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1D-CAE による製品構成の探索

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Design Exploration of Alternative Configurations Using 1D-CAE: A Value-Driven Design Approach Utilizing OPM and Modelica

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The objective of this paper is to describe and demonstrate a methodology and tools to enable System-Level designs to be synthesized, assessed and selected. To accomplish this logically the approach attempts to be consistent with Decision Theory as associated with Value-Driven Design; while to ease adoption it makes use of the standardized modeling languages of Object Process Methodology (OPM) and Modelica as part of the broad area known as 1D-CAE. The approach involves defining unambiguously what value the system aims to deliver in a functional description and then decompose this single function into multiple sub-functions. The sub-functions are used to define system architectures which deliver the functionality which subsequently onto which actual designs are composed. These actual designs are then assessed against the primary value defined at the start of the process. The approach is demonstrated on an automatous solar powered boat where it is shown the primary value of Racing in SolarBoat Race Event can be used to drive the synthesis of designs and assess them.

Key Words : Value-Driven Design, 1D-CAE, Object Process Methodology (OPM), Modelica

1. Introduction

System design currently has many challenges associated with the rate of technological change and ever increasing complexity, however modeling is viewed by the Systems Engineering community as playing a large role in addressing these challenges(1). Figure 1 shows a typical system development lifecycle arranged in a V as is common in Systems Engineering(2) and as highlighted on Figure 1 Systems Engineering generally focuses on the early stages of engineering design before the detail design take place. In the authors previous work(3) it was identified that early stage design problems were major contributors to poor system performance when analysis was performed on a systems development a case study of a student “design, build and race” solar powered boat competition (known herein as the SolarBoat). As such the focus of this paper remains on these early stages of development.

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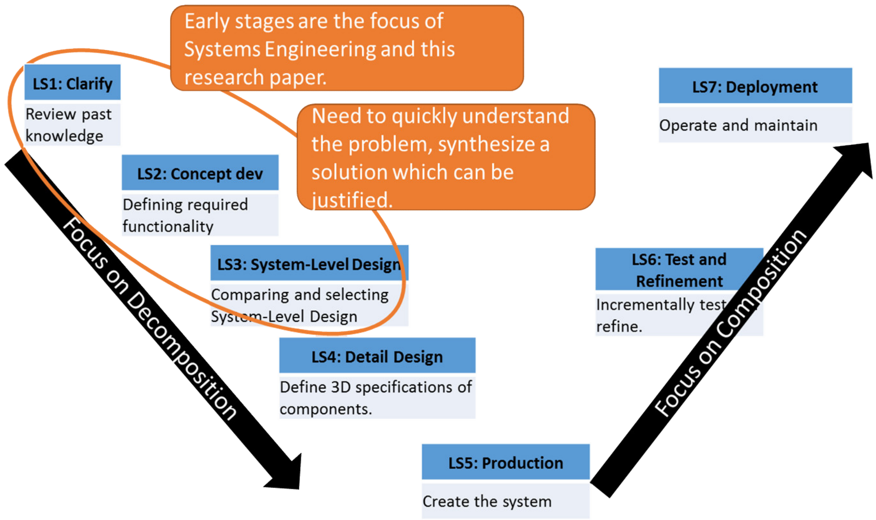

Figure 1　An example product development lifecycle arranged in a V

2. The Current Situation of Modeling in Early Stages of Development – 1D-CAE

2.1 1D-CAE (1 Dimensional Computer Aided Engineering)

1D-CAE is a broad term to cover methodologies and tools which aid the early stages of engineering lifecycles by the utilization of computers(4). The 1D contrasts with 3D typically associated with Computer Aided Engineering (CAE); the 1D indicates the development is at such an early stage that 3D geometry is not necessary or too cumbersome to deal with.

Within any CAE activity modeling is clearly central and in the field of 1D-CAE multiple languages have been developed to conduct the modeling based around two dominant approaches: descriptive and numerical.

2.2 Descriptive Modeling Languages

An example of a commonly used descriptive modeling language is System Modeling Language (SysML)(5). However while its usage is common, it can be inappropriate for early stage designs due to its wide coverage of multiple system aspects across multiple linked diagram types (structure on four diagrams, behavior on four diagrams and requirements on a single diagram). Handling these multiple aspects for multiple designs is time consuming and difficult.

Another example Object Process Methodology (OPM)(6) is an ISO standardized(7) modeling language which takes a different approach to SysML. In OPM all system aspects (i.e. structure and behavior) are displayed on a single diagram type (not the nine of SysML). Multiple diagrams of the same system is encouraged in OPM but all use the same symbols. In OPM all systems consist of Objects (green rectangles) which are optionally stateful (yellow rounded rectangles inside Objects), Processes (blue ovals) and relations between them. OPM Processes are defined by the ISO standard(7) as the transformation of one or more objects in the system and an OPM Object as a model element representing a thing that does or might exist physically or informatically(7). Each diagram has a textual language description to ease readability for those not familiar with the symbols.

Figure 2 provides a simple example for the SolarBoat, where it is shown to consist of three subsystems (“Buoyancy”, “Solar to Electrical” and “Electrical to Thrust”) and enabling the process “Racing in SolarBoat Race Event” (behavior). The said process produces the result “Time to complete race” while consuming Solar Insolation. To manage the amount of detail displayed, hierarchy is used and as such all objects and processes can be further decomposed.

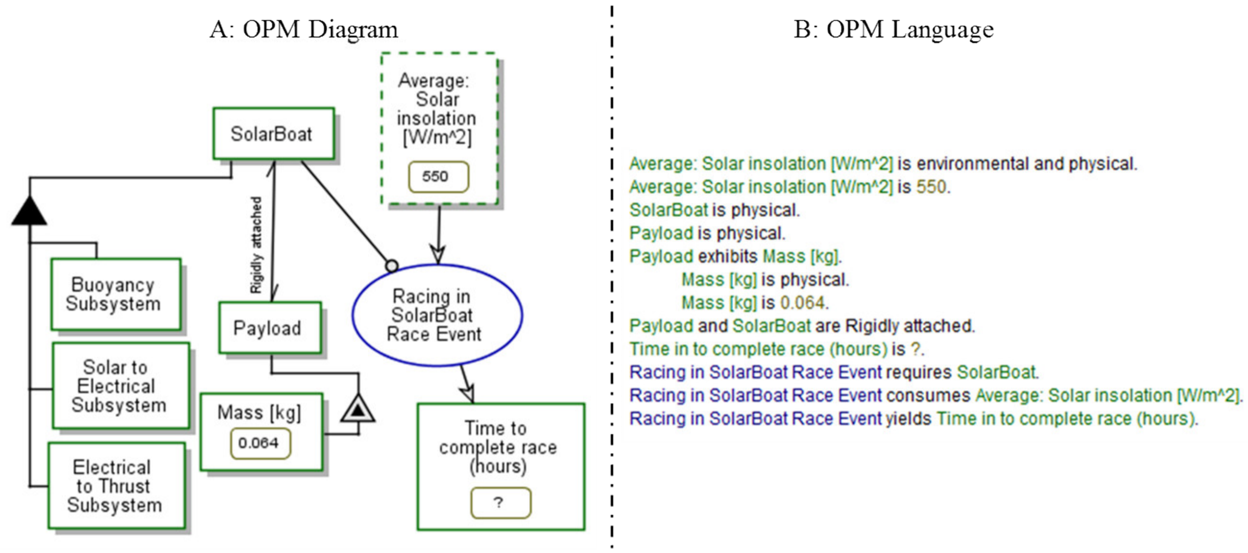

Figure 2 Example OPM for a SolarBoat. Diagram (left) and accompanying language (right)

2.3 Numerical Modelling Languages

Modelica is one example of a numerical modeling language. With Modelica, behavior of individual components is captured by explicit equations. These components are then connected together to develop subsystems which ultimately form the system being modeled. As with all modeling this requires much time and effort. So when considering rapid development projects, such time-consuming modelling needs to be avoided, but given the ideality of multiple alternative designs should be explored, the time and effort needed to create models becomes an ever pressing and important consideration.

2.4 Utilization of OPM and Modelica

The existence of languages (such as those mentioned previously) is not sufficient for them to be of value for early stage design, such languages must be supported by a methodology. As such, the authors previously presented[8–10] an approach to combine the usage of OPM and Modelica for the purpose of developing and assessing system-level designs logically. The stated objective of that work was to rapidly synthesize alternative designs and assess them using the object-oriented paradigm of Modelica but do so logically by building the architecture on which designs are created by utilizing functional decomposition in OPM. The approach met its goals of: 1) Providing clarity of what the design target is and that the designs meet that target; 2) Enabling the consistent assessment of alternative designs (whatever the architecture of the system) and 3) Manage numerical model creation. However the incorporation of decision making by way of a weighted sum objective function (Multi Objective Decision Analysis) in the work was and remains very controversial.

2.5 Decision Theory and Value-Driven Design

The inadequacies of such weighted sum objective function approaches used in the authors previous work[8–10] to adequately model the preferences of the decision maker have been discussed in detail in literature previously[11, 12]. Decision theory from mathematics and economics offers an alternative as a more mathematically rigorous approach. The use of such an approach comes under the category of Value-Driven Design[13] which focuses on maximizing the value the system creates which directly models the decision makers preference.

3. Objective of this Paper

The objective of this paper is to describe and demonstrate a 1D-CAE based methodology and tools utilizing OPM and Modelica for creating and assessing system-level designs which has a more rigorous application of decision theory than that presented previously by the authors[8–10] by utilizing Value-Driven Design. As such this requires the incorporation of a value measure which more explicitly captures the decision maker's preference, can be used to assess alternative designs and drive the synthesis of these new designs. To aid comprehension this is demonstrated on the SolarBoat project.

4. Proposed Methodology

4.1 Overview

As described previously the proposed methodology builds on that presented by the authors[8–10] but places the focus on the core value the system is expected to deliver. To understand the methodology it is important to understand the foundations on which it is built as such the four panels of Figure 3 are provided each of which is designed to be read clockwise from the top left: (A) displays the questions asked and answered at each stage of the lifecycle; (B) states the high level activities which enable the questions to be answered; (C) summarizes those activities into stages and (D) indicates what languages are used to conduct the work. As shown in Figure 3 (B & C) the initial focus is on the decomposition of functionality, which is then mapped to structures which can deliver the functionality and then composed into designs which are assessed.

In Figure 3 (D) the languages used during these stages are shown; the concept is described in Object Process Methodology (OPM) and numerically assessed in Modelica with the control of the Modelica simulation and results consolidation to assess value performed programmatically.

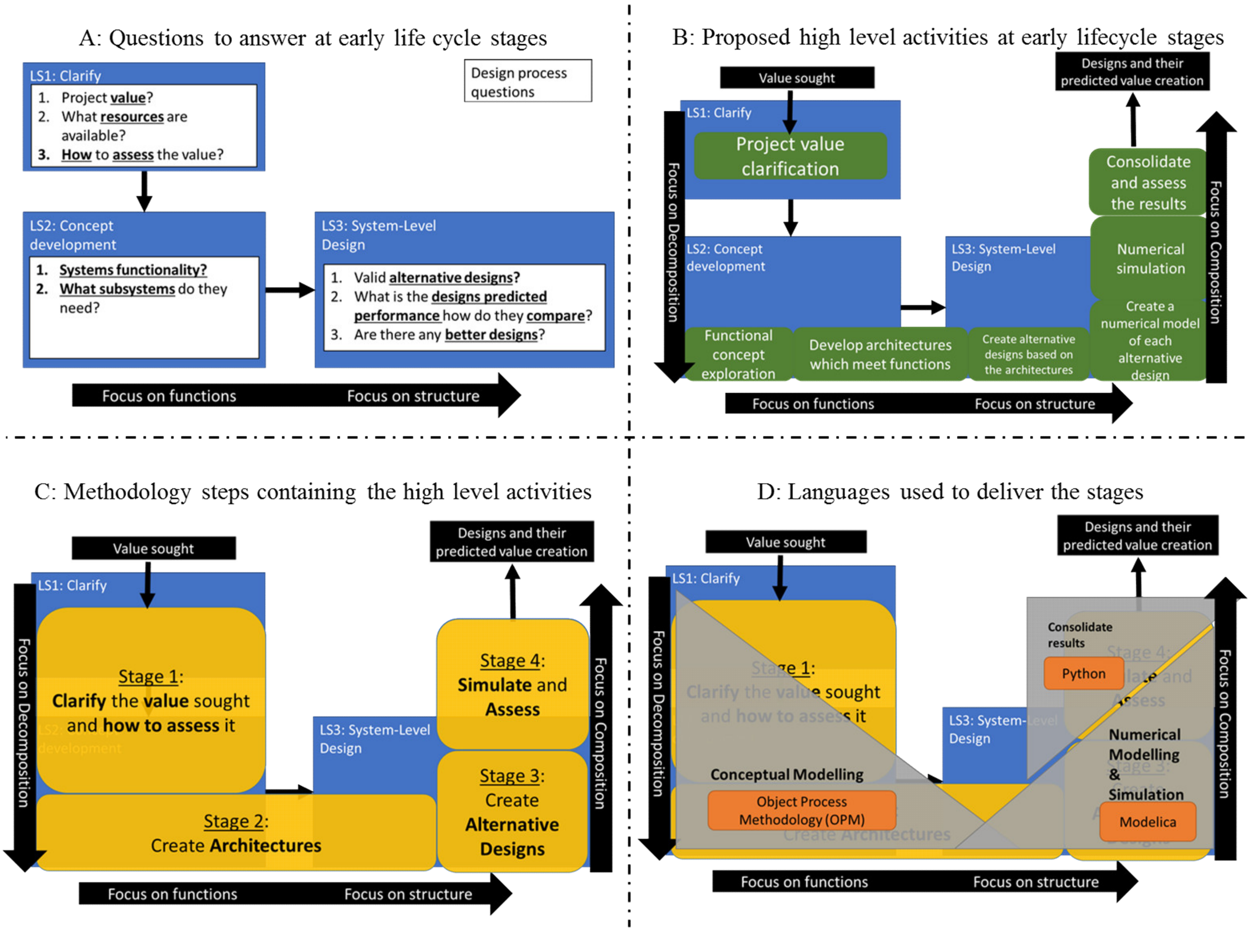

Figure 3 High level logic and description for the proposed methodology

Example contents of the stages presented in Figure 3 (C) are shown pictorially in Figure 4. Which shows four levels of hierarchy (0-3 running vertically) and various model types (OPM and Modelica running left to right). A brief overview of the stages is provided as follows with the reader directed to further sections of this paper for further details:

1) Clarify the value sought and how to assess it: This is the most important part of the methodology. Here the designer must using the OPM language describe clearly what is the value the system creates. In Figure 4 it is possible to see this is "Racing in Solar-Boat Race Event". Further details are presented in Section 4.2 of this paper.

2) Create architectures: The output of this stage is an architecture (or set of) modeled as a Modelica model of partial replaceable components. To create this logically it is proposed to decompose the primary process of Stage 1 and map to Modelica using a library. As such Figure 4 shows the decomposition of this primary process and various models mapped at the same hierarchy levels (note Levels 2 and 3 have been simplified for clarity). The reader should see Section 4.3 of this paper for more details.
3) Create alternative designs: Using the architectures defined in Stage 2 it is possible to compose a design by replacing the various partial components with actual implementations. Figure 4 shows this, for further details the reader is directed to the authors' previous work[9].
4) Simulate and Assess: The individual designs can now be combined with the model used to assess the designs and as such critical information is delivered about their performance. See Section 4.2 of this paper for more details.

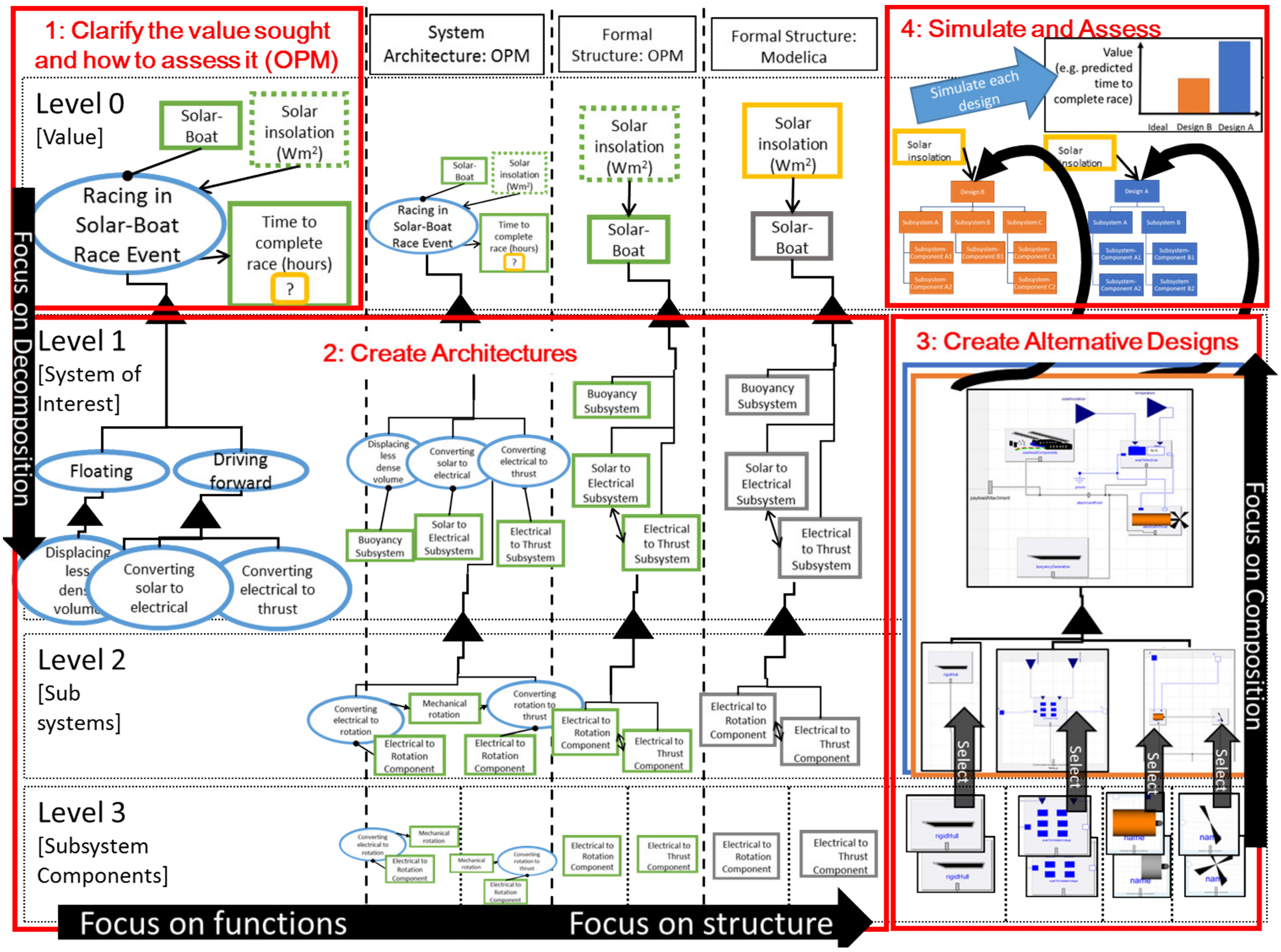

Figure 4 Summary of the proposed system and model types

4.2 Identifying Value and Assessing each Design's Performance

To choose a particular design by way of prediction of performance in simulation, a definition of value must be made. For this purpose OPM is used, where a single process is used to model the value the system of interest delivers. In the simple case study of SolarBoat this is "Racing in the SolarBoat Race Event" which delivers us a race time. As such the design which minimizes the prediction of time to complete the race is the preferred design of the decision maker. An example is shown in Figure 5 (A) where an expression of the value for the SolarBoat project is made. However actual prediction of what value is delivered is made in Modelica. As such a model which can assess the value of various different SolarBoat designs is required, an example of this is provided in Figure 5 (B) where all the components are all labeled. It should be noted that "Time to complete race (hours)" from Figure 5 (A) is not in the diagram (B) but is a variable in the code which drives the model.

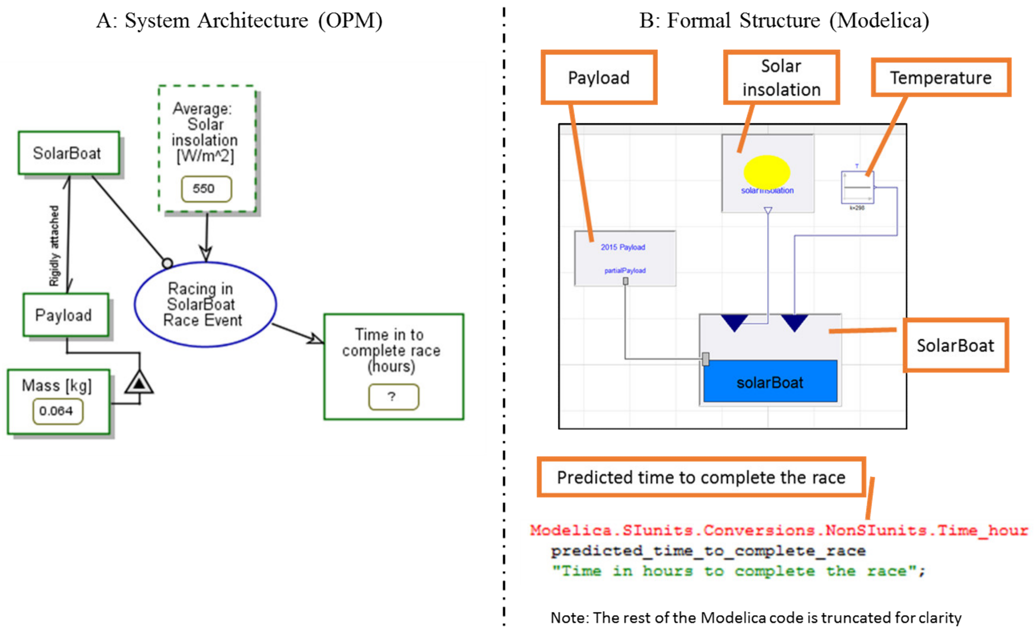

Figure 5 Level 0 (Value) System Architecture and Formal Structure Models

The method to create a Formal Structure model in Modelica from a System Architecture in OPM requires a pass through Stage 2: Create architectures and is described in Section 4.3. As a result the introduction of Temperature in Figure 5 (B) occurs from the search of the Modelica library and discovering the model is dependent on temperature as well as solar insolation, such the logical discovery is considered a feature of the approach advocated by the authors.

By defining a Formal Structure model in Modelica using a defined interface for the System of Interest it is possible to assess all alternative designs using the same Level 0 model quickly. Details of how to do such an approach programmatically provided by the authors previously[9]. A diagram of the approach is provided in Figure 6 where two designs are compared with a common definition of value by placing the SolarBoat designs Level 1 within the Level 0 model to assess value.

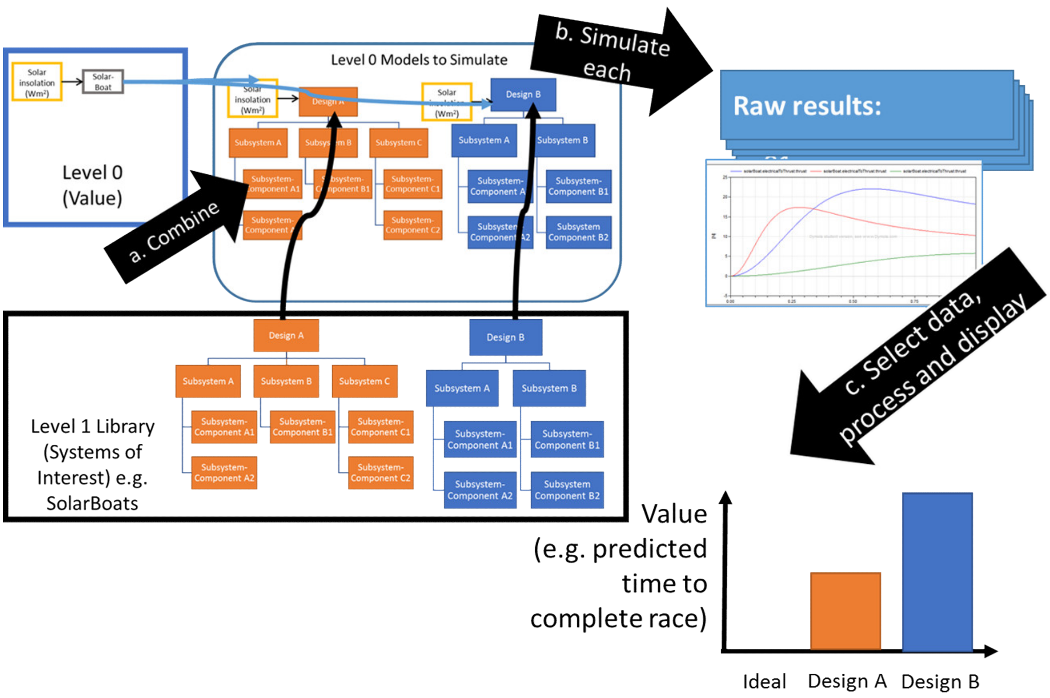

Figure 6 Assessing value in a common way for multiple designs

4.3 Developing Architectures from the Definition of Value

To develop designs the definition of value must be explored such that all the alternative designs are consistent with it and they can all be assessed. To achieve this the definition of value is decomposed into further processes as part of the Operations Decomposition OPM model (far left of Figure 4). Such a decomposition of process is not necessarily unique and as such alternatives can be introduced if the designer feels it serves their project. An example is provided in Figure 7 (A) where "Racing in SolarBoat Race Event" is decomposed into "Floating" and "Driving forward" (a simple design is used to ease comprehension).

Further decomposition enables the identification of subsystems which can deliver the processes identified before as shown by the orange highlighting on Figure 7 (A). To enable the direct assessment of value for the proposed designs from the primary process of "Racing in SolarBoat Race Event" these sub systems are then used to create a System Architecture by being directly inherited from the primary process this is shown by the orange highlighting on Figure 7 (B). This is a different approach described by the authors previously[8, 10] as it assumes that the processes of "Floating" and "Driving forward" are inherently part of "Racing in SolarBoat Race Event" and do not require the explicit Assessment Scenarios of the previous papers which were used as part of the Multi Objective Decision Analysis approach.

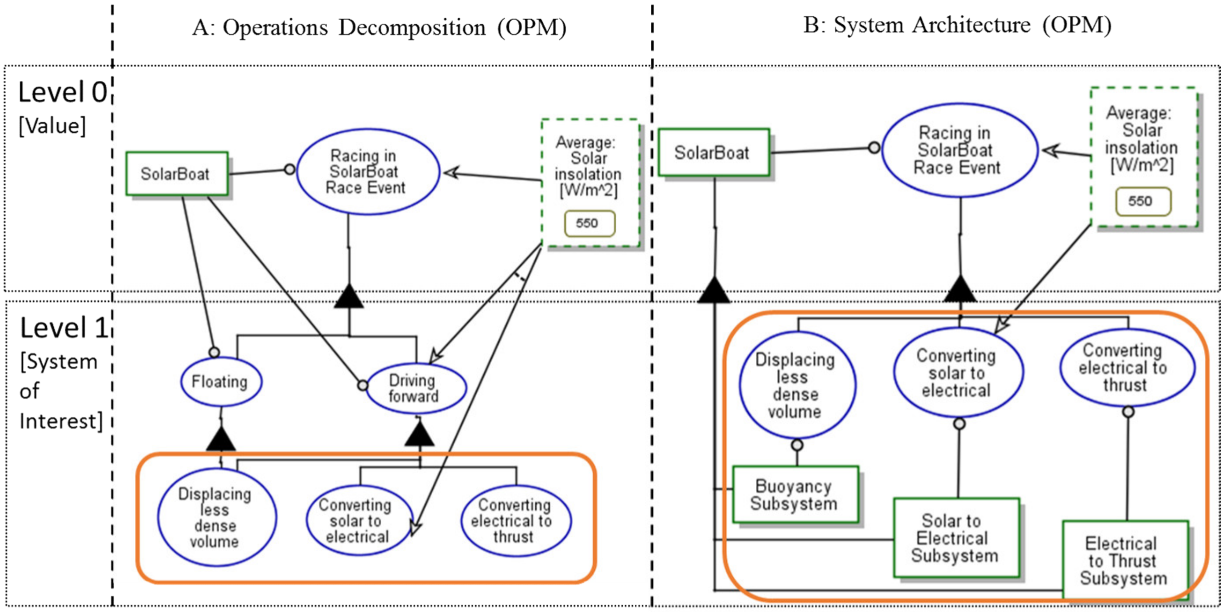

Figure 7 Decomposing the value function (A) to identify a possible set of subsystems which can deliver the value (B)

As shown under the System Architecture column of Figure 4 such a System Architecture can then be further decomposed into the processes enabled by Subsystem Components which can be mapped to an OPM formal structure (by way of a library) as shown in Figure 8. These Subsystem Components can then be integrated into Subsystems and intern the System of Interest and Value model itself, propagating their interfaces.

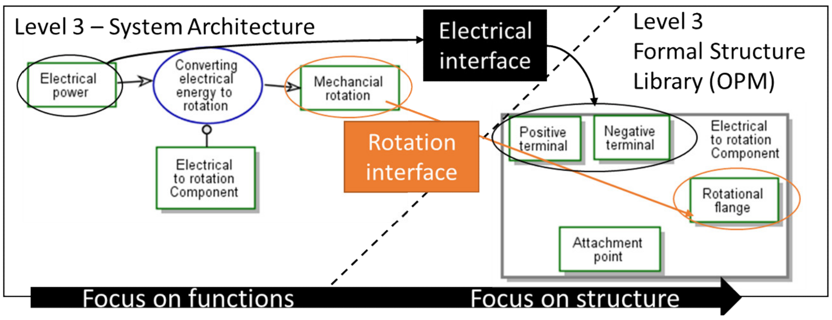

Figure 8 Creating a Formal Structure (in OPM) from System Architecture by means of a library

The purpose of the Formal Structure OPM is to provide a description of the system which can be implemented in Modelica, where the OPM processes are represented as equations and the interfaces between the components must be formally defined. As such by means of a library of Modelica partial component models it is possible to convert the Formal Structure in OPM to Modelica, as shown in Figure 9.

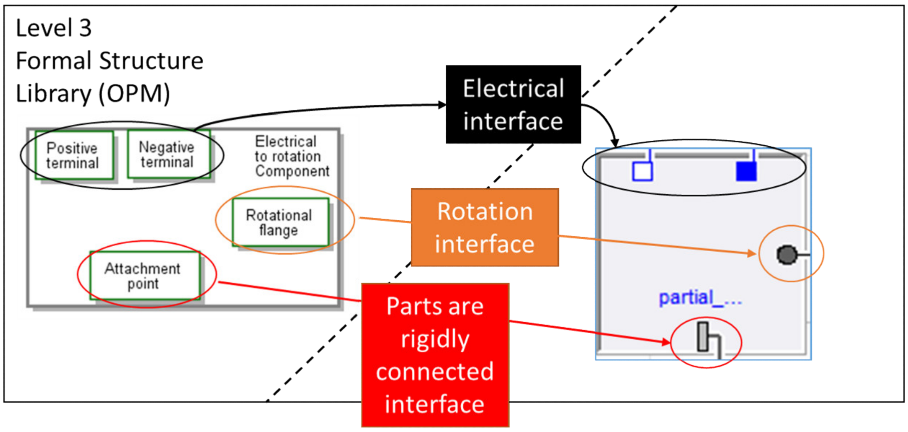

Figure 9 Creating a Formal Structure (in Modelica) from Formal Structure (in OPM)

Once a Formal Structure model has been created in Modelica a sufficient library of Modelica components using the same interfaces can be used to create design alternatives upon this (or any other) architecture in Stage 3: Create alternative designs as shown in Figure 4. Due to space constraints the process was presented only briefly here, however the reader is encouraged to consult [8] for a more detailed description.

5. Example Usage

A case study is presented where the proposed system is used to assess various SolarBoat designs. Given the subsystems identified in the running SolarBoat example for this paper are the same as those presented previously by the authors in[8] the same subsystem decomposition and design composition is used. The result of processing these SolarBoat designs is presented in Figure 10 with (A) showing the predicted results of the first design iteration and (B) the second iteration (which is an alternative drivetrain architecture and as such has differences in the Level 2 System Architecture and Formal Structure).

In Figure 10 SolarBoat designers can easily see the predicted time for the SolarBoat to complete the race for two different designs. Because this was deemed to be the measure of value for the project, selection can be made between the designs (in this case LM_13_200mm would be chosen). Any new designs can also be quickly assessed based on the same criteria using the existing infrastructure.

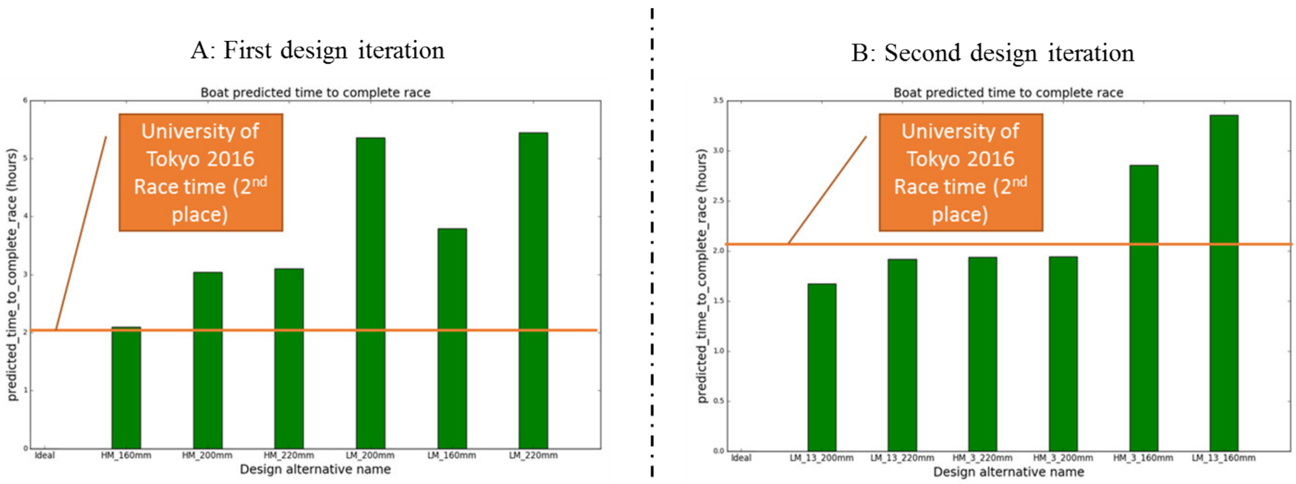

Figure 10 Predicted value for alternative SolarBoat designs (compared to 2016 actual race performance)

6. Discussion

6.1 Benefits

The described tools and methodology offers a logical method to synthesize and then subsequently assess alternative system-level designs based on a clear definition of value that the system aims to provide. This enables the designers to quickly generate alternatives and assess them with the aim of choosing a design which maximizes this value. This contrasts with previous work[8–10] which did not focus on a value definition which explicitly addressed what the decision maker was looking for.

6.2 Shortcomings and Possible Future Work

Shortcomings can be used to create possible future research directions, they are summarized as follows:

- Uncertainty: The current approach does not take uncertainty into consideration. Clearly this is an unrealistic representation of the world. For the simple case study presented some clear sources of uncertainty include solar conditions and breakdowns.
- Value function creation: The singular value function defied by the Level 0 OPM diagram Figure 5 (A) is highly appealing, however on many projects there are other concerns raised by the many stakeholders concerned (e.g. financial cost and project time). However within the context of 1D-CAE providing information to the decision maker on a single topic is perhaps sufficient this however this is for the designer to decide which in itself is not trivial.
- Flow down of requirements: This paper makes no attempt to set performance requirements (or even preference) to subsystems and subsystem components. In a 1D-CAE context this maybe appropriate as a single team will likely be managing the model. But at the interface to the detail design stage this is troublesome and needs more investigation.
- Value function assessment: By simplifying the value to a single measure it leads to a significant modeling and simulation challenge. The current simulations reward very high speed craft but intuitively such a craft would likely have other tradeoffs which lower its ability to produce value (e.g. breakdowns and cost to produce). A fine balance between model accuracy and time to develop such a model is required.

7. Conclusions

The paper has attempted to demonstrate a 1D-CAE based methodology and tools utilizing OPM and Modelica for creating and assessing system-level designs which has a more rigorous application of decision theory than that presented previously by the authors[8–10] by utilizing Value-Driven Design. For this it has been successful in that the primary value of the system can be identified at the very start of the design process with the initial OPM diagram and used in Modelica to assess the alternative designs which have been created by further OPM decomposition of the initial primary value. As such providing logical synthesis and analysis of system-level designs in the context of 1D-CAE.

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