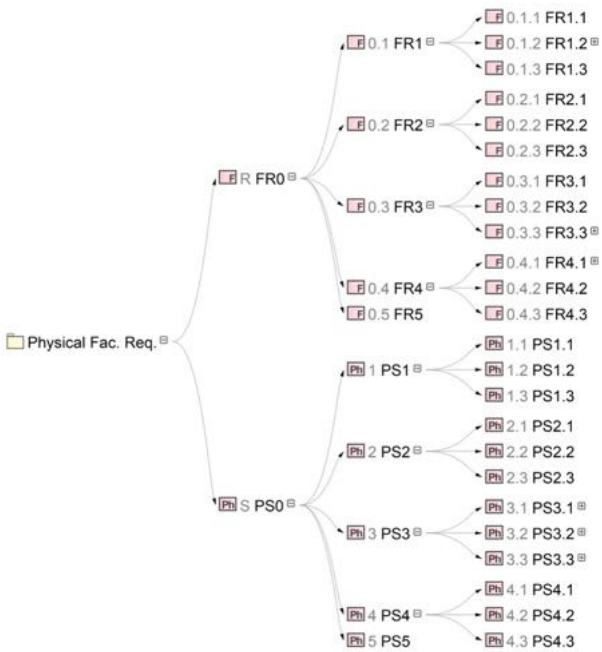


Fig. 9. The relation between FRs and PSs in the Cameo requirements diagram



Requirement Derivation Map (depth 2)

Fig. 10. The requirement derivation map of SMF4INFRA in Cameo



Requirement Containment Map (depth 3)

Fig. 11. The requirement containment map of SMF4INFRA in Cameo

5 Conclusion and Outlook

In this paper, we have introduced model-based systems engineering as an effective tool for alleviating difficulties with axiomatic design problems in dealing with real-world problems which include remarkable and inevitable interdisciplinary interactions in different levels of the system of systems, systems, and sub-systems. To further illustrate the capabilities of such software, the application of Cameo Systems Modeler as part of CATIA MAGIC software for AD of an SMF is proposed. In this respect, one of the projects (i.e. SMF4INFRA) that is defined between ETH Zürich and Unibz to deliver material for the construction of hyperloop infrastructure is presented and the final result of the AD which has been done in a workshop at Unibz is demonstrated. The automation of the AD process using MBSE tools helps managers and systems engineers to easier gather requirements through teamwork procedures and update, trace, and analyze them online. Having worked closely with the requirements management methodology presented herein, it could be expanded for the digital twin work package of the SMF4INFRA and bring the digital model as close as possible to the physical model.

Acknowledgments

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