Exploring the portfolio assessment on novice engineering students' creativity, design and implementation process - setback event based analysis

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Abstract *— Setback event based analysis was proposed as an effective methodology to evaluate the width and depth of a novice's engineering creativity design and implementation project. Two operational procedures were proposed, through which, the mentality and mental process of novice students working through their creativity realization projects were uncovered. The mental processes of working through engineering analysis, application, and design problems were identified. They could be modeled, respectively, as a functional mapping process, its inverse mapping, and an inverse functional mapping into the parametric space. We have been developing a program to bring an integrative creative design and implementation experience to undergraduate engineering students who are novice to hand-on works. We found that most of them would be flunked, if their achievements were evaluated by merely the creativity, the engineering quality of their products, or their procedural compliance to that of a professional. Looking into the engineering journal of these rookies, it were the setback events and compromised results, instead of progresses and achievements, which overwhelmed the insight of worthy efforts and rendered individual exploration progresses indistinguishable. The journals were packed with setbacks, after setback turning points, compromises, abandonment, and restarts from scratch. Short of knowledge on implementation and practical experience, novice students were tangled by setbacks in both design and manufacturing. Moreover, their ideas were jumping, switching, and withdrawn, instead of going through rational and consistent design iterations from breadth to depth. However, analyzing the statistics of the design stages of the setback events, we can uncover the critical threads of the novice efforts. Going through data-driven research, we developed two procedures in Setback Event Based Evaluation to uncover material characteristics: 1. identify "characteristic modal pattern in the Setback Event Stage Count Histogram" and 2. identify existence of "Highly Linked Setback Event Sequence Patterns". These two features reflect "the depth of the exploration", "the versatility of the creativity", and "the quality and functionality of the final product a team had attempted to accomplish". The depth of exploration and the versatility and functionality of the final product attempted revealed critical quality differences among the team efforts, and, therefore, were the keys to enhance the discriminative power of the portfolio assessment. Analyzing the unique characteristics of the novice creativity realization process, we were able to identify pre-requisite knowledge deficiencies of the students at the four stages of realization, which should be the focus of scaffolding improvements in courses incorporating creativity product design and implementation.*

Index Terms *— setback event based analysis, SEBA, portfolio assessment, novice engineering student, creativity product realization, V-dot diagram, creative engineering design and implementation, CED, thinking model, functional mapping and inverse mapping.*

1. INTRODUCTION

1.1 Our Research Problem

"The students' final products were by no means professional, sometimes they may look even childish. However, they all went through the realization by their own motivation and they all experienced the process by heart. We, the teachers, can tell by intuition the differences among the teams: the amount of efforts, coordination among the team members, the extent of realization, and the devotion. However, we are unable to distinguish the students' individual growth through any quantitative measurements known to us, such as evaluating creativity products by multi-dimensional criteria, evaluating the performance of final oral presentation, or by question and answer. Especially, if we would grade according to the quality of their final products, we would have to flunk every one indiscriminatively. "

This was how the professors reflected on their five year experiences on teaching the project oriented course "Open Ended Creative Mechanical Engineering Design (CED)". It is almost impossible to find an undergraduate student who would follow the professional and logical design procedure which they had been taught to develop iteratively from breadth to depth in realizing their creativity products. On the contrary, their engineering journals were packed with setbacks, after setback turning points, compromises, abandonment, and restarts from scratch. They jumped and switched seemingly randomly among design stages. The final products were the results of intuitive trials and errors and were usually very big retreats from original creative ambitions.

Applying existing accomplishment measures to evaluate the performance of these students who were novice in creative engineering design and implementation does not provide relevant information to reflect the effectiveness of the course! To develop a meaningful evaluation on the progress of a novice student's ability on creativity product realization is our research problem. We would apply data-driven approach to discover the meaningfulness and value from collected data.

This was what we observed: The students usually took the CED course in their junior or senior year, they had already at least two years of mechanical engineering mandatory courses in mechanical drawing, mechanics, materials, manufacturing, electricity, and dynamic controls. They were also taught of creative thinking methods, mind mapping, engineering design in the beginning of the CED course. However, in CED projects, their behavior did not reflect the capabilities to apply those knowledge. Most teams demonstrated the following behavioral patterns:

1. While making project plans, the students often decided to stick with a concept or a topic at its occurrence, even if it might look childish.
2. Applying what they learned to do a priori organization, rational calculation and design before dimensioning and material selection is so mind bugling that students preferred to do right forth by instinct and, then, often have to restart all over later after inevitable failures.

Therefore, to evaluate novices' difficulties and efforts is far more important then their accomplishments and progresses. We need to analyze setback events in their journal files looking for appropriate aspects and concepts of analysis in order to reveal the learning path of the rookies. Then, we can uncover their capability deficiencies, behavioral characteristics, and bottle necks, so that we can gather feedback information for effective scaffolding improvements in the course.

1.2 Whom Would This Research Concern?

This research provides insights into the teaching and learning of engineering creativity design and implementation. For teachers of similar courses, they have to encounter students of no experience on design and they would commonly elude difficult obstacles and compromises their creativity ambitions. Through this research, we would understand the novices' shortcomings much better so that we would become much better mentors. For the students, this research would help them to get consciously aware of their own deficiencies and the teachers' objectives, so that they can adapt to a proper attitude and design methodology quicker and easier. To researchers on related topics, setback event analysis enables them to look and ponder deeper into the students thinking processes.

2. METHODS

Our research data were a portfolio of the project journal, reports, and project documentation made on the web through the V-dot diagram interface [1,2], competition records, comments on the course left by the students taking the CED course over several years, and comments by the teachers. We read through the records documented through the V-dot diagram interface back and forth in order to compare with the teachers' impression and comments on the characteristics of each team. Gradually, a research methodology emerged to process the learning records of setback events into appropriate tokens allowing us to interpret the team records in consistent with the teachers' impression. The following is the description of the background of our research data.

2.1 The Students

The research data were collected from all students taking the CED course. They majored in mechanical engineering. They were mostly at their junior year and some were at their senior year. Their education for their live were mostly theoretical and analytical. Most of them did not have design and implementation experiences at all. Therefore, they are called the "novices in creativity product realization".

2.2 The Course

The CED course is two semesters long. Prof. Hsiau has been in charge, and Prof. Tsai and Wu take cooperatively supporting roles. Prof. Chang, Pei-Feng of Teacher Education Center also helped to develop some classroom activities on creative problem solving. On the other hand, Prof. Chen monitors, analyzes, and interviews students for qualitative research for improvements. Prof. Yeh consults on mechatronic implementation issues.

In the first semester, concepts of creativity and design are introduced. Topics covered are engineering design process, designer and team work, creativity inspiration methods, creative competition, project team formation, selection of project topic, and the proposition of the course project plan. In the second semester, the course focuses on carrying out the team project and going through the process of creativity product design and implementation. The process includes marketing research and evaluation, data collection, product design, manufacturing, testing, and final report. The project plan and the engineering journal of each team were documented on the web through its member accounts on the V-dot diagram interface which provides a visual image of the framework of the creativity product realization to guide students through the creativity generation, design and implementation.

The "knowledge" and "design and implementation activity stages" are visually labeled along the two sides of the V-dot interface in their logical and causal sequence of the creativity product realization. It serves as a visual image to establish a shared mental model of the process among team members through out the project. By documenting the thoughts and activities through the V-dot diagram interface, team members also post the information on the web open to other team members within the team for sharing. Through these documentation, the teachers and the researches would obtain "truthful" and "complete" journal records which would reveal the team efforts, the knowledge and experiences gained, and the formation and evolution of the final product.

There are regular checkpoint dates set for the teams to present their progress and to receive inquiry and comments from all course mates and teachers. This is considered as a kind of scaffolding and feedback such that every team has to think through their ideas and concepts and be responsible for their implementation. In this course, students learn to apply their knowledge integratively and to experience hand-on design and implementation so that their flexibility, technological creativity and realization capability get enhanced.

2.3 Data Collection

The main body of the data was collected through the V-dot diagram interface. The original creative ideas are represented by the dot on top of the V shape. It will be taken through a sequence of knowledge driven methodological actions of creativity generation, design and implementation stages to evolve into the final product at the bottom tip of the V. Each action will in turn produce experiences and knowledge gained to be documented on the knowledge side of the V to inspire further actions and evolutions.

The team members are asked to document their engineering journal through the V-dot interface. Every team maintains one data set contributed by all its members. Every event to be documented is to be entered according to its nature − knowledge category or methodological action (design and implementation) stage. The event nature is categorized into 10 knowledge categories labeled along the left side of V and 11 action stages labeled on the methodology side to right of V. The 10 knowledge categories available along the V are "living experience", "theory / principles", "material properties", "manufacturing technology", "data sheet", "budget estimate and execution", "difficulties and solution", "team cooperation strategies and decisions", "self evaluation (product, team work, team members)", and "memorandum and advises to junior school mates regarding the CED course". The 11 action stages are "brain storming", "evaluate and selection of creative ideas", "task assignments / Gantt chart", "market survey", "patent survey", "related product disassembly / reverse engineering", "layout / prototype design", "consulting with experts (teacher, technical master, vender, senior school mate)", "product manufacturing (including manual writing)", "product testing (including report writing)", and "product presentation".

There were totally more than 20 teams in academic year 2001 and 2002. And the amount of documentation by each team ranged between ten to twenty thousand Chinese characters, which is enormous to be analyzed. Therefore, we selected 5 teams listed in table 1 for our pilot research. These five team projects serve as good representatives of all, since their characteristics features cover the combination of "pure mechanical v.s. mechatronic", "successful implementation v.s. failed attempt", "mockup bearing no significant loading v.s. producing physical performance", and "unprofessional trial and error v.s. professional design procedural compliant" as shown in table 1.

Sample Project ID	1. 2001-9	2. 2000-3	3. 2000-2	4. 2001-8	5. 2001-3
Project Title	baggage going upstairs	multi-directional monitor / speaker stand	remote bicycle lock	big tummy garbage tank	Solar power vented backpack

Creativity	slide along the stair railing	adjustable	to be used on bicycle	automatic garbage compression	blowing air on the back for ventilation
Critical Issues & Turning Points	moving mechanism	adjustable mechanism	electronic remote control	moving mechanism	support frame
Mechanical / Mechatronic	mechanical	mechanical	mechatronic	mechanical	mechatronic
Successful / Failure	prototype for concept demo	mock up for concept demo	failure	successful demo	successful demo
Physical Performance	no, test on empty baggage	no, did not test with actual weight	yes, moving lock shaft under spring load	yes, actual compression	yes, fan blowing air
Design Procedure				strictly compliant	

TABLE 1
THE FIVE REPRESENTATIVE TEAM PROJECTS

2.4 Data Analysis – Setback Event Based Analysis

Going through data collected under the 21 knowledge categories and action stages, we found the following clues to the insight of the novice creativity realization process:

1. **Encountering obstacles, novice tends to compromise or go around instead of research and conquer like an expert.** There appeared unusual amount of loop back iterations in the novice's records, which smudged the design logics. For example, novices rarely discussed nor made calculations on the specifications of materials or components before their acquisition. Materials and components were most often come across and picked up by intuition while novices wondered through warehouse stores, hardware markets, and large sale markets. Therefore, the creativity and product realization often changed direction by the availability of materials and components.
2. **The engineering journal records did seem to reveal the dimensions and the depth of the team efforts.** Each team encountered different difficulties at each setback event, turning point, or compromise. Their reaction and the extent of documentation reflected the dimensions, the aspects, and the amount and the depth of endeavor a team had put their efforts into. Therefore, one can expect significant maturity of the team in the direction of their focuses. For example, some teams put down significant records on the experiences of material and component selection, while some teams recorded detailed stories on manufacturing or performance testing. Is there a systematic approach to reveal the characteristics of their individual portfolio records to show the facets in which they had gained significant progress regardless the quality of their final product?
3. **Reconstruction of behavioral track is necessary.** The documentation of events was made by the students on the web through the category items labeled on the V-dot diagram. Therefore, one data entry might have been a story covering a sequence of actions over many different methodological stages generating knowledge of many different categories. Moreover, the students might not have documented every event worthy of mentioning. We had to rely on the teachers and the teaching assistants who were aware of the team history to organize the sequence of the recorded events and to supplement missing links in order to recover the zigzag paths of the episodes of engineering or educational significance. Afterwards, we also had to double check with the original team members on the fidelity of the reconstruction. We also ask for their supplement on the key points and issues regarding critical events from their point of view.

These insights told the differences between the stories of the teams. The thinking and the methodology of the assessment to be developed must be sensitive to and be able to capture these insight features. Therefore, we adopted the following guidelines and steps of the Setback Event Based Analysis (SEBA) in analyzing the portfolio records:

1. Identify setback events from the journal records.
2. Identify the design stages the setback events belong to.
3. From the statistics and the sequencing of the design stages related to the setback events and their aftermath, we identify the characteristics and the facets of individual team efforts.

2.5 Limitations

In order to encourage students making complete and detailed documentation on the generation of ideas, solution plans, and actions through V-dot diagram web interface, we did portion course grades on the amount and significance of the records they logged. However, because of the computer and network may not be available to the students at every occasion and location and the laziness on making up logs afterwards, the journal files cannot be complete. Moreover, writing styles were inconsistent, some teams may be thorough and others quite concise and even brief. Some team might even have dedicated member for the documentation, who tended to beautify the records for extra credits instead of clinging to technical significance. These phenomena rendered the importance of extra verification and clue tracking research works beyond computer records to recover and interpret the truth and the whole truth properly.

V-dot diagram interface does impose restrictions on reporting style. Moreover, it does add layers of menu over the documentation data keeping the records from review all at a glance. Students do have to make regular recordings faithfully and to rely on the system to generate final report without a direct sense of growth in the middle. Therefore, before the V-dot diagram became available, the engineering reports authored by the students as web pages did seem more enthusiastic. To enhance students' sense of purpose in regular documentation, it seems warranted to add a good total report generation mechanism behind the V-dot diagram interface.

3. RESULTS – THE METHODOLOGY OF SETBACK EVENT BASED ANALYSIS

3.1 The Statistics of Setback Event Stages

Obtaining the statistics of setback event stages, we identified setback events, turning points, and compromises from the details in the portfolio records. By data driven categorization, we classified these events into 10 design stages according to their nature in design and implementation as shown in Table 2 which is a partial example. We also supplemented the setback event lists with their direct causal stage and the implied "testing and verification" stage.

The statistics of the counting of the setback events' corresponding design stages collected over the five representative sample projects is shown in Table 3 and 4. Table 3 compares the histograms of setback event stage counts of individual teams revealing the dimensions and characteristics of their individual efforts. Table 4 shows the gross total over all five teams revealing the tendencies of the novices at large. Table 4.b shows the histogram of setback event stages count according to four coarse design knowledge categories to reveal macroscopic characteristics. Characteristic modal patterns of the histograms are marked by different colors and will be discussed in the "Discussion" section.

Corresponding Design Stages	Setback Events and Their Resolution Actions As Found in the Portfolio Records
"material" "budget" "concept formulation"	We designed (figured out) a set of modular supporting frame to affix rollers onto the side all of the baggage while clinging onto the railing of any regular stair. Originally we were to us a clamp. We abandoned the idea because we could not find a suitable one on the market and , moreover, we could not find appropriate material to make for ourselves. Making the parts ourselves would mean expensive new mold or die.
"manufacturing" "tolerance" "concept formulation"	Affixing the supporting frame to the baggage we needed to mark the correct location to drill screw holes, since the holes on the baggage located by metrology usual do not match that of the holes on acrylic plate of the supporting frame. We needed to enlarge the holes to allow fastening screws to go through to hold frame and baggage together.
"testing", "analysis", "concept formation", "material/component", "manufacturing"	Increasing the adaptability to the stair, we added a pair of roller on the side. We tried to adjust the location of the rollers, however, it was not easy to keep the lateral balance and we decided to add a horizontal iron bar at the end of the supporting frame.
"manufacturing", "budget", "team work", "concept formulation", "material"	We realized that, since we over idealized about the implementation, we overlooked practical problems on manufacturing, and budget. We did start to leave time for every team member to raise their concerns and we went through the discussion for solutions one by one. This way we all developed common understanding on the new design so that we worked together for higher design efficiency instead of personal show of the few. This experience told us that "the best plan still needs adjustments facing up realities", "even a flash of idea should be documented and followed up with actions, it could just be a better selection." Of cause, we were not barking at every tree. We did carry out serious analysis and reviews before taking on any turn. However, some materials were hard to acquire …

TABLE 2
DESIGN STAGE DESIGNATION OF SETBACK EVENTS AND THEIR RESOLUTION ACTIONS

Project └————┐ Setback stage	1. baggage going upstairs	2. multi-direction monitor / speaker stand	3. remote bicycle lock	4. big tummy garbage tank	5. solar power vented backpack	total
concept formation	4====	4====	5=====	5=====	4====	22
material / component	6=======	6======	5=====	7=======	7=======	31
analysis / calculation	1=	0	1=	9=========	12============	23
spec selection	1=	2==	1=	8========	13=============	25
tolerance	2==	0	1=	7=======	0	10
manufacturing	5=====	2==	5=====	7=======	5=====	24
fitting / assembly	2==	1=	2==	5=====	0	10
testing / verification	0	0	0	1=	8=======	9

budget	3===	0	2==	1=	2==	8
team work	1=	0	2==	1=	0	4
total	25	15	24	51	51	166

TABLE 3
HISTOGRAM OF SETBACK EVENT STAGE COUNT BY INDIVIDUAL PROJECT

a. setback event frequency histogram by design and implementation stages			
setback stage	counts	portion %	Ranking
concept formation	22	13=============	5
material / component	31	19==================	1
analysis / calculation	23	14==============	4
spec selection	25	15===============	2
tolerance	10	06======	6
manufacturing	24	15===============	2
fitting / assembly	10	06======	6
testing / verification	9	05=====	8
budget	8	05=====	8
team work	4	02==	10
total	166	100	

b. setback event frequency histogram by implementation knowledge categories	
knowledge category	portion %
conceptual design	34==============
Layout	35==============
Implementation: manufacturing, assembly, calibration testing	26==========
Administration, coordination	07===
Total	100

TABLE 4
HISTOGRAM OF SETBACK EVENT STAGE COUNT OVER ALL FIVE REPRESENTATIVE SAMPLE PROJECTS

3.2 Highly Correlated Setback Event Sequences

Looking into the design stage sequence in the setback events, we could uncover the causal factors of setback events and the nature of the novice reactions. We discovered four high frequency sequence patterns revealing common reasons for the difficulties encountered by the novices in creativity product realization. These highly correlated / linked setback event sequences and their interpretation were

1. {“testing/verification”, “analysis/calculation”, “spec selection” } − Our junior and senior year students were still novice in hand on design and implementation experiences. They were not familiar with professional design process. They simply did not believe in the process to do analysis and calculation first before material selection, manufacturing and assembly accordingly. They would rather make purchase and put together by intuition. Therefore, setbacks were inevitable. When there were many material property parameters interacting to influence the performance and functionality of the product, intuitive twigging for one acceptable solution was not obvious at all. The novices were forced back to do analysis and calculation rationally like professionals.
2. {“material/component”, “concept formation”} − Students were also novice to market availability and they did not get much sense in referring to product catalog and product data sheet. Many teams mentioned that wondering through large sale warehouse and hardware stores was the most inspiring experiences.
3. {“material/component”, “analysis/calculation”, “spec selection”} − This is a compound of sequence patterns 1 and 2, which revealed further insight of the novices. In addition to market availability, the novices avoided quantitative analysis on their conceptual design. Moreover, most of the student could not do calculation on admissible sets to define an acceptable range of the material or component properties. They also could not do variational analysis to prioritize selection criteria. Therefore, they ended up with very narrow target of selection and no alternative plans.
4. {“manufacturing”, “fitting”, “tolerance”} − Similar to sequence pattern 3, nothing real is fixed in number. Novices did not think through the tolerance planning in layout process and the clearance control in manufacturing. On site fitting and adjustment were always difficulties causing setbacks.

Note that

1. “Material/component” stage represents the selection of the kind, the type, or the model without the consideration of it property specifications. The former may interact with the conceptual formation inspiring new structural construct for the creativity product, while the latter should be the results of analysis and calculation on a given structure.

2. There were only functional “testing” stages described in the portfolio records. There should have been processes of zero adjustment, calibration, and performance testing for verification and acceptance. The novices simply were not able to reach those final (advanced) stages.
3. There were many other logically possible linked sequences such as {“testing/verification”, “concept formation”} and {“testing/verification”, “material/component”}. However, they were rather rare in our portfolio.

4. DISCUSSIONS

Setback event analysis generated quantitative data revealing the most significant insight into the novice setbacks through the creativity product realization process. We compared the differences between the team projects to come up with seven characteristic model patterns in the histogram of the setback event stage count. Interpreting the meaning of these model patterns we identified the deficiencies in the prerequisite knowledge for creativity product realization. This teaching knowledge would serve as the clue to improve scaffolding in course incorporating design and implementation.

4.1 Differences between Projects – Characteristic Model Patterns in the Setback Event Stage Histogram

Referring to Table 3 and 4, we compared the differences among the histograms of individual team projects with the commonality and differentiations in their properties as listed in Table 1. We discovered eight aspects to assess the depth a team had explored in realizing their “creativity features” and “physical functionalities” of their product. We will discuss them from the simpler to the more complicated ones.

1. The counts (green) at the “budget” stage were low. The “budget” of one to two thousand NTC dollars on the average and a soft budget limit guideline in the course did not impose mental hindrance on their creativity realization. In project 1, 3, and 5, the teams had to purchase market commodities for modification, thus, they tended to run over the budget guideline.
2. All projects had very low counts (bright green) at the “team work” stage. This was even true for project team 3 which, as we knew in fact, segregated into disassociated mechanical and electrical portions without coordination. Their project failed to turn out a demonstrable product. Under segregation, when one member failed to conquer his obstacles, no other team member came to help. The situation caused the missing of critical parts to come together at the last moment. Even so, the situations were not frankly reflected. A mere extra count did not reflect the seriousness of the situation. Therefore, the teachers need to query team members on detailed considerations in their concept, design and implementation during project benchmark presentations. The appearance of one or two counts warrants special attention to look into.
3. All projects had high counts (rose) at the “concept formation” stage, indicating the number of creativity divergence, turns and compromises. An evaluator should also look into the causality sequence of such events whether they were active divergence and inspirations or reactionary turns and compromises after other setbacks. If they were the latter cases, the counts would have come from the linked sequence pattern {“material/component”, “concept formation”}.
4. All projects had high counts (pink) at the “material/component” stage, as the result of short of knowledge in all students on market availabilities. Moreover, the creativity of project 4 and 5 involved the most versatility and, therefore, the highest counts versus those of other projects.
5. Other than project 2, all team had high counts (brown) at the “manufacturing” stage. Project team 2 demonstrated a rough concept model which did not bear any actual physical load. Therefore, they chose acrylic plates as their material. Machining acrylic plates for rough tolerance was by no means difficult. While other teams, having to produce load bearing or physical effect capability, have to choose matelic materials, electrical or more sophisticated components. Difficulties in manufacturing increased.
6. Project 2 and 5 did not have counts in “tolerance” and “fitting/assembly” (blue) because they did not have moving mechanism. Project 1, 3, and especially 4 did have moving mechanism but also sustain heavy loads to compress garbage. The mechanism needed to maintain proper clearance under deformation. Therefore, tolerance planning was critical before implementation. Such project needed to follow professional design and implementation procedure strictly to avoid destined failure. “Tolerance” planning should have been critical to all projects going through “acceptance” testing of mass production even if it was essentially electrical like project 5. Only through “tolerance” planning, one could optimize both ensemble and temporal variations due to environmental changes in temperature, pressure, moisture, etc. Since our course asked for one single realization without mandatory acceptance testing, project 5 did not encounter the challenge of “fitting/assembly” and avoided setbacks caused by negligence in “tolerance” planning.
7. Project 4 and 5 had significant occurrences of the linked setback event sequence pattern {“material/component”, “analysis/calculation”, “spec selection”} as indicated by high counts in all “material/component” (pink), “analysis/calculation”, and “spec selection” stages (red). These two teams attempted products to bear heavy load and to produce enough airflow for effective cooling. Going beyond mere concept demo for physical effectiveness, the

implementations were put to physical tests and the teams, after any instinctive intuitive put together failures, were forced to go back to the drawing board for quantitative analysis for well defined specification. Going through repetitive lessons of setbacks, these teams did mature to commit to professional design procedure much more willingly than other teams as indicated by much higher counts at both “analysis/calculation”, and “spec selection” stages than the “material/component” stage.

8. Project 5 had unusual high count at the “testing/verification” stage (gold) and the highest counts at “analysis/calculation”, and “spec selection” stages (red) because its implementation was essential electrical. Properties and capacities of electrical and electronic components cannot be estimated visually, they had to be put under testing and measured by instruments. An electrical product could be put together successfully only after quantitative design. A team had to realize and became capable of such exercises to finish such a project. Project 3 also had critical electrical component. However, the team member responsible for the electrical work did not possess nor develop the capability to test, to measure, to analyze and to calculate for a quantitative design and implementation. They did not have the counts to reflect the endeavors they should have taken. No wonder they failed.

For a mechanical implementation, “testing/verification” was often embedded in “manufacturing” and “assembly”, since the effectiveness was very much visually and sensually obvious. Lack of effectiveness was often reflected as setbacks at manufacturing or assembly instead of explicit formal “testing/verification”. Even project team 4, supposedly abiding by the professional design procedure, did not have regular quantitative “testing/verification” events recorded in their portfolio file.

Assuming that setbacks are inevitable to novices, the harder the novices attempted, the more setback events would be documented. The more setbacks the novices had encountered, the more they would experience and grow out of, and the more they had learned and progressed. Therefore, the setback event based evaluation from the eight aspects described above fell in-line with the teachers’ intuitive comments on the teams.

4.2 Pre-requisite Knowledge Deficiency of the Novice Students in Creativity Product Realization − Identifying The Focus of Future Course Improvements

In order to derive focuses and strategies to improve the teaching of the course, we generated the histogram of setback event stage counts of all five teams in table 4.a. It was obvious that novices got bogged down at the early stages. In order to have a better macroscopic view we consolidated the detailed design stages into four big sections, like a professional design house, “conceptual design”, “layout”, “implementation”, and “administration”. The macroscopic histogram is shown in table 4.b. Turn out that the novices simply did not have a sense of direction through out the process. The biggest maturity they got out of the course was that sense of direction. Therefore, we looked into and tried to describe the thinking process at each macroscopic design stage explicitly to bring out their conscious awareness early so that the novices would have a clear model to follow.

1. **Key prerequisite knowledge at the “conceptual design” stage** − Know what “materials and components” are available, what kind of functional characteristics various structural system architecture would accomplish, so that one can do structural design.

The thinking process of novices after setbacks (the reversal − right to left) which forces them to retract the logical design procedure (left to right) which should have been followed through:

change of creativity, compromise in functionality and features, go around obstacles for easier degraded target	←	change of design concepts, revise sketch drawing or schematic drawing	←	restriction of availability, manufacturability, utility of materials and components on the open market (according to the vender experts’ opinions)		
	→		→	mechanical drawing (make up after setback)	→	layout, material and component list, budget

FIGURE 1
THE THINKING PROCESS OF NOVICES AFTER SETBACK EVENTS AT THE “MATERIAL/COMPONENT” STAGE

2. **Key prerequisite knowledge at the “layout design” stage** − Layout is the “quantitative design” covering analysis, calculation, defining performance target, tolerance planning, and materials / components specifications. The thinking process at this stage is actually divided into two stages: “analysis / calculation” − a functional mapping process and “parametric design and specification” an inverse mapping process.

- **"Analysis / calculation" is to derive a functional mapping** by analysis, formulation, solving for functional relationship between system variables and structural and material parameters, and the calculation of performance measures. This is the same as solving typical text book problems for the following results:
  $\boldsymbol{y} = \boldsymbol{f}\,(\,\boldsymbol{x}\,;\,\{\boldsymbol{z}\}\,)\,,\ \boldsymbol{J} = \boldsymbol{g}\,(\,\boldsymbol{y}\,)\,,$ (1)
  where the functional format of $\boldsymbol{f}$ is determined by the system structure; vector **y** represents system variables; vector $\boldsymbol{x}$ represents input variables such as driving forces; vector $\boldsymbol{z}$ represents the parameters of function $\boldsymbol{f}$ such as environmental conditions, material properties, structural and dimensional parameters; $\boldsymbol{J}$ represents performance measures calculated from system variables $\boldsymbol{g}$ by functional $\boldsymbol{g}$.

conceptual sketch drawing	→	schematic diagram describing all key functional properties of the design	→	algebraic analysis	physical laws and compatibility equations + material and component characteristic property equations	→	symbolic algebra: solving equations for state variables as functions of material property parameters	→	deriving from the solution of state variables:	expected performance measure material and component endurance rating

FIGURE 2
THE THINKING PROCESS OF ANALYSIS AND CALCULATION – DERIVING A FUNCTIONAL MAPPING

- **"Parametric design and specification" is to derive an inverse mapping** from design criteria to get material and component specifications and even to go back to the conceptual design to alter concept structures. The inverse mapping may have too big a range. One has to look for additional design criteria or proper performance measures to carry out optimization. If the solution space is too small, one has to prioritize design criteria and performance measures for trade offs. This process is not explicitly discussed nor practiced in regular textbooks. People generally take this process as the application of theories and the results of analysis. However, there is indeed a big threshold for novices to realize the flow of thinking in design is in the reverse direction contrary to what they have been taught. They have become consciously aware before they can start to mimic.

There are two types of design problems, the control or input design versus the dimensioning and material design for dimensional parameters and material properties. Their functional description follows:

control / input design: $\boldsymbol{x} = \boldsymbol{inv\_f_x}\,(\,\boldsymbol{y}(\boldsymbol{0})\mid \boldsymbol{J}{=}\boldsymbol{J_0}\,;\,\{\boldsymbol{z}\}\,)\,,$ (2)

dimensioning and material design: $\boldsymbol{z} = \boldsymbol{inv\_f_z}\,(\,\boldsymbol{x}\mid \boldsymbol{J}{=}\boldsymbol{J_0}\,,\boldsymbol{z}{=}\boldsymbol{z_0}\,)\,,$ (3)

where $\boldsymbol{inv\_f_x}$ represents the inverse mapping into the control/input space; $\boldsymbol{inv\_f_z}$ represents an inverse mapping into the parameter space; $\boldsymbol{y}(\boldsymbol{0})$ represents the initial value of $\boldsymbol{y}$; and $\boldsymbol{J_0}$, $\boldsymbol{z_0}$ represents the admissible range of $\boldsymbol{J}$ and $\boldsymbol{z}$ respectively.

←	If there is no solution to be found, one needs to go back to conceptual design to look for structural creativity, thus, altering the functional format of the equations.	←	[[[check for market availability]		record, examine, explore the necessary conditions allowing the performance requirements be met, investigate the logical sequences to prioritize the design requirements and performance measures		define the acceptable range of the performance measure
			↑ ↓		↓		
	clean up, inventory checking, documentation	←	define obtainable range of the material property parameters and endurance ratings]	→ ←	establish the system of equations to do inverse mapping into the parameter space to solve for acceptable parameter ranges (Unique solution is usually very rare.)	←	

↑ ↓ ↑ ↓

adjust manufacturing, assembly, fitting, calibration procedure and conditions]

contemplating on the priority of trade offs

└ — — → — — — — — — — — — — → material and component endurance rating

FIGURE 3
THE THINKING PROCESS OF LAYOUT DESIGN – AN INVERSE MAPPING PROCESS

Failing to follow through the forward and inverse thinking processes, the novices turned “research and development R&D” into miserable “repeat and debug r&d”. Overcoming the trap takes mind-boggling cognition of the inverse mapping process.

3. **“Implementation” covers manufacturing, assembly, calibration and testing**. Manufacturing alone requires the integrative knowledge of the full mechatronics and control program.

Tooling / actuator → preparation → physical / chemical machining → sensing / measurement → accuracy and precision monitoring

↑ ↑ ↓ ↓

↑ real time feedback controls ← — — ┘ ↓

└ — — — — — environmental control ← — — — — — --— — — —┘

FIGURE 4
THE THINKING PROCESS OF MANUFACTURING

Moreover, in the school, we do not seem to put much emphasis in calibration, testing, and verification for an industrial grade product quality acceptance. Therefore, students went through the CED course without much setback experiences at the tailing stages. They still did not get ready to fulfill the industrial work requirements yet. Therefore, we need to keep the full macroscopic view of the Creativity Product Design and Implementation to check for scaffolding improvements in any CED flavored course.

creative ideas → conceptual design → layout → manufacturing → assembly calibration → testing → acceptance certification

↑ ↑ ↑ ↑ ↓

creativity in depth ← verification of theoretical understanding ← tool invention ← clearance control ← ┘

FIGURE 5
MACROSCOPIC THINKING MODEL OF CREATIVITY PRODUCT DESIGN AND IMPLEMENTATION

4. “Administrative capability” requires the bring up of a personality so that setback experiences can be overcome and cumulated – honesty, bravery, self reflection, self recognition, self motivation, discipline; visionary, daring, resource planning; ability to capture the essence of values, to narrate, to clarify, to discuss, to persuade, to perceive the macroscopic point of view for strategic planning. In summary, we need to setup a philosophical foundation in our youngsters [3].

We attempted to enlist the novices deficiencies explicitly above to serve as a check list for students to do self examination. We also depicted the prerequisite thinking processes visually for easy cognition and awareness. We hope that the threshold for novices to evolve into professionals can, therefore, be lowered.

5. CONCLUSIONS

Conventionally, “creativity product design and implementation” is graded by creativity at every stage and the functionality and quality of the final product. Iterative efforts due to mistakes or procedural incompliance get not only no credits but also demerits. After all, novices are not fluent with, do not believe in, and do not abide by formal design procedures. Therefore, conventional evaluation has rather poor discriminative power. However, without enough prerequisite knowledge nor experiences, novices do have their survival instinct to negotiate a compromised path to reach for a final product. By changing the aspect of evaluation, we value how much the novices had benefited from the process instead of how much had they accomplished and been compliant. We developed the methodology of setback event based analysis SEBA to be encouraging and pro growth. We used the “histogram of setback event stage counts” and the “highly linked setback event stage sequence pattern” to reveal the “versatility and functionality of their product attempted” and the “depth of exploration into the realization process”. Therefore we were able to detect the level of novices’ self expectation and the extent of their commitment of efforts with enhanced discriminative power.

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