The Ecosystem for Engineering Design Applied to Formula SAE

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Robert Jones
Portland State University

Baldur Steingrimsson
Portland State University and Imagars, LLC

Faryar Etesami
Portland State University

Sung Yi
Portland State University

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Abstract

Modern mechanical design is heavily supplemented by computer-aided design and engineering (CAD/CAE) tools. The predominance of these tools have been developed to augment the analysis efforts during the detailed phase of the design process. Yet, many design oversights and inefficiencies are the result of inadequate vetting of engineering requirements, and vague accountability to those requirements during conceptual design. The Ecosystem for Engineering Design is developed herein as an immersive CAE tool for comprehensive design process support that facilitates the elimination of these sources of design inefficiency. In addition, the Ecosystem promotes rigid adherence to phase-appropriate design process activities increasing productivity. Many time-consuming administrative and information management tasks are automated to further increase designer efficiency. The Ecosystem for Engineering Design incorporates an array of phase-based design utilities including Total Design [1] and Axiomatic Design [2], making it a flexible and capable design-decision support tool. Designers are able to consolidate efforts in the most promising direction and design iteratively within each phase to avoid costly, whole-process iterations. In this vein, the Ecosystem innately supports lean design philosophies by minimizing the time to achieve a high-quality solution, minimizing resource use, and maximizing product value. The tools chosen for development and implementation are those with proven track records for maximizing design efficiency, and resulting design quality including Axiomatic Design, Total Design, and many prolific high-quality CAD/CAE tools available today. Using structured, relational data objects, archived information can be used for concept development, and also for requirement construction. The Ecosystem is developed as a comprehensive project management and design tool and is demonstrated in the context of undergraduate Society for Automotive Engineers (SAE) team design competitions, such as Formula SAE. The Ecosystem is shown to provide value to all stakeholders of design including the designer, the customer, and supervisors.

Keywords

Design Process Automation, Automotive Design, Design Software

Introduction

SAE team design competitions aim to challenge university students to conceive, design, fabricate, develop and compete with small vehicles. The competitions require teams to execute a complete product design process from beginning to end. Good processes result in successful teams, and product quality is directly evaluated by industry and academic experts in accordance with the established criteria. The competitive design space provides an opportunity to develop competitive advantage through design process improvement and monitoring.

The Ecosystem for Engineering Design facilitates successful design by structuring design activities by phase, beginning with robust requirement analysis and development. Once formulated, the requirements form a baseline product design specification (PDS) as envisaged by Pugh [1] to which all concepts are accountable. The requirements also provide a meaningful method to evaluate design fitness and identify fruitful solution paths.

Beyond PDS development, the Ecosystem promotes thorough concept development by mapping physical design features to basic, independent functions. Systematically building concepts in this manner takes advantage of Axiomatic Design [2] to ensure a controllable, robust and reliable system for which performance can be predictably determined.

Ecosystem e-Design Process

The design process describes the evolution of concepts from vague, immature ideas to highly refined, optimized solutions. It represents a divergent-convergent thinking process in which diverse solutions are developed to their refined form. The Ecosystem supports designer decisions by mediating user inputs and the outputs from various integrated tools.

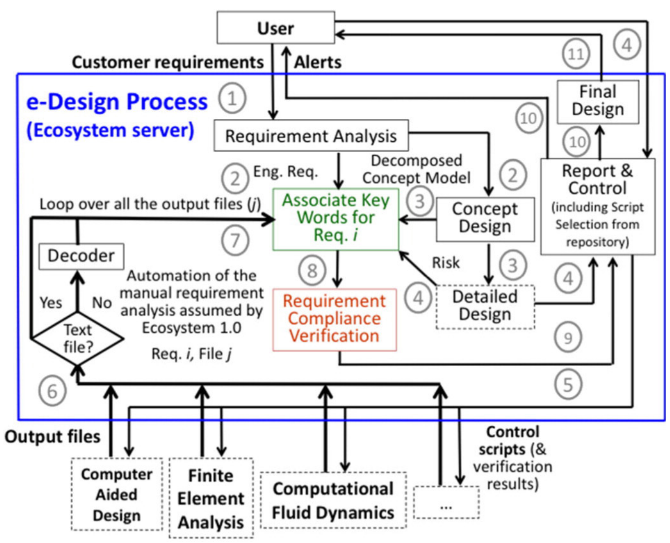

Figure 1. e-Design Assessment Engine [1].

The e-Design process, shown in Figure 1, is initiated in the Requirements phase of the design process. The deliverable manifestation of this phase is the product design specification (PDS). The PDS formulates global requirements from potentially subjective and vague customer requirements. The manner in which it is developed in the Ecosystem is what enables significant automation and accountability. All requirements, constraints, and objectives constitute risk factors that require verification by acceptable means. Typically, this is accomplished through analysis or testing.

PDS Formulation: Global Requirements

The Ecosystem builds engineering requirement on the language of Axiomatic Design [2] and a modification to it proposed by Dyas [3] to translate customer requirements into specific boundaries on the design space. In general, requirements impose two distinct types of boundaries: plane margins (constraints and performance requirements), and topology (functional requirements and objectives). From Jones, et al. [4], a design space, which is fully bound, is necessary, but not sufficient, to define a complete PDS global requirement set.

Formula SAE Example: Global Requirements

The Ecosystem PDS serves as the foundation of the e-Design process. It is particularly apt to handle SAE design competition regulations [5]. For example, functional requirements (FR) and objectives (OBJ) can be interpreted from competitive event regulations and technical regulations. Top level FR can be determined directly from the governing articles and include:

1. Vehicle must be able to accelerate from rest under its own power controllably (Event Articles 5 and 7);
2. Vehicle must be able to maneuver both left and right of course controllably (Event Articles 6 and 7); and
3. Vehicle must be able to decelerate and stop under its own power controllably (Event Article 7 and Technical Article 7).

Performance requirements (PR) are thresholds applied to the FR. Sometimes, PR are directly obtainable from regulation language. Other PR must be deduced from desired performance targets, often resolved from historical performance or perceived competitive needs. For instance, PRs pertinent to FR 1 above can be obtained from event Articles 5 and 7:

1. Vehicle must be able to accelerate from rest under its own power controllably such that:

a. From a standing start 11.8 inches (specified) behind the starting line, the vehicle reaches a maximum speed of [desired performance targets] in 82 yards (specified).

Notwithstanding technical regulations defining PR, the majority of FSAE technical regulations can be input to the Ecosystem as global constraints (GCN). For example, from technical Article 7 pertaining to brake systems, the following non-exhaustive constraints can be deduced:

1. No portion of the brake system that is mounted on the sprung part of the car can project below the lower surface of the frame;
2. The brake pedal shall be designed to withstand a force of 2000 N without failure of the brake system or pedal box;
3. The brake pedal must be fabricated from steel or aluminum or machined steel, aluminum, or titanium.

Objectives can be easily determined by the goals of the design, and even justified by event regulations. For example, top level objectives taken from the static and dynamic event articles might include:

1. Minimize cost;
2. Maximize autocross course average speed;
3. Maximize competitive endurance.

In general, OBJ do not exhibit thresholds of performance defining the design space, but form optimization functions that should be considered throughout the design. Whereas PR and GCN are mapped to specific design features in the concept functional model, OBJ are used as justification for design parameters that do not directly affect design envelope dimensions.

All different categories of global requirements are entered with an Importance factor. The Importance factor attributes are appended for requirement accountability with respect to design evaluations and decisions. The Ecosystem expects design decisions corresponding to advantageous solution paths. As a default, the Ecosystem is setup for objective function evaluations of the following exponential form:

$$Fitness = \sum_{i=1}^{n} Requirement[i]^{(Importance[i])}$$

This power-law function is generic in the sense that it evaluates the design choices on technical merit, with respect to the requirements, but can also account for the associated importance, per customer specification. *Requirement*[*i*] refers to the designer's assessment of the suitability for the solution path under scrutiny as it applies to the *i*th requirement, typically on the scale of 1 to 5. The importance factor *Importance*[*i*] refers to the designer assigned relative importance of the ith requirement, typically on the scale of 0.0 to 2.0. The Ecosystem allows for the inclusion or exclusion of any requirement to ensure the correct representative effects on design decision making.

Local Requirements and Concept Development

Global requirements defined in the PDS lead the designer to develop concepts in accordance with established priorities. Concepts are matured in the Ecosystem by mapping physical design features (DF) to each FR. Both FR and DF are systematically decomposed in a zig-zag fashion [2] until sufficient fidelity is obtained to make informed decisions on the most fruitful path.

Concept decomposition results in a set of local requirements that apply to the specific concept under development. DF reveal additional FR in accordance with their solution principles. A depiction of the relationship between the local requirements for three independent, general concepts and the established global requirements is shown in Figure 2.

Figure 2 also illustrates another useful attribute revealed by Ecosystem concept development. As the number of local requirements grows, so too do the number of DF. Typically, this reflects an increase in the magnitude of information content required to make a design successful. Suh [2, 6] explained that among equally adept designs, the one comprising the least information content is the better design. Then, for the case that the objective functions each evaluate the same, the magnitude of the local requirements set can be used as an effective tie-breaker to determine the most promising concept among those presented. In Figure 2, for the case of equal evaluations discussed, Concept 2 would be the most promising candidate for further development.

Objective function evaluations are not only useful for first tier (concept) selections. At each stage of decomposition, it is expected that multiple options might exist as DF for locally established FR. An identical procedure can be used to weigh each option for maximum effectiveness.

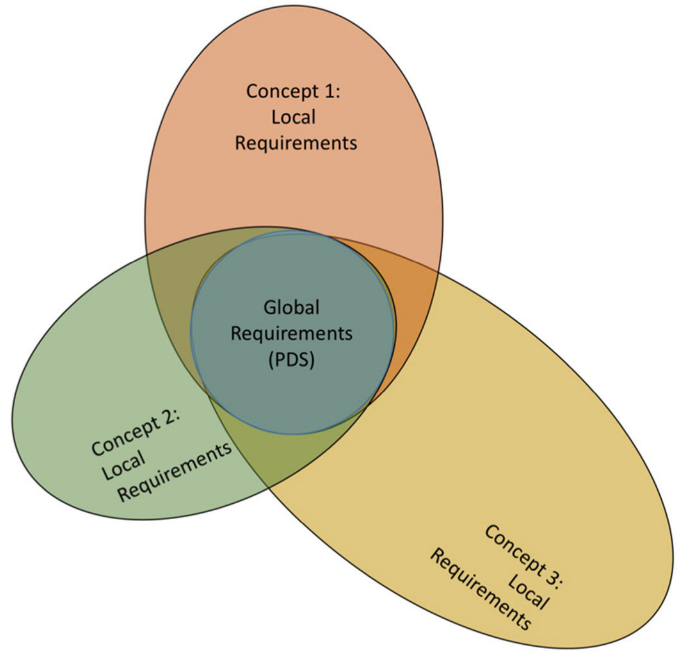

Figure 2. Concept local requirements in relation to PDS global requirements.

Objective function evaluations in the Ecosystem are derived from the matrix method of evaluation proposed by Pugh [1] and, at present, incorporate designer judgement to adequately characterize values corresponding to each option's suitability with respect to each requirement. While this method introduces subjectivity and makes evaluations susceptible to perceptive errors and deficient designer experience, it is mitigated by the requirement for full accountability to requirements in the detail design phase.

Formula SAE Example: Local Requirements

Presume that a Formula SAE internal combustion (IC) engine-powered vehicle is being developed in response to the global requirements. That concept can be decomposed locally based on the requirements and limitations of the internal combustion engine. For example, if the IC engine is the DF mapped to FR 1: enable automotive acceleration, then the next tier of requirements should pertain specifically to the IC engine design. Other concept options, such as an electric motor-powered vehicle would not exhibit all the same FR as the IC concept. It is also presumed that DF1 was chosen by objective evaluation. Then, due to the solution path specified by DF 1, the second-tier FR 1.n might be decomposed as follows, where x is defined as the list number:

1. Store chemical energy (fuel); and
2. Convert chemical energy to mechanical energy.

Appropriate DF 1.x selections in response to these decomposed FR might resolve to:

1. Fuel tank; and
2. IC engine system.

Progressing further for illustrative purposes from DF 1.2: IC engine system, the designer should consider further decomposition. DF 1.2 might drive the following decomposition into third tier FR 1.2.x:

1. Intake chemical energy;
2. Convert chemical energy to heat energy;
3. Convert heat energy to mechanical energy;
4. Expel waste byproducts.

DF 1.2.x pairings to each of the above FR are easily determined:

1. Induction system;
2. Commercially-obtained IC power plant;
3. Commercially-obtained IC power plant;
4. Exhaust system.

The decompositions for DF 1.2.2 and 1.2.3 can be terminated at level 3, because they have been specified at a practical available level. Many times options are clearly restricted by regulation, and at other times by practicality. It should be noted that regulations might translate to local requirements rather than global ones.

Figure 3. DF 1.2.1.1 attribute with respect to orientation (DP 1.2.1.1.1).

Figure 4. DF 1.2.1.1 attribute with respect to materials and manufacturing method (DP 1.2.1.1.2).

In the quantitative domain, DF are supplemented by design parameters (DP). DP are mapped to PR and are adjustable to ensure compliance. DP often materialize as geometric dimensions, derived parameters, or material specifications.

Figure 3 and Figure 4 show two characteristic DP for the DF: intake plenum. It is possible that two DP are available to satisfy a single PR. In this case, the DP for which the PR is most sensitive should be assigned to the PR, and the other available DP is determined by objective function evaluation

Design Accountability

Concept design culminates in a refined design candidate and also a set of global and local requirements that must be validated. Designers are prompted to identify the method by which the requirement will be assessed. When complete, pertinent results are either uploaded to the Ecosystem or accessed directly via established scripting. Deficient results are prompted for designer response through design modification or analysis revision.

Accountability is enhanced by top-down design. An examination of the generalized concept design tree in Figure 5 shows effective project modularization. Designers can be assigned individual areas of responsibility for which they are accountable, and the team leader maintains overall responsibility. Modular design is an important accountability and project management feature of the Ecosystem that synthesizes the focused efforts of all team members.

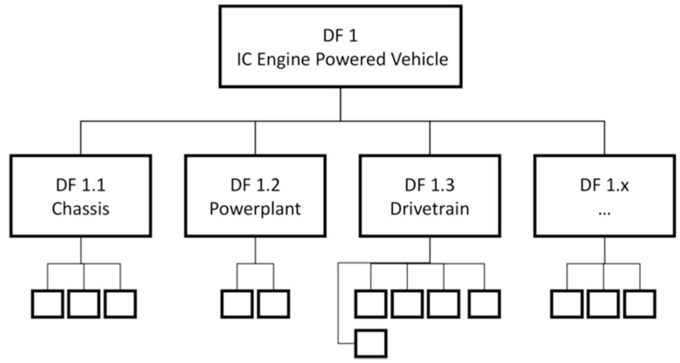

Figure 5. Generalized sample design tree layout for a Formula SAE design.

Application

The Ecosystem for Engineering Design has been used by a BAJA Dynamometer capstone design team at the University of Nebraska Lincoln (UNL), the Formula and BAJA SAE teams at the Oregon Institute of Technology (OIT) as well as the Berkeley Formula Racing (BFR) team.

The BFR team considered the logging and tracking of their design decisions the weakest link in their project management system, and hence welcomed the ability to capture their design review deliverables in the Phase Review tabs of the Ecosystem, as shown in Figure 6. With the team planning an adoption in stages, BFR also liked the ability to configure the Ecosystem to their needs and processes (deselect the tabs not presently of interest, or rename tabs).

The faculty advisor for the Formula and BAJA SAE teams at OIT highlighted the value of the e-design notebooks for holistic capture of the design content. The ability to automatically export the design information into a formatted report would help the teams present their design work in an organized fashion to the judges at competition.

The capstone design teams at UNL generally valued the automatic report generation, as well as the Ecosystem's interfaces to facilities for team communications and engineering design (in particular the Google Drive and SolidWorks). The BAJA SAE Dynamometer team specifically acknowledged time savings associated with the ability to insert information into the facilities for meeting minutes, information sources, and deliverables for each design phase, and export into formatted reports. The Dynamometer team considered he user interface was easy to understand. It allowed the team to insert information quickly and painlessly. The detailed outline helped the team understand each component for the design report. The examples provided helped the team understand the information to be included in each tab.

Full testimonials both from the BAJA SAE Dynamometer team and its faculty advisor, Dr. William Dick, can be accessed through http://www.imagars.com/testimonials-ecosystem/ and a sample video recording through http://www.imagars.com/applications-ecosystem/.

Summary/Conclusions

The Ecosystem for Engineering Design alleviates various sources of design oversight, rework, and productivity interruptions. Additionally, it is shown to be an effective learning and project management tool for comprehensive design process activities including those rarely supported by advanced CAD/CAE software.

As a result, the Ecosystem can be implemented by experienced and inexperienced designers alike in the context of SAE design competitions to enhance design process efficiency, and improve overall design quality through structured requirement and concept development, design decision justification, and full requirement accountability with automatic compliance verification. The Ecosystem automates the collection, development, and use of design information content, and substantially alleviates designer administrative workload. The e-Design process integral to the Ecosystem focuses designer efforts on fruitful activity, enhancing a design team's overall competitive advantage.

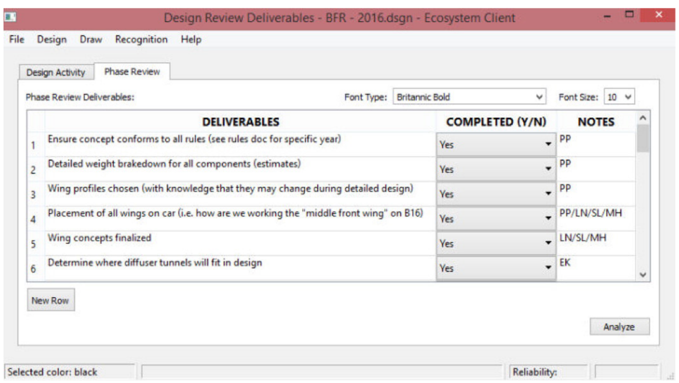

Figure 6. Deliverables from Concept Design Review for the BFR 2016 race car.

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Contact Information

Dr. Baldur Steingrimsson
TEL: 763-439-6905
baldur@pdx.edu

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The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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