WHICH DESIGN METHODOLOGIES ARE EFFECTIVE TO SUPPORT A CAPSTONE PROJECT IN AEROSPACE DESIGN ENGINEERING?

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Abstract – Considering the challenges in the aerospace industry, the NSERC (Natural Sciences and Engineering Research Council of Canada) Chair in Aerospace Design Engineering (NCADE) has launched its own version of a final year undergraduate engineering capstone project at Concordia University. NCADE's objective is to expose students to the immense complexity of an aircraft design, thereby better meeting the industry needs of newly graduated students. Four design methodologies (i.e., systems engineering – SE, quality function deployment – QFD, theory of inventive problem solving – TRIZ, and environment-based design – EBD) were evaluated in the context of the NCADE project to answer the research question such as “to what extent do these methodologies provide effective support across the activities in the capstone project?” The evaluation was subjective discussing whether the design methodologies support the activities in the project. From the evaluation, it can be concluded that the studied design methodologies perform poorly to support the activities in the capstone project. Therefore, future research should investigate a better support for the capstone project to achieve NCADE's goals.

Keywords: Capstone project; Aerospace design engineering; Design methodologies; NSERC Chair in Aerospace Design Engineering (NCADE); Environment Based Design (EBD).

1. INTRODUCTION

The Aerospace Review [1] indicates that the aerospace sector growth will require a decisive and coordinated effort to strengthen and expand the supply of skilled and experienced workers and professionals to capitalize in new market opportunities. Four important outcomes are expected to maximize workplace entry-level skills of Canadian aerospace candidates, as summarized in Table 1. To contribute to the achievement of those outcomes, the NSERC Chair in Aerospace Design Engineering

(NCADE) has launched its own version of a final year undergraduate engineering capstone project at Concordia University. NCADE's objective is to expose students to the immense complexity of aircraft design; thereby better meeting the industry needs of newly graduated students equivalent to several years' experience in the field [2, 3]. In general, design methodologies suggest processes, methods and tools (defined in Table 2) to support the design process (i.e., tasks and timeline in the capstone project) to achieve the creation of the desired design outcomes (i.e., expected deliverables in the capstone project) [4-7]. The aerospace design process and deliverables in the capstone project imply necessary knowledge, skills and affect (KSA) [3, 8] required by the new workforce to achieve the expected outcomes in Table 1. Main definitions of KSA can be found in Table 3.

Table 1: Expected outcomes to maximize workplace entry-level skills of Canadian aerospace candidates by Aerospace Review [1].

#	Expected outcomes
1	Ensure the competencies of new entrants are aligned with industry requirements and keep pace with rapid technological changes
2	Ensure that industry has access to the right skills at the right time to meet the forecasted demand for skilled labor, particularly in light of the aging workforce
3	Increase productivity and competitiveness by reducing the time it takes for new graduates from university and trade schools to begin adding value to an organization
4	Effectively capture and transfer the knowledge of older members of the workforce to new entrants before this knowledge is lost due to retirement

The capstone project consists of a design-build-test and validate/iterate process during two semesters [9]. The project consists of a team of 32 students being multi-disciplinary acting as one integrated product development team (IPDT) [2, 9]. The process starts with a request for proposal (RFP) detailing the needs for a new aircraft in

terms of anticipated mission, performance and cost requirements and constraints. After the RFP is provided to the students, they are expected to create several deliverables in the process; for instance, design requirements document and project schedule. The creation of deliverables involves the use of different KSA in aerospace design engineering [3]. Design methodologies are expected to support students during the process and the creation of deliverables [10]. These deliverables and the process will be further introduced in Section 3.

Table 2: Definition of process, method and tool [5, 11].

Concept	Definition
Process	A process may be structured into more or less complex partial processes, phases, and detailed design steps. Processes results in changes in the state of information (e.g., from requirements to description of systems).
Method	A method refers to rules of designer's behavior and methodical directions to progress processes in a planned and methodical way. Methods may also involve to regulate the collaboration between engineering designers with available technical means (e.g., computers), technical knowledge (e.g., science, alternative principles, know-how), and environment conditions (e.g., working conditions).
Tool	A tool is a technical means to perform the method. For example, cost estimating during design where designers need to obtain cost estimates on alternative ways of solving some problems sufficiently quickly and accurately to influence their decisions requires the use of cost estimation tools.

The study of design methodologies has evolved since the 1940's through different regions such as Europe (e.g., Germany, Switzerland, Great Britain, France, Italy, and Scandinavia), North America (USA and Canada), Euro-Asia (e.g., Russia), and Asia (e.g., Japan), and other international developments [12, 13]. There is a plethora of design methodologies [4-6, 14], so this paper tries to build in the suggestions of systematic engineering by Eder [12, 15]. The combination of systematic engineering (systems engineering - SE) with Quality Function Deployment (QFD), and Theory of Inventive Problem Solving (TRIZ) is not a new attempt in the design engineering research community [16-23]. Environment-based design (EBD) [24, 25] is a systematic design methodology under research and development at Concordia University by Professor Yong Zeng. EBD has also reported positive research attempts in aircraft design [26, 27] and potential integrations with design methodologies such as TRIZ, and axiomatic design [28]. Mavris and Pinon [20], and Price, et

al. [19] demonstrate that SE exhibits strong similarities with the aircraft design process, as both build on decomposition, synthesis, and verification to achieve successful systems. Considering all those contributions in design methodologies, and the workforce competencies in Table 1; this paper is intended to answer the research question "*to what extent do these methodologies (i.e., SE, QFD, TRIZ, and EBD) provide effective support across the activities in the capstone project*"?

Table 3: Definition of KSA [3, 29].

Concept	Definition
Knowledge	Knowledge is influenced by the structure of knowledge and the availability of cognitive resources. Examples include synthesis knowledge, evaluation knowledge, critical requirements, primitive design solution, partial design solution, etc.
Skill	Skills refer to the thinking styles, thinking strategy or reasoning methods. Examples are identify, search for, generate, evaluate, analyze, redefine, and recompose.
Affect	Affect refers to emotion, and any state associated with feeling such as tiredness. Affect is also affected by personality, attitude, belief, motive and stress.

The rest of the paper is organized as follows. Section 2 reviews SE, QFD, TRIZ, and EBD. Section 3 introduces the evaluation methodology to answer the research question. Section 4 presents the results and discussion about the research question. Section 5 closes concluding about the findings and implications for future research.

2. DESIGN METHODOLOGIES

2.1 SE

According to the SE Handbook Working Group (INCOSE) [30], SE's modern origins can be traced back to the 1930's until the recent publication of the standard ISO/IEC/IEEE 15288:2015. SE is defined as an interdisciplinary, collaborative approach that derives, evolves, and verifies a life-cycle balanced system solution [19, 31]. Based on Mavris and Pinon [20], the purpose of SE is to transform needs and requirements into a description of system configuration (e.g., airframe system composed of subsystems such as empennage, fuselage, wings, and landing gear) and ensure that the developed system addresses the specified cost, schedule, and performance objectives. In the model of SE by Mavris and Pinon, the life cycle covers from identifying a need to

phase out and disposal of the systems. In the scope of the life cycle, the suggested processes are: 1) requirements analysis (aka problem definition), 2) functional analysis, 3) design synthesis, 4) repetition of the previous 1-3 processes in preliminary and detailed design, and 5) supporting processes such as project management. To represent the interactions between these processes, a variety of life cycle models have been proposed such as the Vee, Waterfall, Spiral, and the US Department of Defense [20]. The entire SE process is performed many times during the design and development process, with the output of each application being recursively verified and validated against requirements and specifications, and further used as input to the following application [20]. Each of the processes in the models requires the use of specific methods, tools, and KSA.

2.2 QFD

QFD originated in 1972 at Mitsubishi's Kobe shipyard [32]. QFD is a design methodology to support project team for the identification of customer needs, and then interpreting these needs into technical parameters and target values [33]. There are three main elements in QFD: customer attributes (customer requirements/voice of customer (VOC)), engineering characteristics (EC), and a relationship matrix between them [32]. Customer attributes (CA) also called "the what's" define "what" the customer think is important in the product [32]. The second element – EC – lists the technical aspects of designing the product such as "How the customer wants can be met". The relationship matrix is represented using a tool called house of quality (HOQ) consisting of a left wing (CA), top (EC), roof (relationships between EC), body (relationships between CA and EC), right wing (competitive analysis), and basement (relative importance of EC and their target values). The HOQ includes the main components needed to use QFD methodology. In a general sense [32], QFD serves as a methodology to support the processes: 1) defining the decision context and the decision maker's objectives, 2) identifying/generating alternatives, 3) creating a decision model, 4) analyzing the alternatives, and 5) selecting the best alternatives. The whole QFD procedure uses a series of matrices (HOQs) to express linkages between input and outputs of different phases of development (e.g., design, manufacturing, and quality control) [34]. Although the integration of QFD and SE has been suggested in the literature, some difficulties in applying QFD exist such as 1) its popularity has not always been translated to successful practice, and 2) when applied inappropriately, it may increase work without producing any benefits [34]. Based on Eversheim [18], comprehensive implementations of the QFD methodology may involve processing up to 30 matrices.

2.3 TRIZ

TRIZ is a toolkit of methods to support systematic creativity [35]. TRIZ started developing by the Russian named Genrich Altshuller in the 1950s [36]. The main method of application, i.e., algorithm for inventive problem solving (ARIZ), has evolved through several editions from 1965 to 1985 [36]. TRIZ was born after Altshuller studied 40,000 patents from where he proposed tools such as 1) 39 engineering parameters, 2) a contradiction matrix, 3) 40 inventive principles (technical contradictions), 4) 4 separation principles (physical contradictions), 5) statistics on the usage of the inventive principles in Altshuller's matrix, 6) laws of technical systems evolution, and 7) suggestions to overcome psychological barriers in the creative process such as a) study leading industry, b) study follower industries in technology fields, c) collect information about physical effects, new materials, methods for solving technical problems, and so on; d) study patent information, e) keep track of literature on inventive creativity theory, f) accumulate experience in solving exercise problems, g) learn creative thinking, h) recognize the tendency in technical evolution, i) search for the by-pass methods (i.e., outside customary boundaries of specialization) of the solution, and j) do not rely on easy implementations [36-38]. These tools are applicable under different conditions [36, 37] especially during idea generation or detailing [18]. In a general sense, these tools enable designers to solve technical problems using analogies from the abstract solution patterns extracted by Altshuller [18]. To use TRIZ, Savransky [37] suggests the processes: 1) understand the problem, 2) identify and evaluate all possible solutions, 3) select the best solution, 4) demonstrate that the best solution solves the problem and verify & validate the solution, and 5) document the problem solving process. During the process, ARIZ algorithm suggests more detail actions, and applicable KSA and tools. In addition, implied from Savransky [37], it can be interpreted that the design and development of a new aircraft involves several level of inventions at different level of abstraction of the aircraft.

2.4 EBD

EBD is defined as a transdisciplinary design methodology that provides step-by-step procedures to guide designers [24, 25]. Zeng and Cheng [39]'s effort in the evolution of EBD can be traced back to 1991. EBD defines that design is driven by a need or inspiration from the environment (i.e., human, natural, and built), serves the environment, and changes the environment [24, 25]. These needs or inspirations from the environment are called conflicts in EBD. EBD includes three activities: environment analysis, conflict identification, and solution generation [24, 25]. The activities in EBD can be

interpreted as processes that happen concurrently, iteratively, and recursively. EBD methods and tools are based on linguistic analysis to problem formulation, conflict resolution through causality (i.e., systematic analysis & evaluation between requirements and solutions), recursive resolution (solution generation) of complex problems, atomic design & TRIZ, and life cycle considerations [24, 25]. Considering the affective component of designers, EBD adopts the Yerkes-Dodson law, i.e., medium level of arousal (mental stress) results in the best performance (innovation); where creativity can be interpreted as the process that creates innovation. Zeng [24] further discusses the theoretical formulation of EBD and its research evolution.

2.5 Closing Remarks about SE, QFD, TRIZ, and EBD

Based on the introduction of each design methodology, it can be appreciated that these methodologies overlap suggesting similar processes of design. It can be inferred that the methodologies have similar goals, but they use different terminologies, methods and scope to conduct design. The approaches can be complementing, but at the same time may generate a greater workload for students without achieving benefits in design. The evaluation of effectiveness in Section 3 will be cautious excluding the word efficient referring to reduce time/cost, or improve quality in design. This paper does not explore, and it is not intended to address efficiency in design.

3. EVALUATION METHODOLOGY

To answer the research question “*to what extent do these methodologies (i.e., SE, QFD, TRIZ, and EBD) provide effective support across the activities in the capstone project*”, the capstone project is the source of data collection and theoretical framework of analysis.

The framework of the capstone project is summarized in Table 4. The framework was used by the authors to rate whether the investigated methodologies support the activities in the capstone project. The scope and deliverables relate to the conceptual design phase. Percentages in the deliverables mean the relative grade related to the total 100% of the entire capstone project. Conceptual design corresponds to the first semester of the 2-semester capstone project, so the summation of the indicated deliverables in conceptual design total 60% of the entire project. In the case of test, evaluation and validation; the deliverable overlaps between the first and second semester of the project. Besides the deliverables, other important components are the specific tasks and supporting activities such as teamwork, reports, referencing, budget, and resources. The numbers in the specific tasks is for

listing purposes not to indicate priority. The tasks happen concurrently, iteratively and recursively in reality.

Table 4: NCADE capstone project semester 1 [9].

Input: Request for proposal (RFP)	
Specific tasks	Deliverables
1. Determine detailed customer requirement needs and formulate the design problem	1. Design requirements document and project schedule (5%) (written) (team)
2. Establish performance parameters and measurable measures of merit for functional requirements for each of the aircraft systems	2. Conceptual design report (15%) (written) (team & individual)
3. Collect data on existing designs and brainstorm multiple design concepts that meet the requirements	3. Conceptual design review (20%) (presentation) (team & individual)
4. Decide on a single design concept using a systematic decision-making process (trade study) and produce a simple geometric model	4. Test, evaluation and validation (15%) (written) (by discipline)
5. Perform aerodynamic analysis and propulsion modeling in support of a constraint analysis to demonstrate that the concepts meet the customer requirements and constraints	5. Workbook (5%) (written) (individual)
6. Carry out mission analysis, weight prediction and aircraft sizing tasks	6. Peer evaluation (0%) (written)
7. Analyze anticipated costs and compare to customer cost constraints	
8. Provide a preliminary structural layout	
Teamwork: multi-disciplinary, integrated product development team (IPDT)	
Reports: format all written respect to guideline (type of font, size, margins, double-sided printing, minimal spacing between sections)	
<ul style="list-style-type: none"> - Academic references (permitted): textbook, journals and conferences - Web-page references (no marks): use if taken figures, advertisements, company products, material data, etc. from web-sources to avoid plagiarism - Be familiar with: academic integrity, code of conduct, and plagiarism 	
Budget: funds for prototyping (if justified & approved) & purchases (if justified & approves)	
Resources: Capstone lab/room spaces: 1) basic/advanced machining, 2) assembly, 3) 21 capstone project rooms, and 4) 2 conference presentation rooms	
Output: Grade (A+) // Validated design	

For each design methodology, common suggested processes, methods, and tools were extracted. In addition, for the suggested processes, the authors defined KSA from

the perspective of aerospace design engineering suggested in the design methodologies. Sometimes KSAs were explicit in the context of aerospace design engineering; other times, they were generic for engineering design. In the latter case, the authors interpreted the methodologies and adapted the generic KSA to the context of aerospace design engineering in the capstone project.

A generic representation of the design methodologies with their respective processes, methods, tools, and KSA is presented in Table 5. As each design methodology suggests more than one process ranging from 1 to n processes, Table 6 is a generic representation for one design methodology. A sample representation for SE is presented in Table 7 excluding three more suggested processes (i.e., 1- design synthesis at the conceptual phase, 2- application of requirements analysis, functional analysis and design synthesis in preliminary and detailed design, and 3- additional activities during the aircraft design life cycle – e.g., project management). A sample representation of the allocated knowledge and skills for the requirements analysis process in SE is described in Table 8. Affect is not presented for the requirements analysis process in SE described in Table 8 as the reviewed publications do not consider this aspect.

Table 5: Generic representation of design methodologies (DM), their Processes (P), Methods (M), Tools (T), Knowledge (K), Skills (S), and Affect (A).

DM	P	M	T	K	S	A
SE						
QFD						
TRIZ						
EBD						

Table 6: Generic representation for one design methodology (DM), its processes (P), Methods (M), Tools (T), Knowledge (K), Skills (S), and Affect (A).

DM	P	M	T	K	S	A
DM1	P1	M1	T1	K1	S1	A1
	P2	M2	T2	K2	S2	A2
	Pn	Mn	Tn	Kn	Sn	An

Table 7: Sample of SE Processes (P), Methods (M), and Tools (T).

DM	P	M	T
SE	Requirements analysis	Quality function deployment (QFD)	House of Quality
	Functional analysis and allocation	Hierarchical tree decomposition of functions	Tree diagrams
	...	...	...

Table 8: Sample of SE Requirements analysis Process (SERAP), and required knowledge (K) and skills (S).

DM	K	S
SERAP	1- Knowledge about (existing and desired) aircrafts, its systems & sub-systems and new technologies (e.g., wide body/regional jets, airframe/propulsion systems, and fuselage & wings) 2- Knowledge about the stakeholders' perspectives and voices involved in the design activities (e.g., safety, costs, schedule, usage, range, speed, altitude, payload, noise, emissions, and other functionalities). ...	1- Ability to identify aircraft and its systems 2- Ability to identify stakeholders 3- Ability to capture requirements 4- Ability to translate requirements into engineering specifications ...

Considering the framework in Table 4, a subjective evaluation of the design methodologies was conducted following the generic evaluation logic in Table 9. It is important to highlight that specific tasks, deliverables and design methodologies in Table 9 have sub-elements, for example refer from Table 4 to Table 8.

Table 9: Generic evaluation logic of design methodologies in the context of the capstone project.

Capstone/DM	SE	QFD	TRIZ	EBD
Specific tasks	y/n	...		
Deliverables	...			
Teamwork				
Reports				
References				
Budgeting				
Resources				

The conducted evaluation is aggregated based on the perception of the authors. Due to the type of evaluation, the interpretations may be subject to errors. Nonetheless, they may foster discussion in the subject and suggest future paths for empirical explorations. The evaluation approach can be transferred to other capstone projects or design processes, but the interpretations in the paper are not intended to be generalized out of scope of this capstone project. Further results and discussion of the evaluation are presented in Section 4.

4. RESULTS AND DISCUSSION

After evaluating the design methodologies in the context of the capstone project, the first impression of

results are summarized in Table 10. The results are further discussed from Section 4.1 to Section 4.7 to provide more details of the effectiveness of the design methodologies in the context of the capstone project. These sections may highlight weaknesses in terms of KSA that apparently design methodologies provide at a high level, but at a closer look some limitations or vagueness arise. Section 4.8 is a brief summary of the results and discussion.

Table 10: Results of design methodologies evaluation in the context of the capstone project (empty means no).

Capstone/DM	SE	QFD	TRIZ	EBD
Specific tasks	y	y	y	y
Deliverables	y	y		y
Teamwork	y	y		
Reports				
References				
Budgeting				
Resources				

4.1 Specific tasks

This section discusses the specific task (i.e., from task 1 to task 8) in Table 4. The section ends with an overall discussion about the specific tasks in the capstone project.

For task 1, SE, QFD, and EBD make explicit the task of requirements and formulation of the design problem. For task 2, establishing performance is emphasized in SE and QFD. For task 3, TRIZ, SE and QFD recognize the need to collect data on existing designs to meet the requirements. For task 4, SE and QFD specify the need to decide on design concepts using a systematic decision-making process. For task 5, SE publications express the generation of geometric models and configurations, and an application of different engineering analyses such as aerodynamics and propulsion. SE and QFD also support traceability in the process of design between analyses, solutions, requirements and constraints. Specific tasks 6-8 have also been integrated in SE.

SE seems an effective design methodology to equip students with processes, methods, tools, and KSA to perform the specific tasks in the project. However, a more exhaustive examination in SE, and the rest of methodologies is recommended to understand their scope of application. For example, it is difficult to evaluate the level that SE equips students with KSA to define/identify/interact with customers, validate their needs, establish aircraft performance, and conduct the rest of specific tasks in the capstone project. Assuming that SE in an aircraft design's textbook has 1,000 pages, it can be reasonably arguable that some gaps may exist in KSA in aerospace engineering. So, such gaps should be identified and understood if using SE in aircraft design.

4.2 Deliverables

This section discusses the deliverables in Table 4. The section closes synthesizing the discussion about deliverables in the capstone project.

For deliverable 1 (i.e., design requirements document and project schedule), SE, QFD, and EBD make explicit the process of identification, traceability, and evaluation of requirements. SE suggests the integration of project management during the design process.

For deliverable 2 (i.e., conceptual design report), none of the methodologies provides guidance in creating and structuring the report, but in theory, some of the contents in the report are created based on the specific tasks in Section 4.1. Considering the investigated design methodologies, it is difficult to judge if students will be able of creating the conceptual design report, which includes topics such as technology capability survey, concept sketch and alternative solutions, first-guess sizing, initial layout, initial analysis, sizing and performance optimization, revised layout for each design iteration, design schedule/Gantt chart, budget, references, etc.

For deliverable 3 (i.e., conceptual design review), similar arguments as for deliverable 2 can be risen. In the same line of reasoning, it is also difficult to assess if using the suggested design methodologies the students will have the readiness level to approach, invite and host guests for the conceptual design review, prepare the venue for the design review, present their design and respond to questions.

For deliverable 4 (i.e., test, evaluation, and validation), it is also difficult to evaluate if students will be capable to prepare a test plan to validate their systems design against customer and airworthiness regulatory requirements, to prototype their system design (which may include psychomotor abilities), to perform tests, to analyze their results, and to document the process and results.

For deliverable 5 and 6 (i.e., workbook and peer evaluation), they are not discussed in the evaluated methodologies.

In synthesis, if 60% out of the 100% grade of the total capstone project is represented in the evaluated deliverables, the studied design methodologies score highly poor to support the capstone project. Although difficult to assess objectively in this discussion, the design methodologies are perceived to focus mainly in the design requirements documents and project schedule deliverable which represent only 5% of the 60% grade evaluated in this section. The rest of deliverables are seemed to be supported at a high level of abstraction which not necessarily include the KSA needed to equip students to develop most of the deliverables in the project.

4.3 Teamwork

Based on the reviewed literature, SE and QFD are found to mention the teamwork effort needed in an aircraft design. However, a closer look does not find any method or tool for the process of forming, storming, norming, performing, and adjourning teams. Considering that this project integrates a single group of 32 students, the investigated methodologies are perceived to be weak addressing teamwork.

4.4 Reports

Although Section 4.2 discussed about the conceptual design report, this section focuses on aesthetics including type of font, size, margins, etc. It was found that none of the investigated design methodologies address the KSA needed to create the reports in the capstone project. It is important to stress that writing reports is required in aircraft design to create manuals & training material, and document tests for certification purposes.

4.5 References

EBD indicates high level sources to find knowledge; however, they are not customized to satisfy the specific knowledge required by the students in the capstone project. As suggested in the capstone project, students should be equipped with KSA to use appropriate resources, keep track of records, and complies with academic integrity, code of conduct, and plagiarism.

4.6 Budgeting

It was found that none of the investigated design methodologies provide the KSA needed to justify the request of project budget for prototyping and testing. Additionally, none of the design methodologies equips students with the implicit identification of suppliers and cost data to justify any needed purchase.

4.7 Resources

It was found that none of the investigated design methodologies equip students with the KSA needed to perform any machining, interact with the lab/room responsible staff, create design presentations, and operate the conference rooms.

4.8 Summary of results and discussions

Based on the evaluation discussed from Section 4.1 to Section 4.7, the investigated design methodologies are perceived to score poorly to support the capstone project. At a high level, they seem to support specific tasks, but a more detailed look is advised to be taken cautiously. In the

creation of deliverables, the design methodologies are only perceived to tackle 5% of the 60% grade in the evaluated deliverables. The rest of KSA needed by students in teamwork, writing reports, references, budgeting, and resources are not evidently provided in the investigated methodologies. This leads to conclude that the investigated design methodologies should be improved to provide students with the KSA needed to perform the capstone project and consequently satisfy the expected outcomes in Table 1.

5. CONCLUSIONS & FUTURE WORK

This paper investigated the research question “*to what extent do these methodologies (i.e., SE, QFD, TRIZ, and EBD) provide effective support across the activities in the capstone project*”?, The paper assessed these methodologies in the context of the NCADE capstone project at Concordia University. From the evaluation conducted in Section 4, it can be concluded that the studied design methodologies perform poorly (refer to Section 4.8) to support the capstone project. Although the evaluation is subjective, an effective design methodology in the context of this paper should support the activities in the capstone project equipping students with KSA required in aerospace engineering.

Considering the ultimate goal of satisfying the needs in Table 1, an effective design methodology to support the NCADE capstone project in aerospace design engineering should be further investigated. As future work, *how can the KSA to perform the activities in the capstone projects be incorporated into one design methodology?* is proposed as a research question for further investigation. This research question can be followed by *how to measure the effectiveness of the resulting design methodology?*

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References

- [1] Aerospace Review, "People and Skills," Aerospace Review 2012.
- [2] R. Cassidy, J. Bentley, A. Cundell, and A. Cartile, "Center for teaching and learning / NCADE research meeting," ed, 2016.
- [3] S. Tan, C. Marsden, and Y. Zeng, "Educating aerospace design engineers: perspectives from design creativity theory," presented at the Canadian Engineering Education Association (CEEAA16) Conf., 2016, Halifax, Nova Scotia, Canada, 2016.
- [4] J. Estefan, "Survey of model-based systems engineering (MBSE) methodologies," 2007.

- [5] V. Hubka, "Design tactics = methods + working principles for design engineers," *Design Studies*, vol. 4, pp. 188-195, 1983/07/01 1983.
- [6] G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, *Engineering design: a systematic approach*, 3rd ed.: Springer-Verlag London, 2007.
- [7] J. D. Anderson, "Airplane Design Methodology: Setting the Gold Standard," *AIAA Journal*, vol. 44, pp. 2817-2819, 2006/12/01 2006.
- [8] J. Angeles, R. Britton, L. Chang, F. Charron, P. Gregson, P. Gu, et al., "The engineering design competency," presented at the Canadian Engineering Education Association, 2004.
- [9] C. Marsden, *NCADE Aircraft Capstone Design Project Course Outline*, 2016.
- [10] V. Hubka and W. Eder, "Pedagogics of Design Education," *International Journal of Engineering Education*, vol. 19, pp. 799-809, 2003.
- [11] V. Hubka and W. Eder, "A scientific approach to engineering design," *Design Studies*, vol. 8, pp. 123-137, 1987.
- [12] W. Eder, "Comparison of several design theories and methods with the legacy of Vladimir Hubka," Royal Military College of Canada, The Design Society 2012.
- [13] A. Chakrabarti and L. Blessing, "A Review of Theories and Models of Design," *Journal of the Indian Institute of Science*, vol. 95, pp. 325-340, 2016.
- [14] M. C. Yang, "Design methods, tools, and outcome measures: a survey of practitioners," presented at the ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Las Vegas, Nevada, USA, 2007.
- [15] W. Eder, "Design engineering and need for methodology," presented at the International conference on engineering design, Stanford University, Stanford, CA, USA, 2009.
- [16] W. Eder, "Designing and life cycle engineering—a systematic approach to designing," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 215, pp. 657-672, May 1, 2001 2001.
- [17] B. Lu, P. Gu, and S. Spiewak, "Integrated life cycle design approach for sustainable product development," presented at the Canadian Engineering Education Association, 2004.
- [18] W. Eversheim, *Innovation management for technical products : systematic and integrated product development and production planning*: Springer, 2009.
- [19] M. Price, S. Raghunathan, and R. Curran, "An integrated systems engineering approach to aircraft design," *Progress in Aerospace Sciences*, vol. 42, pp. 331-376, 2006.
- [20] D. N. Mavris and O. J. Pinon, "A Systems Engineering Approach to Aircraft Design," in *Encyclopedia of Aerospace Engineering*, ed: John Wiley & Sons, Ltd, 2012.
- [21] S. Gudmundsson, *General aviation aircraft design: applied methods and procedures*: Butterworth-Heinemann, 2014.
- [22] J. Hsu, "Using system engineering on an aircraft improvement project," *The Aeronautical Journal*, vol. 110, pp. 813-820, 2006.
- [23] K. M. Kamarudin, K. Ridgway, and M. R. Hassan, "Modelling the conceptual design process with hybridization of TRIZ methodology and systematic design approach," *Procedia Engineering*, vol. 131, pp. 1064-1072, 2015.
- [24] Y. Zeng, "Environment-Based Design (EBD): a Methodology for Transdisciplinary Design," *Journal of Integrated Design and Process Science*, vol. 19, pp. 5-24, 2015.
- [25] Y. Zeng, "Environment-based design (EBD)," in *Proceedings of the ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE*, 2011.
- [26] X. Deng, G. Huet, S. Tan, and C. Fortin, "Product decomposition using design structure matrix for intellectual property protection in supply chain outsourcing," *Computers in Industry*, vol. 63, pp. 632-641, 2012.
- [27] S. Tan, Y. Zeng, G. Huet, and C. Fortin, "Effective reverse engineering of qualitative design knowledge: A case study of aerospace pylon design," in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, pp. V004T05A026-V004T05A026.
- [28] S. Dubois, D. Tate, C. Conrardy, T. An Nguyen, R. De Guio, and A. Gaik-Wad, "Comparing the strategies and outputs of designers using Algorithm of Inventive Problem Solving, Axiomatic Design, or Environment-Based Design," *Journal of Integrated Design and Process Science*, vol. 16, pp. 89-110, 2012 2012.
- [29] T. Nguyen and Y. Zeng, "A Theoretical Model of Design Creativity: Nonlinear Design Dynamics and Mental Stress-Creativity Relation," *J. Integrated Design & Process Science*, vol. 16, pp. 65-88, 2012.
- [30] SE Handbook Working Group (INCOS), *Systems engineering handbook: a guide for system life cycle processes and activities*. San Diego, CA, USA, 2011.
- [31] BKCASE community, *Guide to the Systems Engineering Body of Knowledge (SEBoK) - v1.6 - Full version*, 2016.
- [32] G. Delano, G. S. Parnell, C. Smith, and M. Vance, "Quality function deployment and decision analysis - A R&D case study," *International Journal of Operations & Production Management*, vol. 20, pp. 591-609, 2000.
- [33] N. Roozenburg and J. Eekels, *Product design: fundamentals and methods*: Wiley, 1995.
- [34] S. B. Han, S. K. Chen, M. Ebrahimpour, and M. S. Sodhi, "A conceptual QFD planning model," *International Journal of Quality & Reliability Management*, vol. 18, pp. 796-812, 2001.
- [35] L. Chechurin, "TRIZ in Science. Reviewing Indexed Publications," *Procedia CIRP*, vol. 39, pp. 156-165, 2016/01/01 2016.
- [36] L. Chechurin, *Research and Practice on the Theory of Inventive Problem Solving (TRIZ): linking creativity, engineering and innovation*: Springer, 2016.
- [37] S. D. Savransky, *Engineering of creativity: Introduction to TRIZ methodology of inventive problem solving*: CRC Press, 2000.
- [38] G. Altshuller, *The innovation algorithm: TRIZ, systematic innovation and technical creativity*, 2nd ed.: Technical Innovation Center, Inc., 2007.
- [39] Y. Zeng and G. Cheng, "On the logic of design," *Design Studies*, vol. 12, pp. 137-141, 1991.