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Ecosystem for Engineering Design Learning—A Comparative Analysis*

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Design is a human activity that encompasses a broad array of tasks. In engineering design, individual efforts can be aggregated into teams to maximize collective progress. Effective teamwork, however, requires extensive management, organization and communication. Furthermore, modern challenges encompass complicated multi-disciplinary problems with faster schedules, fewer resources, and greater demands. Design, as a process, can be dissected into characteristic phases. Within each phase, design solutions are gradually developed. Technological tools have prioritized the structured analyses of the detailed and final design phases and have proven to be powerful multipliers for effective design efforts. It has long been the case, however, that major commitments of intangible resources are made as a result of efforts in the less emphasized *earlier* phases. These commitments and lack of modern toolsets for requirement development and conceptual design activities materialize as major sources of design pitfalls, both in industry and on student design projects. This paper presents a digital Ecosystem for Engineering Design Learning as a comprehensive, yet flexible, framework for capstone design teams. The digital Ecosystem has been developed as a feasible technology to bolster student information management, teamwork, communication, and proficiency in fundamental design principles, and as a technology capable of alleviating rework and process-related productivity interruptions. Its primary innovation, for capstone applications, is the ability to assess design work automatically against the design process, as well as against ABET compliant learning objectives, and provide prompt advisories in case of design oversights. The digital Ecosystem is compared to tools for project management, team communication, and requirement management.

Keywords: design process; design software; project management; team collaboration; ABET learning outcomes; engineering education

1. Introduction

Engineering design is a broad term describing the evolution of a product from need to manifestation. In a synergistic process, design involves aspects of organization, communication, creativity, and robust analysis. The framework that directs this spectrum of necessary and complementary activities can make or break the success of design projects. Therefore, it is highly advantageous to create a modern tool for modern design tasks that can help designers navigate the landscape of engineering design and avoid common pitfalls, traps, and hopefully disasters, such as the disintegration of the Mars Climate Orbiter from inaccurate metrication, or the collapse of the Tacoma-Narrows bridge in November 1940, from an unpredicted aero-elastic utter event [1–3].

The complicated job of today's engineers and designers can be supported by such a tool. The tool integrates and captures the benefits of advanced specialty tools designed for project organization, efficient information flow, advanced analysis, and modelling, while minimizing re-work, productivity interruptions, and the need for re-design. The benefits that can be realized by practicing designers are magnified in the context of engineering education, where design process learning must be accomplished in context, and while students are striving to achieve fundamental proficiency in each required design skill.

Engineering design can be described as the systematic and creative application of scientific and mathematical principles to practical ends. The majority of research into creativity has taken the psychological-constructivist viewpoint, inferring that designers' knowledge and subsequent innovation are products of their environments, memories, and prior experiences. It has understandably become standard practice within engineering to manage creative efforts without undue subversion or restraint, but also without a substantial focus on promotion or inspiration. In the so-called Information Age, it is natural to expect an advancement in this area.

The advancement proposed requires an integrated suite of requirement analysis and concept design tools—a "best of" collection—from the numerous acclaimed and accepted design methodologies, to guide and facilitate informed, purpo-

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seful *early*-process decisions. Through hierarchical functional modelling, physical solutions to complex problems can be assembled modularly. Utilities from morphological ideation techniques employed conjunctively with axiomatic methods effectively justify and correct problem statements, identify viable concept solutions, and optimize the solution path [4–7]. While morphological methods excel at generating plausible solution paths, axiomatic methods excel at evaluating the problem statement and guiding solution decisions [1, 2]. As a result, the integration of multiple methods can assist a designer with faster, more efficient progression through the design process and help eliminate wasted effort and other major pitfalls [6]. This integrated suite of requirement analysis and concept design tools can be considered as a part of a general movement towards "digital ecosystems" [8].

Computer Aided Design (CAD) software offers full spectrum of support for design and engineering tasks. Chandrasegaran highlighted the trend of modern software development in focusing on late conceptual design solid modelling, detailed design analysis, and interfacing with Computer Aided Manufacturing (CAM) tools [9]. An acknowledged shortfall of digital engineering tool development has been support for *early* design process phases, and the lack of a comprehensive design process support framework.

An Ecosystem for Engineering Design has been introduced as a design decision support tool capable of integrating the modern capabilities for team collaboration, engineering design and analysis, and project management [1, 2]. This Ecosystem is intended to aid designers in efficient, comprehensive, and effective completion of their duties and responsibilities. Minimizing the impact of predictable issues and maximizing the quality of design efforts is a clear path to increasing productivity, compressing timelines, and easing strained budgets. With emphasis on *early* design phases, the Ecosystem provides a robust Product Design Specification (PDS) development tool which enables automatic downstream enforcement of concept accountability to design requirements.

The Ecosystem provides benefits to all education stakeholders: students, mentors, faculty, and sponsors, as noted in Table 1 [10]. Its innovation can be characterized as follows:

- *Technology integration:* The digital Ecosystem integrates design decision support and design process learning. It incorporates several notable and proven design methods, and advanced digital tools, to provide a powerful design accountability capability that automatically assesses design activity quality and helps the designer detect and mitigate design errors and maximize productivity.
- *Assessment against ABET compliant learning outcomes:* In the case of generic ABET outcomes, as they apply to capstone activities, the Ecosystem has the ability to discern designer performance using an extensive list of performance indicators derived from the Information Literacy Competency Standards for Higher Education (now Framework for Information Literacy for Higher Education [11, 12]).
- *Compliance assessment for structured engineering requirements:* The built-in assessment mechanism can be extended to verification of structured engineering requirements in industry. Here, the cost implications of design oversights identified can be significant.
- *Usability aspects*: In addition to standard features, such as row insertion or deletion, the Ecosystem provides a number of usability features, such as automatic population of multi-selection drop-downs.

The Ecosystem provides the realism expected by capstone students. The Ecosystem offers facilities for bill of material, analysis of manufacturing options, cost analysis, and design iterations. Yet, the emphasis is on engineering design (design decision support). Organizations in the Portland area practicing lean six sigma have commended attractive design facilities in the Ecosystem. The Ecosystem offers tools for requirement tracking and critical parameter management, for real industry projects, and yet is much easier to configure (and cheaper), compared to requirement management packages with more extensive facilities for supply chain management and marketing [13].

This paper presents a digital Ecosystem for Engineering Design Learning as a comprehensive, yet flexible, framework for capstone design teams [1, 2]. Its primary innovation, for capstone applications, is the ability to automatically assess design work against the design process, as well as against ABET compliant learning objectives, and provide prompt advisories in case of design oversights. The digital Ecosystem is also compared to other common tools used by capstone design teams for project management and team communications, and by industry for requirement management.

While the focus of this paper is on capstone design, it is worth emphasizing that the Ecosystem is a general engineering design framework, which can be applied both to top-down design and to improvements of a sub-module of an overall design. Jones describes how to configure the Ecosystem to suit the needs of Formula and BAJA

Table 1. The Ecosystem's primary benefits to designers, supervisors and sponsors [10]

Designers (Students)	Supervisors (Instructors)	Sponsors
• Learning of proper design techniques). • Helps with productivity, planning and team work. • Greatly helps in terms of keeping things organized. • Automation of administrative tasks. • Editable progress reports.	• Guarantees all students go through same design process. • Having SW teach key concepts and methodology, and identify elementary oversights, frees up instructor bandwidth. • Standardized progress reports are easy to grade. • Objective score cards: ABET learning objective (guideline). • Easy to demonstrate compliance, and report results back.	• Ability to informally track progress without excessive handholding (e.g., through the online message board). • Formal progress reports.

Society for Automotive Engineering (SAE) student design teams, through definition of global requirements, identification of associated local requirements and design off the local requirements [14]. The Ecosystem is also being considered for critical parameter management and requirement tracking by design organizations in the Portland area (capstone sponsors).

2. Methods

2.1 Overall structure and typical design flow

Previous publications describe the overall Ecosystem framework, and its extensions, including the cloud architecture [1, 2]. An outline of the Ecosystem support for different design methodologies, is given in Table 2. Fig. 1 represents typical design flow suitable for most capstone applications. The Ecosystem utilizes a four-phase model similar to the one proposed by Pugh, and assumes a default waterfall design approach [5]. While the facilities currently provided in the Detailed and Final Design phases are particularly geared towards mechanical or aerospace design, the tools provided in the Requirement Gathering and Concept Design phases apply to engineering design in general. Although the Ecosystem lends itself naturally to a traditional, process-oriented design approach, the desired trade-off between thoroughness and expediency can be attained, through deselection of tabs not considered essential for a particular application. Design activities are accomplished by inputting appropriate information into electronic design (e-design) workbooks. A workbook page represents deliverable milestones, and each phase is a compilation of pages consisting largely of tabular or tree-based interfaces. Data is entered into structured fields for storage and analysis.

The Ecosystem software presently runs on Windows or Mac desktops, laptops or tablets. Typically, capstone students store (share) their design files in a centralized repository, such as on a Google Drive, OneDrive or in a Dropbox, but synchronize their local clients with the centralized repository [10]. For capstone applications, the Ecosystem provides a faculty support (supervisor) mode separate from the standard capstone design process. It also provides the students with access to an online message board through http://ecosystem.imagars.com/.

The Ecosystem clients offer educational instructions to the students, in part, through placeholders outlining expected content for given tabs and informal pop-up tips. Each tab also contains an Analyze function for formal assessment of the design content against the design process. This results in sample alerts, as illustrated in Fig. 2. The Ecosystem interface was developed with efficiency in mind. The designer can switch between any given tabs in only

Table 2. Versatility of the Ecosystem framework

Design Approach	Ecosystem Configuration
Waterfall (top-down)	None: The default Ecosystem configuration provides a thorough layout.
Hybrid (top-down)	Through deselection of tabs not considered essential for a particular application, one can attain balance between thoroughness and expediency.
Agile (top-down)	Here one would configure the Ecosystem only to show the tabs considered absolutely essential. The designer can iterate the design through these few tabs as often as considered necessary. Quick iterations can be accounted for using the Design Revision tab. The Testing tab supports Test-Driven Development (TDD). The Design Description tab can list multiple models. Changes in requirements can be tracked using the Notes section of the Design Review tab.
Sub-system (not top-down)	Population of global requirements for the overall design, combined with identification and design off local requirements for the sub-system [14].

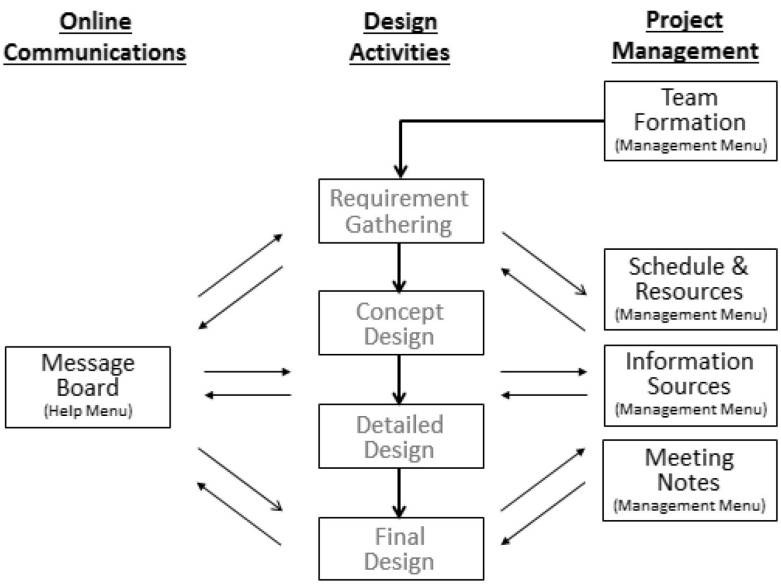

Fig. 1. Flow through the Ecosystem for a typical capstone design project.

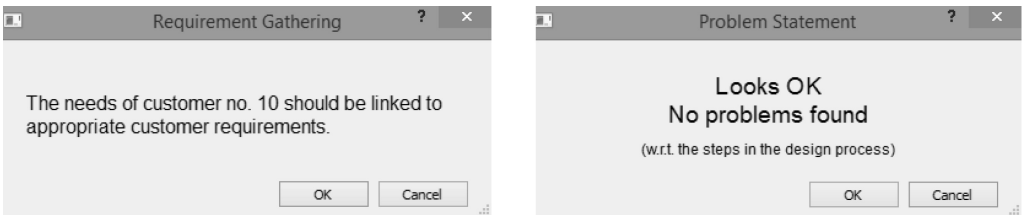

Fig. 2. Sample Ecosystem alerts corresponding to an unaccounted customer (left) or the case of no problems found (right).

two mouse clicks. The interface, further, emphasizes auto-population for ease of reference, and sound logical relations between entities (e.g., between the customer feedback, customer requirements and engineering requirements).

2.2 Pedagogical utility: Assessment against ABET-compliant learning objectives

In order to ensure the pedagogical utility of the Ecosystem, several ABET-derived learning outcomes have been extracted. They reflect the skills that student engineers are expected to demonstrate at the completion of a capstone project [15]:

- The group demonstrates the ability to evaluate and incorporate information into the design;
- Members function as part of a team;
- The group communicates in the language of design;
- The group defines, performs, and manages the steps of the design process.

Information in each phase is mined to extract pertinent performance indicators reflecting the learning outcomes. Performance indicators for each outcome are collectively extracted from the Information Literacy Competency Standards for Higher Education and are compiled into phase-specific rubrics enabling the interpretation of the completeness and quality of the design activities [11]. The phase-specific rubrics are formulated in terms of discrete metrics, as exemplified in Table 3. A spectrum of evaluable activity enables opportunities for timely automated prompts and targeted mentor feedback to upgrade deficient areas. The tabular layouts, and thorough tracking of design entities throughout the design process are essential to programmatically evaluating the discrete metrics. As shown in Fig. 2, when no problems are found, the Ecosystem refrains from making blanket statements about the quality of the design under consideration, but notes the assessment is with respect to steps in the design process.

2.3 Management menu: Project management and instructor facilities

The Management Menu is intended for project management facilities for the students, and through the supervisor mode, for instructor support [10]. The tools presently offered involve team formation, scheduling and resource management, information

Table 3. Concept design phase specific rubric with sample evaluation based on content from an e-design notebook

	Outcome				Performance Assessment					Outcome Binary			
Performance Indicator	**1**	**2**	**3**	**4**	**Beginning**	**Developing**	**Developed**	**Accomplished**	**Exemplary**	1	2	3	4
Defines and articulates the need for information	X	X	X	X	No concepts proposed	1 concept proposed, but not developed	>1 concept proposed, but not developed	1 concept proposed and decomposed to exhibit DF and DP	>1 concept proposed and decomposed to exhibit DF and DP	1	1	1	1
Extracts, records, and manages information and its sources	X	X	X	X						1	1	1	1
Synthesizes main ideas to construct new concepts	X	X	X	X	No members contribute to concept ideation	1 member contributes to concept ideation	Some (<50%) members contribute to concept ideation	Most (>50%) members contribute to concept ideation	All members contribute to concept ideation	1	1	1	1
Reevaluates the nature and extent of the information need	X			X	No concept models are feasible	1 concept model is feasible	Some (<50%) concept models are feasible	Most (>50%) concept models are feasible	All concept models are feasible	1	0	0	1
Summarizes the main ideas to be extracted from the information gathered	X		X		No concepts evaluated for fitness	Some concepts evaluated for fitness, but no DF evaluated	Some concepts evaluated, some DF evaluated	All concepts evaluated and some DF evaluated	All concepts and all DF evaluated	1	0	1	0
Articulates and applies initial criteria for evaluating both the information and its sources	X			X						1	0	0	1
Compares new knowledge with prior knowledge to determine the value added, contradictions, or other unique characteristics of the information	X			X	Concept not selected for development		Concepts too similar for selection, fitness variation too narrow		Concept selected for development	1	0	0	1
Applies new and prior information to the planning and creation of a particular product or performance	X		X	X						1	0	1	1
Determines whether the new knowledge has an impact on the individual's value system and takes steps to reconcile differences	X	X		X	DF and concept selections do not agree with fitness evaluation	Some DF (<25%) and concept selections agree with fitness evaluation	Many DF (25-50%) and concept selections agree with fitness evaluation	Most DF (25-50%) and concept selections agree with fitness evaluation	All DF and concept selections agree with fitness evaluation	1	1	0	1
Validates understanding and interpretation of the information through discourse with other individuals, subject-area experts, and/or practicioners	X	X			Members have not communicated within the habitat	1 member has attempted to establish thread communication	Members have established communication thread with some members participating (<50%)	Members have established communication thread with most members participating (>50%)	Members have established communication thread with at least 1 post from each	1	1	0	0
Determines whether the initial query should be revised	X	X		X	All requirements must be altered	>1 CN and FR to be added or altered	1 CN and FR to be added or altered	1 CN or FR to be added or altered	No new CN or FR to be added or altered	1	1	0	1
Communicates the product or performance effectively to others	X	X	X	X	No concepts have associated graphical representations	1 concept has associated graphical representations	Some (<50%) concepts have associated graphical representations	Most (>50%) concepts have associated graphical representations	All concepts have associated graphical representations	1	1	1	1
									Subtotal	55	33	27	46
									Possible	60	35	30	50
									Performance	0.92	0.94	0.9	0.92

sources and meeting notes. The scheduling facility, shown in Fig. 3, offers access to an interactive calendar, applies color coding to draw attention to possible problems or concerns, and provides explanations in part through graphical display (for ease of communication).

2.4 Requirement gathering phase

It is presumed that a design problem has been provided from outside the Ecosystem as a statement of need, and it is up to the designers to populate applicable elements of the product design specification including the identification of all applicable customers and their collected influence on the problem. The backbone of the PDS are the "foundational", i.e. common-core Functional Requirements (FRs) of the problem statement, corresponding Performance Requirements (PRs: the quantitative specifications of each FR; or UPRs: Unattached Performance Requirements which are necessary qualitative Constraints), Constraints (CNs: the binary boundary of the design solution domain), and Objectives (OBJs: or optimizable qualities of a design), as shown in Fig. 4. Each FR, OBJ, and potentially UPR are formulated into a "fitness function", also presented in Fig. 4, which algorithmically ranks design options according to the mission statement of the PDS. The fitness function is generic, in that it both accounts for the technical merits of the designs

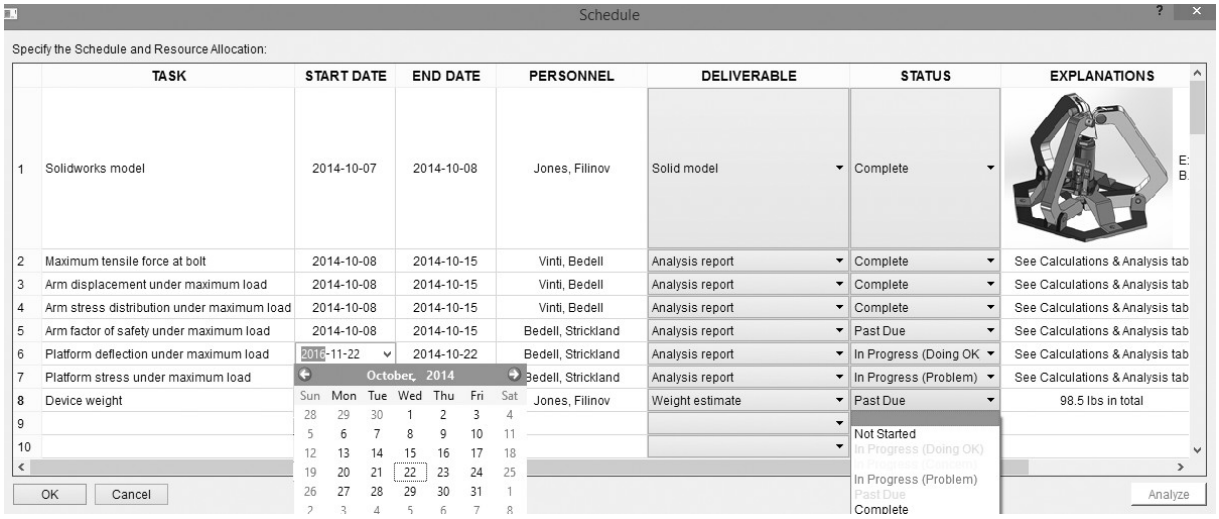

Fig. 3. Facilities from the schedule dialog (bolt tester example).

under consideration as well as the associated customer importance. Fig. 5 presents the Customer Interview tab. The Ecosystem helps the designer identify relevant questions to ask (identify the categories to be covered), collect verbatim customer feedback (to minimize the chance of interpretations down the road), and extract from it specific customer requirements. As demonstrated in Fig. 6, the Ecosystem, then, assists the designer with consolidating the customer requirements, linking the Engineering Requirements (ERs), and making sure the engineering requirements offer adequate numeric characterization of the customers' expectations. When a given interviewer (team member), customer or customer requirement has been defined, the Ecosystem auto-populates the pertinent drop-downs in subsequent tabs, for ease of reference. As expected, the Ecosystem also provides many standard usability features, such as row insertion and deletion for the tabular menus. Changes in requirements can be accounted for in the Notes section of the Phase Review tab.

2.5 Concept design phase

Figure 7 shows how the Ecosystem allows the designer to succinctly associate the textual description of a design idea with an accompanying sketch, for effective presentation [10]. Next, the design candidates are scored against the engineering requirements. With the functional modeling provided, the designer can decompose the design problem into several lesser problems (define subsystems and interfaces irrespective of physical attributes). Concept-specific FRs, and the representative solution paths are outlined in the form of a design tree. The solution paths are formulated as Design Features (DFs) which act as macro-scale binders for the

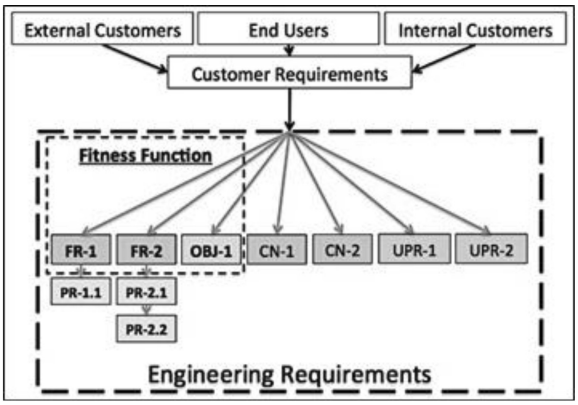

Fig. 4. Ecosystem PDS feature architecture.

discrete design point delineators: Design Parameters (DPs). The hierarchical decomposition of the functional model continues until parallel fundamental problems are determined which can be solved by basic solution principles.

The basic solution principles are drawn from Systematic Design. Axiomatic Design (AD) principles identify the relationship between parallel problems. Functional modeling is given high priority for enforcement of the rules of AD. To continue with appropriate context and allow future use of supporting AD principles, the terminology and procedure for functional decomposition is specific to this application, and is represented in Fig. 8.

Pure AD is intended as a top-down approach. To some extent, it is possible and beneficial to design in this manner. However, a hybrid approach can be used more effectively in most cases. The hybrid method, illustrated in Fig. 9, employs functional decomposition in a top-down manner but also utilizes controlled convergence via design para-

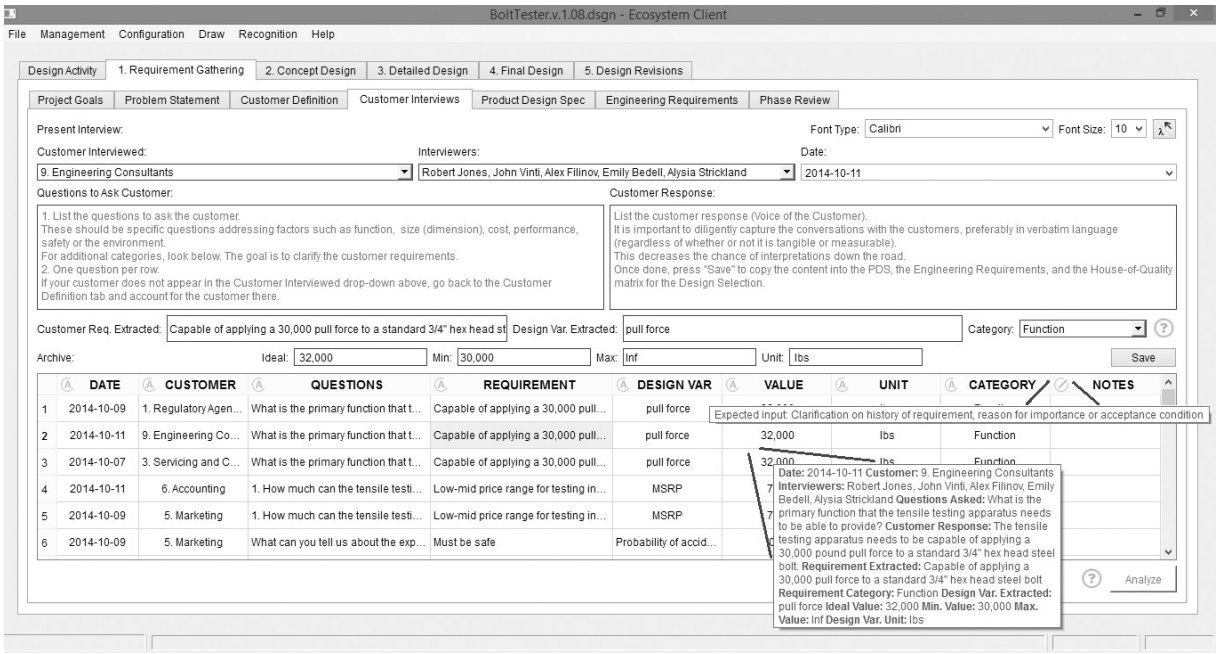

Fig. 5. Facility supporting formulation of customer questions, collection of feedback and extraction of customer requirements.

House of Quality:

	CUSTOMER NEED	CUSTOMER	IMPORTANCE	*Dimension*	*People needed to operate*	*Weight*	*Mean operating temperature*	*Useful life*	*pull force*	*MSRP*	*Probability of accident*
1	Capable of applying a 30,000 pull force to a standard 3/4" hex head steel bolt	1,3,9	9	0	0	0	0	0	9	0	0
2	Low-mid price range for testing instruments (MSRP < $1000)	5,6	9	0	0	0	0	0	0	7	0
3	Must be safe	10,2,3,5,9	6	0	0	0	0	0	0	0	8
4	Fit within the dimensions of 30" x 12" x 12"	2,7,9	7	7	0	0	0	0	0	0	0
5	Must allow single-person installation and use	2,4,7	7	0	7	0	0	0	0	0	0
6	Must be portable	2,4,7	9	0	0	9	0	0	0	0	0
7	Use in temperate environment	4,5,9	5	0	0	0	8	0	0	0	0
8	Reasonable useful life (2 year < Life < 20 years)	5,8	6	0	0	0	0	8	0	0	0
9			**Absolute Importance:**	49	49	81	40	48	81	63	48
10			**WEIGHTS:**	**0.11**	**0.11**	**0.18**	**0.09**	**0.10**	**0.18**	**0.14**	**0.10**
11			**MIN:**	2.2	1	40	40	2	30,000	0	0
12			**IDEAL:**	2.5	1	60	50	10	32,000	750	0.1
13			**MAX:**	2.8	1	80	60	20	Inf	1,000	1
14			**UNIT:**	ft^3	person	lbs	F	years	lbs	$	%

Fig. 6. Facility for consolidating the customer requirements and associating the engineering requirements (bolt tester example).

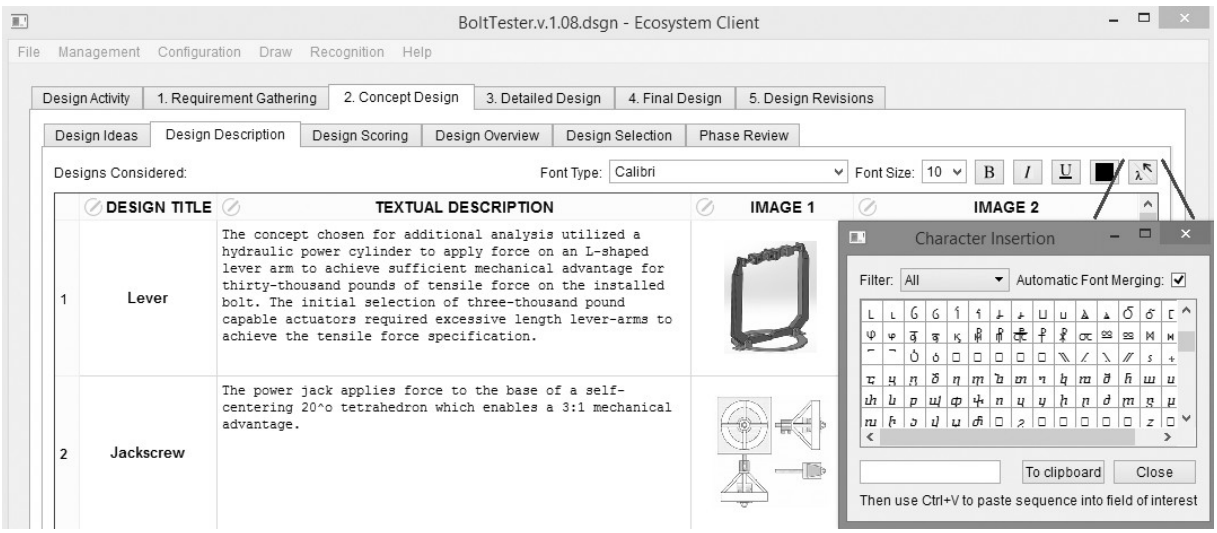

Fig. 7. Textual and graphical outline of designs considered (bolt tester example).

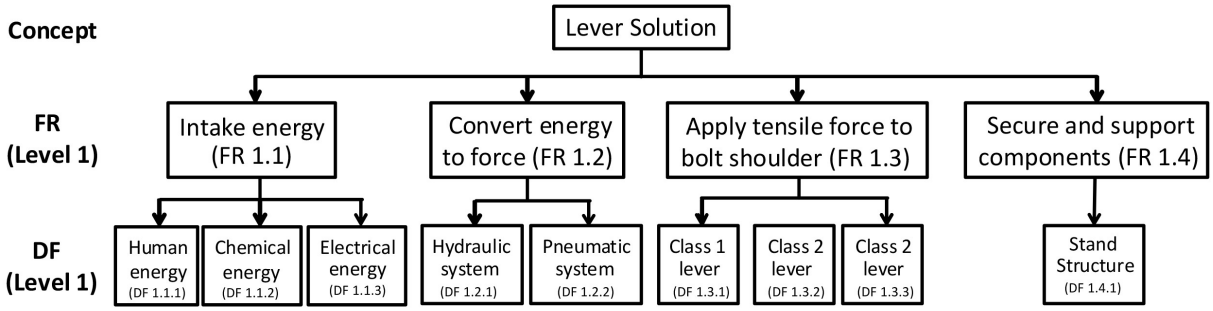

Fig. 8. Functional decomposition for the bolt tester example.

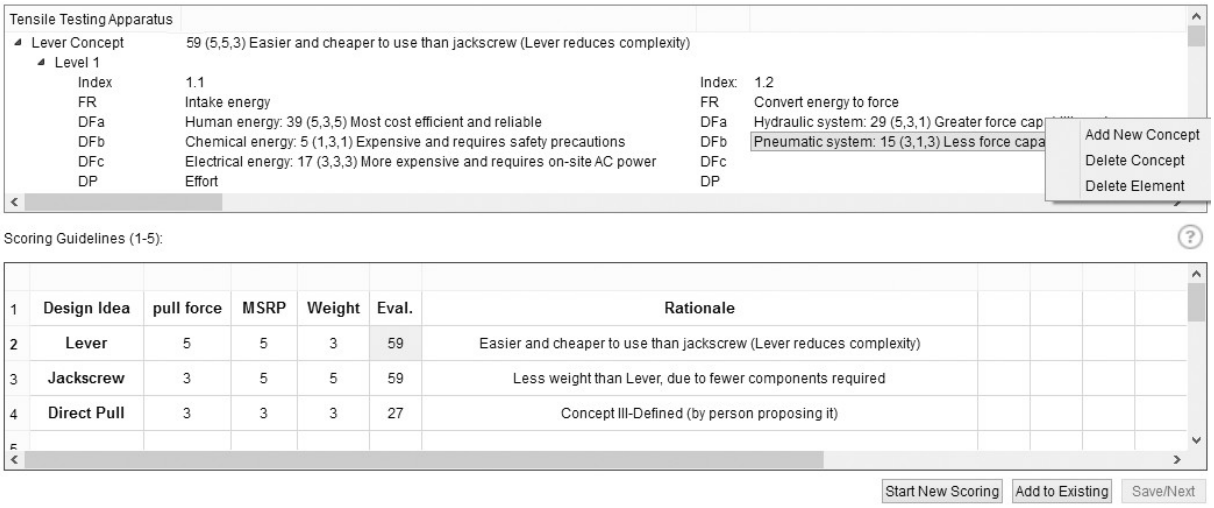

Fig. 9. Objective scoring of concept design solutions with supporting rationale (bolt tester example).

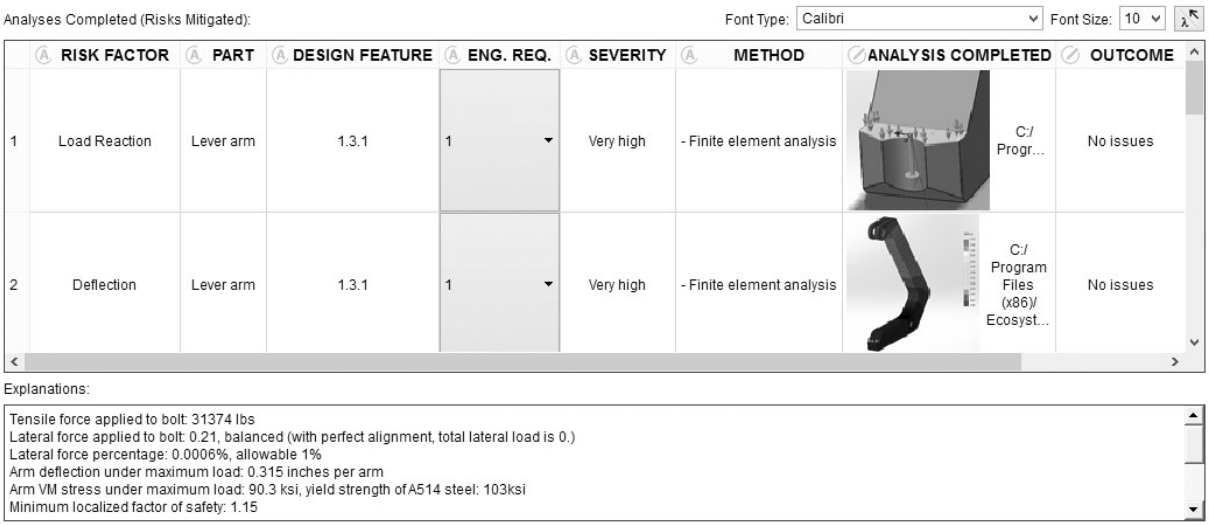

Fig. 10. Analysis of high-severity risk factors with supporting analysis and outcome specification.

meter optimization in a bottom-up manner. The Ecosystem guides the designer through the decomposition process and automates many of the administrative functions, such as evaluation of the fitness function. Despite the automation, the Ecosystem in no way alleviates the designer from critical thinking. Quite to the contrary, the Ecosystem prompts for, and makes sure to capture, the rationale supporting the design decisions.

2.6 Detailed design phase

The concept solution that survives the fitness com-

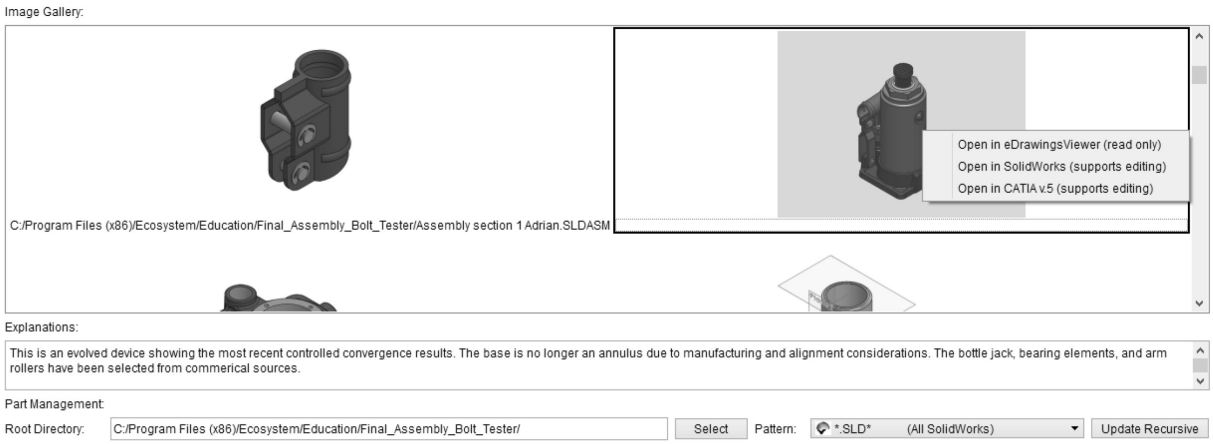

Fig. 11. Real-time visualization of part and assembly files with interface to e-Drawings Viewer and SolidWorks.

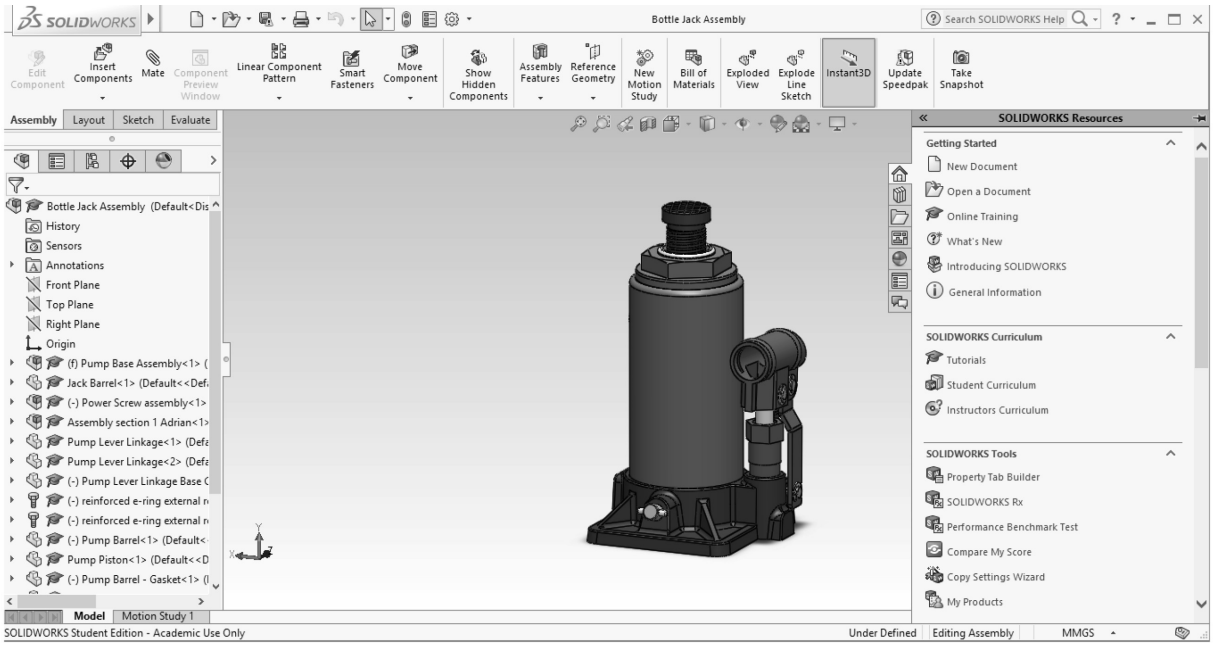

Fig. 12. SolidWorks assembly opened from Ecosystem by right-clicking on the image in Fig. 11.

petition in the Concept Design phase advances to Detailed Design. At this point, efforts to improve multiple species are redirected towards evolution of the design selected. From the engineering requirements and functional decomposition, all PRs, CNs, and OBJs are specified by assessable quantities. It is imperative in this step to specify analyses to verify those requirements. While unlimited project time would yield unlimited analysis capability, limited resources typically require a degree of triage to determine the analyses that must be completed. The importance categorization associated with each applicable engineering requirement ensures designer efforts are appropriately guided. It should be the intent of a successful team to analyze all fitness parameters and verify at a minimum all requirements listed with very high, high and medium priorities (for an example, refer to Fig. 10). Note the thorough association (tracking) of the part names, design features and requirements with the risk factors.

For detailed design, the Ecosystem offers interfaces to popular engineering design tools, such as SolidWorks. Fig. 11 and Fig. 12 highlight the Ecosystem's ability to rapidly search archives of design files and extract thumbnail images, corresponding to given part of assembly files in real-time. Such visualization allows the designer to rapidly locate part or assembly files of interest. Through simple right-clicking, the designer can open these files up in the e-Drawings Viewer or SolidWorks, for further inspection, or for editing.

Table 4. Utility of the Ecosystem on a range of capstone design projects from the MME department at PSU

Project	Sponsor	Category	Ecosystem Main Utility
Go Kart Lifting Stand	Internal		Report generation, Solidworks interface
Quail Egg Embryo Extractor	Children Hospital	Traditional	Risk identification
Redesign of a seat latch	Hyster-Yale	(with prototype)	Complete design journal for sponsor
Button testing robot	Simplexity		Functional analysis
Sensors & platform for air quality	Ventacity	Conceptual	Requirement formulation &
Device to rescue drowning people	Intel	(no prototype)	design scoring (through functional analysis)
Injection molding	3D Systems	Process only	Archival of meeting notes

2.7 Final design phase

When a fully evolved design meets the engineering requirements, it is fit for advancement to final design. In case of mechanical engineering, the final design phase is concerned primarily with the generation of production documentation and the creation of subsequent plans for manufacturing and testing. The user uploads pertinent part files, assembly files, and bill of material (BOM) files from the solid modeling package to ensure completeness. For parts purchased off-the-shelf, detailed drawings can often be uploaded from the manufacturer and can therefore be specified as such for BOM accounting purposes.

The Ecosystem also offers generic design facilities, such as for Requirement Verification. The ability to track requirements throughout the design process, verify status, level of completion and supporting test results has been welcomed both by capstone teams at the Portland State University (PSU) and even more so by some of their sponsors.

3. Results from pilot testing

The Ecosystem has demonstrated utility on a variety of capstone projects in the Department of Mechanical and Materials Engineering (MME) at PSU, as illustrated in Table 4. While devised with traditional design projects and process-oriented focus in mind, the Ecosystem has also been welcomed by design teams working on conceptual-only design projects, due to the emphasis on early process activities (requirement formulation and design scoring).

Table 5 further summarizes the significant, favorable feedback from evaluations conducted by undergraduate capstone courses at PSU, the University of Nebraska—Lincoln (UNL), and the University of Minnesota—Twin Cities. Note, in particular, the comment by Dr. William Dick of the University of Nebraska:

> "I have only two teams and they both have performed admirably. The Dynamometer team has managed to stay on schedule a little better but I'm not certain whether that is due to Ecosystem or some other factor."

Overall, the students have found the automation of the administrative functions most useful, in particular the ability to export the entire design content into well formatted project reports. Table 6 similarly, summarizes the favorable feedback received from the Formula and BAJA SAE teams evaluating the Ecosystem SW [14]. In addition to the design specific facets, the capstone and SAE teams have welcomed the Ecosystem's support for backward compatibility and team communication facilities resembling those provided by Google Docs. Designers want to be able to modify the same design files, at the same time, but still without the risk of overwriting the work of fellow team members. And they want new additions from team members to show up on their system in real time with proper annotation (color coding). This sentiment is also shared by industry designers, such as from 3D Systems. The Ecosystem addresses this in part through provision of an auto-save and an auto-recovery facility, and in part through reliance on external tools [10]. The User Manual explains how the Google Sync application can be configured for near instantaneous uploads and downloads [10]. In case of PSU, the Manual also explains how the locking mechanism of the Stash can be utilized to prevent overwriting, when simultaneously accessing design files on a network drive [16].

4. Comparative analysis of software tools

4.1 Project management by capstone design teams

Hurst reviewed several modern project management tools popular among undergraduate engineering capstone design teams and provided a summary feature comparison [17]. Table 7 has been adopted from Hurst's work to include the capabilities of the Ecosystem. Most commonly-adopted project management tools are capable of task management, file sharing, and communication via instant messaging or e-mail. Interestingly, the least capable tools adopted for project management could be the Google Suite of applications. But, the Google Suite has been widely adopted due to their ease of use, user experience, reliability, impressive team

Table 5. Sample feedback from evaluation of Ecosystem 1.0 β SW at different capstone design programs

University	Capstone Structure	Period	Feedback
Portland State University (ME)	3-quarter program	Winter & Spring '16	"Ecosystem 1.0 SW could have helped with everything in our project, as long as we would have used it consistently from Day 1. We liked the interface with SolidWorks and the Google Drive as well as the mechanism for automatic report generation" (The Electric Go Kart Lifting Stand team). "We found the functional decomposition useful for our project. It helped us assess our design candidates, in an objective fashion, validate our selection of the suction-tension design as well as of the mechanical approach for the kinematics and the exterior vacuum pump for the suction. If adopted earlier in the project, we think the Ecosystem 1.0 SW could have helped a lot in terms of early identification of the risk factors for our project (which in our case were identified super-late in the game)" (The Quail Egg Embryo Extractor team).
		Fall '16	• Students felt a little intimidated when first exposed to Ecosystem framework (had questions about the learning curve involved). • But when exposed to the SW, they considered it intuitive, straight forward and easy to use.
University of Nebraska, Lincoln (ME)	2-semester program	Winter & Spring '16	"I really do see a lot of potential in the Ecosystem as a template for design teams within the college in the future" (Josiah Johnson, Low-Cost Straw Flattening Machine design team).
		Fall '16	"I got the Ecosystem downloaded to my Mac using WineBottler. It works very well, haven't had any problems. The previous project examples in the help section are very useful" (Taylor Ackerman, BAJA SAE Dynamometer team). "I have only two teams and they both have performed admirably. The Dynamometer team has managed to stay on schedule a little better but I'm not certain whether that is due to Ecosystem or some other factor" (Dr. William Dick, faculty adviser, BAJA SAE Dynamometer team).
Univ. of Minnesota (ECE)	1-semester program	Fall '15	• Valued the Mac support and facilities for requirement definition. • Emphasized the importance of good training material: Students needed to learn the SW and realize benefits in a single semester.

Table 6. Feedback from evaluation of Ecosystem 1.0 β SW from different Formula and BAJA SAE student design teams

SAE Team	Period	Feedback
Illini Motorsport (Univ. of Illinois)	Summer '15	"This software seems like something that would be very useful to all Formula SAE teams. One of the biggest challenges we face is not the engineering, but the project management of all of the different components on the car."
OIT Racing (Oregon Tech)	Fall '16	Great tool for capturing design work (rationale for design decisions), greatly expedites knowledge transfer between years (identification of opportunities for improvement). Ecosystem is being extensively used by the OIT Racing team. Efforts to support backward compatibility motivated by requests from OIT and UNL.
UC Berkeley Formula Racing (BFR)	Fall '16	BFR team decided to adopt the Ecosystem in stages, starting with the weakest link in their project management system (capture & tracking of design review decisions). The Phase Review tab was added per request from the BFR team.

communication facilities, and generic inter-operability. In addition to the inter-operability with the Google Drive, and its free access, MME capstone teams at PSU valued the ability of Google Suite to support simultaneous editing of documents without overwriting, as noted above. This had resulted in Google Docs becoming the de facto tool used by most MME capstone teams at PSU. For the same reasons, the BFR team had adopted the Google Apps for managing their projects. The team also utilizes Slack for team communication and coordination. The free version of Slack, which is supported by standard mobile platforms, provides a venue for communications within the overall BFR team, and for communications within specific sub-teams, but also allows members to send private messages, send invitations, create new channels, etc.

The Ecosystem seeks to leverage those same attributes by dovetailing with popular collaboration applications such as Google Drive, MS OneDrive, Dropbox, and more. Additionally, the Ecosystem incorporates the utilities of other third party applications facilitating thread-based communication with archival capabilities, and incorporates milestone tracking with an interactive calendar functionality. The closest analogue to the Ecosys-

Table 7. Comparison with common tools from capstone design programs (adopted from [17])

Tool Name	Task Management	Sharing and Collaboration	Communication & Notification Alerts	Budget/Milestone Tracking	Issue Management
MS Project [18]	X	X	X	X	
Kickstart [19]	X	X		X	
Google Suite [20]		X	X		
Basecamp [21]	X	X	X		
Asana [22]	X	X	X		
Slack [23]	X	X	X		
Trello [24]	X	X	X		
JIRA [25]	X	X	X	X	X
Ecosystem	X	X	X	X	X

tem, based on the comparison in Table 7, is JIRA. JIRA is bug-tracking, issue-tracking and project-management software, prominent among agile teams, but with no design decision support (assessment) capability.

4.2 Education courseware

The majority of existing CAD and project management software lacks the specific support functions desired by higher-education users to run a productive capstone design course. In particular, Blackboard, Moodle, Desire2Learn (D2L), and the platforms exhibited by Massive Open Online Course (MOOC) providers, are not tailored to interface with advanced CAD software, nor handle the iterative or compliance features necessary to assess design activity quality relative to desired course outcomes [35–37]. Blackboard is, for comparison, used at Iowa State University for general course management, Moodle at the University of Minnesota and D2L at PSU. While the aforementioned courseware may provide great support for exams, surveys and general course deliverables, the Ecosystem is specifically tailored to engineering design. The requirement for compliance to the established design process, offered by the Ecosystem, ensures efficient development of design information, expeditious progress in a time-constrained environment, and most importantly, design process learning.

Table 8. Common tools for managing design projects (requirements) used by student design teams and industry

Tool Name	Description	Sample Usage
IBM Rational DOORS [26]	• Impressive capabilities for requirement management • Can support 100,000+ requirements • But only a single database & no assessment	• Automotive vendors and suppliers • Military & aerospace • Not used much by academia
IBM Rational Team Concert [27]	• An Agile application lifecycle management solution • Agile, formal and hybrid planning & reporting	• Agile project management at large design organizations, such as at Intel
Cockpit [13]	• Enables teams to collaboratively manage customer inputs and voices, features and requirements, risks, costs, and critical parameters	• Medical device companies • Pharmaceutical companies • Not used much by academia
GRAI [28]	• Handles more complex goals, such as profitability	• Limited?
Siemens TeamCenter PLM [29]	• Nice database interface & support for multiple projects • No free version, not even for students? • No design decision support (real-time alerts)	• New Mexico State University • United Technology
SolidWorks PDM [30]	• Nice database interface: "good for a lot of things" • Free student version • Allows Formula SAE teams to cost things out	• Extensive usage among Formula SAE team, e.g., U. of MN or UC Berkeley
CATIA Enovia PLM [31]	• CATIA's PLM solution for small & mid-size enterprises	• Honda & Boeing rely on CATIA v.5 & 6 • Not used much by academia
PTC Windchill [32]	• Advertised as smart, connected, flexible and complete	• Used by Airbus, but not much by academia
Fusion 360 PLM [33]	• Advertised as first ever end-to-end PLM in the cloud • Mobile version available	• Used by a variety of industry customers, but not much by academia
Arena Solutions PLM [34]	• Advertised as easy to use, web-based data management system, connected to supply chain, and not costing much	• Used by companies such as Cadence, Intuit & eBay, but not much by academia

4.3 Requirement management

Looking back at the requirement definition and the early design activities, it appears the facilities provided by the Ecosystem offer enough rigor for most, if not all, capstone programs. Some programs emphasize rapid prototyping and a less formal (leaner) approach, based on requirement-measurement (RM) matrices [38]. The advantages of the Ecosystem have to do with design optimization, through the objective function provided, and scalability: While separate RM matrices may be created for separate subsystems, it seems to be easier to assign the engineering requirements offered by the Ecosystem to categories (and/or sub-systems), and systematically keep track of everything.

Now, looking at larger student teams, such as those participating in Formula or BAJA SAE student design competitions, or affiliated with university innovation spaces, the Ecosystem has the advantage of bridging the gap between different CAD vendors. While some universities may not afford the TeamCenter, those that do seem to like it. Even though TeamCenter and SolidWorks PDM are restricted to accessing data files from a single vendor, they do offer capability for managing multiple projects. The Ecosystem presently does not have the ability to access the databases of TeamCenter or SolidWorks PDM, but seems to be less clunky (easier to learn). Access to the databases would open up a world of new opportunities for the Ecosystem (ability to infer constraints (dimensions) of various parts and assemblies and check against the requirements).

Next, with regards to tools used by industry for requirement management, such as the ones listed in Table 8, it is important to keep in mind that these tools can support much, much larger projects than the typical capstones. United Technology spends millions of dollars per year on the enterprise version of TeamCenter. Looking at small-to-medium sized design organizations in the Portland area, it has taken some capstone sponsors several weeks to configure the Cockpit SW for their needs (for requirement management and critical parameter tracking). Even though the Ecosystem has major advantages in terms of cost and agility, there are still valuable lessons to be drawn. DOORS provides means for identifying contradictions or dependence between requirements. Mechanism for importing requirements from DOORS into the Ecosystem, for assessment, may be warranted.

5. Conclusions

The digital Ecosystem is a comprehensive design framework that can be applied to engineering education, such as capstone design. The Ecosystem is a flexible framework that incorporates common project management utilities and allows design teams to harvest user-friendly and popular applications for collaboration and communication. This paper compares the Ecosystem to other notable tools used by capstone teams, for project management and team communications, and by industry for requirement management, and highlights the relative advantages. The Ecosystem, in an educational environment, is tailored for design process learning, in contrast to some commonly encountered educational courseware. The Ecosystem provides benefits to all education stakeholders: students, mentors, faculty, and sponsors, and seems to suit most capstone programs and design methodologies. In a comparative study at the University of Nebraska, the capstone design team, that used the Ecosystem, did track a little better against the schedule than the one that did not.

Based on the comparative analysis, we have identified multiple avenues for future enhancements:

- We have already started to incorporate tools, such as RM matrices or slip-writing, for users aiming for a less process-oriented approach.
- The Ecosystem could be tailored towards "Research as Inquiry" by asking "increasingly complex or new questions, whose answers in turn develop additional questions or lines of inquiry in any field".
- One could look to harvest information provides by databases, such as provided by the SolidWorks PDM or TeamCenter, for the purpose of extracting information (constraints) on various objects, checking against the requirements, and producing prompt alerts in case of mismatch.

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