Introducing the Design Process to Beginners: The Spiral Model

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Abstract

This paper describes the extension of the typical sequential design process to a "spiral" process, where the design activities are repeated, producing outcomes that have increasing levels of detail. It is especially useful for beginning students of design, since they gain repetitive experience with the design activities in the same project. The approach also facilitates a quick start for a project, by encouraging a first pass through the design activities with modest skill levels and producing partial outcomes, which helps direct what needs to be improved for the next pass. The approach is useful in systems projects, with many interacting elements, since it accommodates developing system descriptions at increasing levels of detail. The approach is described in terms of vehicle design projects such as solarcars for Sunrayce events, Formula SAE vehicles and SAE Mini Baha vehicles, and is illustrated with a start-up pass through the design activities for a solarcar.

Introduction

This paper describes a useful perspective on the generic product Design Process as taught to undergraduate engineering students with no prior design experience. The work was motivated from past experience with groups of undergraduates who were involved with vehicle related design projects at the University of Minnesota. Since 1992, the lead author has been advisor to thirteen teams of students who created vehicles for Sunrayce solarcar events, Formula SAE events, and the SAE Mini-Baha events. As these projects provide the setting for this paper, they will be briefly described.

Sunrayce events are biennial cross-country races where collegiate teams compete in solar-electric vehicles that they design and build. In the past, rules have limited the battery and photovoltaic cell technologies, but are now relaxed for the 2001 event, which is renamed as the American Solar Challenge (ASC) and will run "Route 66" from Chicago, IL, to Los Angeles, CA, in June 2001. The 1999 event ran from Washington, D.C., to Orlando, FL, and had 49 entrants, of which 29 qualified for the event by passing an extensive technical inspection and running a specified number of laps above a minimum speed on a closed course prior to the event.

Formula SAE refers to an annual competition where teams design and build a single seat, open wheeled racecar, with a four cycle motor having a maximum displacement of 610 cc, an intake restrictor of 20 mm diam., and stringent driver protection requirements. Vehicles are judged in static events, including a "design competition" where experienced race engineers inspect the vehicles and interview the students to assess their knowledge of vehicle technology and the use of a design process. There are also dynamic events including acceleration over 100 yards, skid pad to determine maximum lateral g's, an autocross, where individual vehicles negotiate a course outlined in pylons, and an endurance event where groups of seven vehicles run together on an autocross course with controlled passing. There were over 100 entries for the year 2000 event, held in Pontiac, MI.

The SAE Mini-Baha competition is an annual event where student teams design and build four-wheeled off-road vehicles using a 10 H.P. motor provided by Briggs and Stratton and compete in static and dynamic events. There are usually three annual events, East, Midwest, West, each posing specific challenges, but, the basic vehicles are similar and all have stringent driver protection requirements. Dynamic events include acceleration, maneuverability, skid pull and hill climb, topped off with a four hour wheel-to-wheel endurance race where 60-70 vehicles are unleashed together on a moto-cross course having many turns, hills, bumps, and muddy sections. Typically about one third of the entries are running after four hours.

Creating a vehicle for any of these competitions is a hands-on experience with the complete product development process, from a "blank sheet of paper" (computer screen) to an operating system of diverse, integrated technologies.

The participants in the solar vehicle project are freshmen through seniors from various engineering disciplines including Mechanical, Electrical, Aeronautical and Chemical, with additional students from Math, Physics, Computer Science and a few from the College of Liberal Arts. The SAE projects are mostly Mechanical Engineering majors, freshmen through seniors. Participants are highly motivated, with a can-learn, can-do attitude, and have a variety of skills from prior experiences. Most are interested in vehicles or specific vehicle-related technologies. However, they also have little or no experience in (1) working on a technical team, (2) recognizing and understanding the importance of system interactions, (3) defining and scheduling tasks and (4) following any Design Process.

The scope of the projects also presents challenges to the delivery of the academic experience. Most projects have been extra-curricular activities, supported by experimental courses on vehicle dynamics and design, numerous independent study projects, and some Senior Design projects in the capstone courses in Mechanical and Electrical Engineering. The Solar Vehicle Project extends over nearly two years, and begins with a semester long no-credit weekly seminar with homework exercises and visiting speakers, some of whom are project alumni who help initiate the technology transfer process. The Formula SAE project has been on a yearly cycle, but this was only possible since the "core group" remained the same for three years, allowing their third vehicle to be created and tested as Senior Design and Experimental Senior Lab courses, due to their familiarity with the domain, and demonstrated dedication. It is now on a two-year cycle. Mini-Baha vehicles have been designed and constructed as a two quarter Senior Design activity and also as a yearlong extra-curricular activity with freshmen through junior students. The projects have weekly meetings, start-up workshops where the Design Process is emphasized, and periodic design reviews, attended by some alumni.

The scope of the projects challenge the timing of our delivery system. Presuming that a new Formula SAE and Solar Vehicle will be constructed every two years, and will be an expression of the design ideas of Seniors, then initial design activities must occur in their junior year, which requires design skills prior to their usual introduction in the curriculum.

As a design domain, vehicle projects are attractive to many students, and introduce Systems Engineering challenges. Most students have informal knowledge of vehicles, interpreted broadly, based on their experience with bicycles, wagons, scooters, motorcycles, push carts, wheelchairs, golf carts, garden tractors, automobiles, trucks and also with scale models of varying degrees of complexity. Some have hands-on skills, based on upon take-apart and repair activities, but few have connected their experience to topics in their courses. These past hands-on activities focus upon the "how" questions (How does it work? How can it be fixed?) rather than the engineering design related "What and Why" questions (What is the function of this? Why this configuration with these dimensions and this material?) Still, this informal knowledge is a useful starting point and a strong motivator when the advisor shows how some principles and methods of students' coursework apply to selected design decisions.

Another attraction is that vehicles utilize a broad array of technologies and thus offer opportunities to students with interests in internal combustion engines, electric motors, electronics and controls, aerodynamics, suspension design, electro-chemical processes, composite materials, vehicle dynamics, structures, various manufacturing methods and project management.

The broad array of technologies also provides a setting for introducing the System Engineering concept of interactions among design decisions across disciplines. For students who are deeply involved in studying their technology of choice, and are beginning to understand the design decisions associated with that technology, it can be a discomforting eye-opener to realize that certain options may be constrained by system-wide criteria, and that some of their options may limit the design choices of others. For example, many solarcars are three-wheelers, and for stability reasons, the vehicle center of gravity (CG) should be located to equalize the weight at each wheel [1]. The two heaviest components are the battery pack and the driver. The system voltage, which at first appears to be "an electrical team decision," will affect the CG location in at least two ways. One is through the number and weight of batteries which then must be located in the chassis, and another is through the number and layout of separate solar array panels on the top surface of the vehicle. As some provision must be made for the driver to see out of the top surface, the array options are limited. Also, aerodynamic concerns favor certain shapes to accommodate driver vision. Since the vehicles are usually quite thin, with the driver in reclining position, locating the driver's head for vision will locate the driver, and the subsequent influence on the CG. Thus, choosing system voltage will influence the options available for the solar array, the body shape and chassis layout.

System interactions can be used to underscore the need for communication. Students who have not participated on a design <u>team</u> generally do not appreciate the need for communication, especially if they have prior experience with building models, with take-apart and repair activities or with CAD projects, where things were accomplished <u>individually</u>. Since the vehicle is a <u>system</u> of interacting components and each student will assume responsibility for the creation of selected components, it becomes very clear that individual efforts must be interconnected just as the components. An individual's activities must be described to other team members and vice-versa, which means tasks must be defined, due dates estimated, and combined to produce a coordinated schedule. It also means that progress must be reported.

Typical Product Design Process

This section describes the version of the typical product design process that is presented to students in our vehicle projects. It is similar to processes described in a broad range of literature over the past 25 years, and has withstood the test of time. [2, 3, 4, 5] Figure 1 shows the process as a sequence of activities. Some versions in the literature have a different number of activities, but these are adequate for the vehicle projects, with one exception. Some versions begin with an "accept" or "commitment" activity where a potential participant determines whether or not he or she has the time, ability, and energy to dedicate to an intense learning activity that will involve new knowledge, new skills and delivering results on time. In a required design course, students "commit" to a project, but usually only to a certain number of hours per week, defining a scope that is consistent with activities in other courses. Some of the students may be interested in design activities and really delve into a project, but most find a path that requires about the same level of involvement as other courses. The word "commit" in a required design course means showing up, following the process, and obtaining a grade. Rarely are products delivered that have hundreds of components and must operate as a system. In the vehicle projects, there is a real external deadline: an operating vehicle must be presented on a certain date, to be inspected by people who are not affiliated with the school, and it must run the qualifying event. In Sunrayce 1999, 49 teams showed up and 29 passed technical inspection and qualified. The others went home. There were no excuses, no notes from the doctor, no "Incompletes". This requires participants to commit to a learning process where they will gain domain knowledge and skills and to a hands-on design and build process where a product will be delivered by a deadline. As the projects are largely extra-curricular, the degree of commitment is easily demonstrated to peers as showing up, defining appropriate tasks and completing them on schedule. The next section will present an extension of the design process that provides a multitude of opportunities for participants to demonstrate their commitment.

The following describes some aspects of the Figure 1 Design Process that are emphasized to the neophyte vehicle designers in order to underscore the utility of the process.

* The Design Process partitions the overwhelming task of "Design a Vehicle" into a sequence of smaller <u>activities</u>, each depicted as a box and each described by a <u>verb</u>. That is, something <u>to do</u>.
* Each activity has an <u>outcome</u>, that signals when it is completed, and the general <u>form</u> of each outcome is shown.
* Following the process transforms a need, expressed in words, to a physical product that can meet the need. The implication is that the activities unfold in <u>time</u>, so a <u>schedule</u> with due dates for the various outcomes is expected as part of the process.
* The process provides a <u>vocabulary</u> to say what is being done ("I'm defining specs") and the outcomes provide means of reporting progress ("Here's my list of specs").
* The process is generic, and applies to the entire vehicle and to each component.

While the latter is true, it is not clear to beginners how the act of decomposing a systems design into smaller chunks fits into the process. The extension in the next section will show how the need for decomposition is recognized and accommodated.

The activities and outcomes of Figure 1 are sufficient for an introduction, but beginning vehicle designers need more detail to get started. Figures 2 and 3 are from a handout that shows the same activities with lists of <u>skills</u> and more detailed <u>outcomes</u> associated with each activity. The lists are not exhaustive, but representative of things relevant to vehicle projects, and readers are encouraged to develop their own. There are also implied skills dealing with ability to produce outcomes. The lists of skills and outcomes are useful for beginning student for many reasons.

The lists breakdown the general activities into smaller pieces that can be used to identify "what to do now".

The lists can be customized with vocabulary of a specific system or component, encouraging students to learn the terminology and methods of the domain.

The lists show the breadth of design activity, and underscore that to be good at this will take more than one course or one project. The skills also show why a team is needed: not everyone needs to know how to do everything, but everything has to be covered by someone!

The lists put the rest of the curriculum in perspective, relative to design activities. Most of the courses deal with introducing physical processes and analysis methods that are relevant for the design activity of Evaluating Concepts.

The lists help separate "domain know-how" from "design know-how". The ability to use a CAD system to detail a promising concept does not imply skill in choosing one concept over another.

For students with prior "domain know-how", the lists show where and how that experience is useful, which can contribute to an individual's decision to commit to the project. On the other hand, the lists also suggest that members with such experience should not be viewed as authorities of "design know-how".

All descriptions of the Design Process acknowledge the presence of feedback where it is discovered that an outcome is deficient and it is necessary to go back and re-examine one or more activities. For example, during the "Detail the Design" activity, students may find that the selected concept cannot be made to work as expected, and must be modified in ways that cause it to violate certain specifications. Feedback would then refer to revisiting the Concept Evaluation and Selection activity, or perhaps further back to create more concepts or revise the specifications. It is generally accepted that feedback among the first few activities incurs the least costs of time and resources, but from the later activities is much more costly. The implication is that when the process is done "correctly", it is done in a single pass: All needs are identified, all specifications are stated, all alternative concepts are generated, a thorough evaluation and selection occurs with one alternative being clearly the best, etc. This may be a goal for experienced designers in a familiar domain, but for beginners with much enthusiasm but with no Design Process experience and little knowledge of the vehicle domain, a single pass through the process is unrealistic. We know that no one learns by doing anything once, especially if it's a series of process steps as opposed to an analysis method. Rather, repetition is needed.

Suppose we step back and reflect upon what is being asked of beginning students as they encounter the Design Process. They are to develop know-how and skills in the technical domain and know-how and skills in applying the Design Process steps. In the vehicle projects, students volunteer to join so they are poised to benefit from the natural learning process that we are all equipped to do: learn from experience. Taking a group of beginners through a single pass of the process does not capitalize upon the natural learning by experience process.

The Design Process as a Spiral

This section presents a variation on the product Design Process that provides multiple passes through the process with the same product, thereby providing repetitive learning opportunities in the product domain and with the process activities. Figure 4 shows the "Spiral Model" where each of the six axes corresponds to a Design Process <u>activity</u>, and the scale on each axis refers to the level of detail of the corresponding <u>outcomes</u>. The figure is handed out to the students and used to narrate the repetitive learning process. If we regard the lists of outcomes of Figures 2 and 3 as having a range from "few or partial" outcomes to "complete", then we can imagine overlaying that range upon the axis, where the highest level of detail of an outcome would be when it is "complete". The ability to move outward requires the <u>skills</u> of figures 2 and 3, which can also be regarded as having a range from few skills to many. A pass through the activities is represented as a cycle around the axes where the intersections with each axis represent a level of detail of an outcome. The cycle spirals outward, suggesting that the next cycle will produce outcomes with a higher level of detail, which presumably would require expanded skill levels. Figure 4 shows a spiral of two cycles, where the inner cycle can be interpreted as being carried out with few skills and producing partial outcomes for each activity. That is, the outcomes of the inner cycle would have few stated needs, few specifications, few concepts (or perhaps only one), simple analysis or "judgement" used to select among the concepts, dimensioned sketches of what are believed to be the few key components and a mock-up or model of one or more components.

The next cycle represents a pass through the activities with broader skills and know-how in the domain, which are used to produce outcomes of an increased level of detail, again denoted by the spiral-axis intersections. After a number of cycles, participants would decide that all pertinent needs, specifications and alternate concepts have been identified and that all appropriate evaluation methods have been applied to select the best concept. Furthermore, all appropriate detailing tools are being utilized, the purchased items are identified along with vendors, and the manufacturing methods, operations and tooling are identified. Then the final Build Activity begins, though some prototypes may have been built as part of the Evaluation activity, or as a test of a manufacturing method. The corresponding outcomes would be "complete", including a "product", from the final Build and Test activity.

The final version of the outcomes, including the product could also be viewed as resulting from a single pass through the Design Process that would be done by experienced designers. However, in the spiral approach, the outcomes evolved by cycling through the activities many times, which provides educational benefits to the beginning students and facilitates teaching of selected aspects of the process. Some benefits to the students are as follows.

* Students gain Design Process experience through repetition, since during each cycle, each process activity is addressed, outcomes are expanded, and decisions are made to move to the next activity.
* Documentation of the outcomes is recognized as essential, since progress is identified by increased levels of detail from cycle to cycle. Without documentation, how is it known the level of detail has changed?
* The expectation that the level of detail will increase drives the need for additional skills. Students enter the next cycle with a better understanding of what skills are needed and how they help produce the next level of detail.
* The increased level of detail also demands that the vocabulary become more precise as the skills in the domain increase.
* The decision to "accept" the project can be delayed as one participates in a few preliminary cycles to assess the scope of the project and the skill levels of the participants.
* The multiple visits to each activity and the creation of expanding outcomes provide multiple opportunities to contribute and demonstrate commitment, thereby gaining the confidence of team members.

The Spiral approach is helpful in teaching the Design Process as follows.

* The spiral model integrates feedback into the process as an expected phenomenon and not a "failure" of the process. Previous activities will be revisited with new information learned during a cycle.
* The model facilitates a quick start of the design process, as described previously with an initial cycle having few needs, few specifications, etc., where all activities are experienced, some skills are utilized and partial outcomes are produced. This can be done in a few sessions and gets everyone into the process and the domain.
* The use of cycles is especially useful for systems projects, like the vehicles. When the task of "Vehicle Design" is introduced to a new team, we say: "The first task is to design the entire car. The second task is to design the entire car. The third task is to design the entire car". The audience looks at you funny, when we ask, "How could these statements make sense?" Eventually it leads to design process cycles where the level of detail of the entire car increases at each cycle, and decomposition into functional areas occurs naturally as the increasing level of detail shows the need for it. Starting with a low level of detail in systems projects also allows all participants to see the overall scope and discover interactions. The next section shows an example from the vehicle projects.
* The spiral approach uses the typical sequential Design Process as its foundation, so those who are familiar with the process can easily adapt it to a spiral approach for teaching beginners.

Getting Started Via the Spiral Model

This system describes the use of the Spiral Model in getting started on "designing the entire car" at increasing levels of detail, using a solarcar example. The participants were attending the no-credit recruiting and orientation seminars, and had seen slides of various solarcars, heard overviews of the technology from faculty and team alumni, examined race programs, technical summaries and event rules, and had been introduced to the Design Process skills and outcomes of figures 2 and 3. Each had also chosen to affiliate with one of four design teams:

Aerodynamics, responsible for the vehicle body,
Array, responsible for the solar array,
Electrical, responsible for batteries, motor, controls, and
Mechanical, responsible for chassis and suspension.

Within these teams, they created preliminary lists of tasks as an exercise at their initial meetings. The lists were incomplete with wide range of detail levels, but showed that most had seriously thought about the overall task, and had an idea of the range of components associated with their design team. A few workshops were then held for all teams with the intention of describing "the entire solarcar" at a low level of detail by performing one cycle of the spiral. Outcomes of the activities were as follows.

STATE NEED: The vehicle competition makes it easy to state an initial need as, "pass technical inspection, qualify for the event and finish in first place." Later versions become more specific about completion dates, testing and the educational benefits.

DEFINE SPECIFICATIONS: The rules for the event are the starting place. The vehicle size and solar array size is limited, various safety measures are stated regarding driver protection and electrical and mechanical components. Also, the layouts of previous vehicles that performed well, either our own or those in the literature, are surveyed and nominal values, ranges or locations can be stated for the number of wheels, wheelbases and track, and driver position with respect to some reference such as the front axle line, and possible battery placements. With the Spiral Model, it is understood that these are starting places and may be revised as cycles occur. This is also the place to apply system level performance values and constraints, such as locating the vehicle center of gravity to provide equal weight on each wheel for a three-wheeled vehicle. The "why" of such a constraint can be examined later as a domain skill for those interested in vehicle dynamics.

GENERATE CONCEPTS: This is where the initial vehicle description occurs, and needs to be done via diagrams. All major components need at least one option stated, diagrammed, and a story of how the pertinent rules, which are the specifications at this stage, are met. There should be side, top and front views of a "chassis", which may be absent, and simply show the spatial locations of the driver, wheels, rollover protection, pedal assembly, steering, batteries and major electrical components. Similar sketches of an outer body, showing the location of the driver's head and the extent of which the array covers the body. A typical solar cell is a 100-mm square, and if the body has severe curvature, the cells may be cut into smaller pieces, which introduces more connections, layouts, and labor. Suspension types should be described and the sizes of candidate tires should be known. Major electrical components should be named as black boxes on a diagram with interconnections, including sensors and telemetry elements, and some battery and motor options should be specified.

EVALUATE AND SELECT: For the first cycle, it is useful to identify analysis methods that could be used to predict the performance of the individual concepts, and of the entire vehicle, and also to identify criteria that should be used to select among alternate concepts, even though only one may be offered at this cycle. Identifying analysis methods helps build skills by forcing a review of topics in prior coursework or learning a new method, and helps direct the pursuit of more details of concepts, since applying a method usually requires a more detailed description of a concept. Evaluation criteria can be developed from new specifications which may be "implied" by the concepts. The current concepts will have some "features" in addition to meeting the rules. The body shape may have a low estimated aerodynamic drag, the suspension may accommodate a certain level of wheel travel or produce low loads upon the chassis, the electrical system may have a modularity feature that allows easy diagnostics and replacement, the chassis or body may be easily manufactured so that lead time is reduced and testing time is increased. These "features" can be rephrased as possible specifications for the next cycle, and can be used as evaluation criteria.

Since a system level specification was to provide equal weight on each of the three wheels, this needed to be evaluated. It requires estimates of the weights and locations of all components and a spreadsheet to accept and compute the center of gravity location and wheel weights. Estimating the weights and specifying the locations forced a level of detail upon the process, and fostered discussion. Components were aggregated for the first cycle as "front suspension, rear suspension, chassis, body-array, batteries, motor and controller, driver, and electronics (telemetry, switches, etc.)". Some locations were known (front suspension), but others, such as the driver and batteries had a major impact upon the CG location, and their placement was interdependent, as discussed earlier. This was the first "systems issue", and required that some members of each design team become familiar with all the interacting decisions that affected the CG location, and develop confident weight estimates and suggested locations for their components. For each successive cycle, more individual components were considered (less aggregation) until each component was identified on the spreadsheet.

DETAIL THE DESIGN: For the first cycle, it is useful to emphasize that dimensioned sketches are appropriate, where nominal values of certain critical dimensions are identified, but that CAD tools will be expected to be used later. Since rendering with a CAD system requires all dimensions, its forthcoming use will demand an increase in the level of detail, which corresponds to future cycles. At the first cycle, simply identifying the CAD tools that will be employed, and vendors for parts that are expected to be purchased is sufficient. From the analysis and evaluation methods identified in the previous activity, there were corresponding parameters of concepts to be developed in more detail. From the system level interactions, there were interface parameters that needed to be explored in order to accelerate the decisions that cross design teams.

BUILD AND TEST: For the first cycle, it is useful for each design team to describe the steps required to manufacture at least one of their concepts, including naming the materials, the machines or processes, and identifying possible sources of help. A useful build activity was to fabricate a mock-up driver compartment, and fit different team members into it, measuring the comfortable positions for steering controls, switches and pedals, identifying eye locations relative to a ground plane, and finding the range of the locations of the CG of different drivers.

At the end of the initial cycle, team members had experienced all design activities and produced outcomes, thus gaining design process experience. They produced dimensioned sketches of the vehicle along with locating and estimating the weights of major components. They found plausible specifications based upon features of concepts, identified analysis methods to use in subsequent evaluations, and identified detailing tools and manufacturing processes that will be employed. Identification of these things gave direction to developing the needed skills and level of detail for the next cycle. The neophyte vehicle designers were off and running.

Conclusion

This paper described a spiral representation of the typical sequential product Design Process, which accommodates successive passes or cycles through the individual design activities and thus providing beginning design students with repetitive experiences with each design activity using the same product domain. The spiral incorporates the notions of a range of skills and a range of level of detail for outcomes of each activity, which allows explicit descriptions of what is learned as successive cycles unfolds. We encourage design instructors who are familiar with the typical Design Process to consider the Spiral Model approach when introducing beginning design students to the process.

References

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Figure 1 GENERIC DESIGN PROCESS

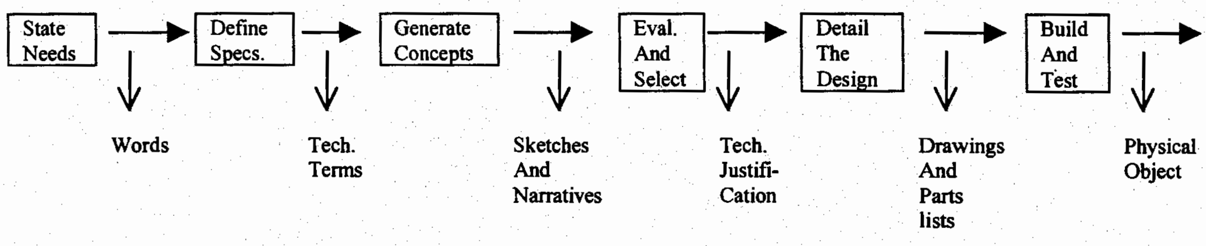
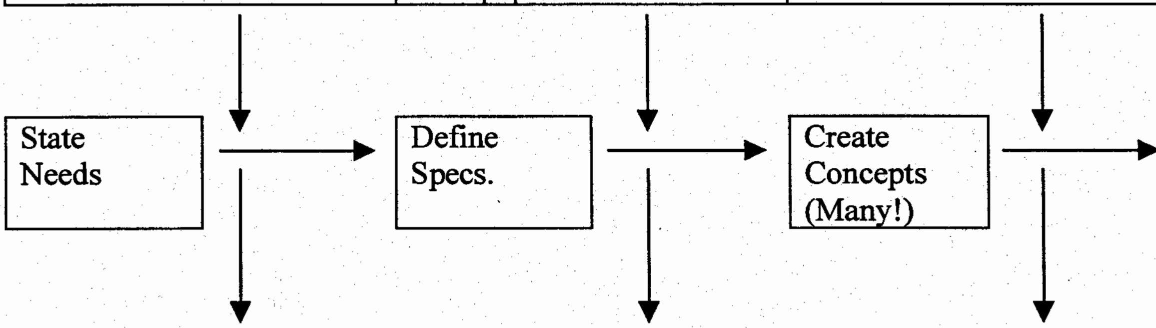


Figure 2 DESIGN ACTIVITIES, SKILLS AND OUTCOMES

SKILLS	SKILLS	SKILLS
* Identify the customer	* Interpret the rules	* Identify applicable existing technologies
* Know the rules	* Knowledge of inspection, qualifying and evaluation at event	* Describe technologies in functional terms
* Think "System Level"	* Knowledge of applicable tech. Terms and physical processes	* Invent concepts via individual and group activities (brainstorm)
* Think "Symptom Level"	* Ability to describe functions	* Think in user terms
* Imagine User Actions	* Ability to seek out devices and interpret their specs.	* Suspend judgement
* Think interconnections	* Communicate with non-tech people	
	* Estimation skills-back of envelope performance estimates	



Outcome expressed as words:	Outcome: translates the need into technical terms with quantitative levels and/or ranges. Some categories are:	Outcome: a concept is a description of the technology which could meet the specs, expressed as:
* Customer desires	* Functional requirements	*Sketches of what it is, and how it would fit with other components and a
* Non-tech terms	* Performance levels	* narrative of how it works and meets specs
* Gross overall function	* Environment-physical and regulatory	
*"Mission Statement"	*Constraints-hard and soft. All expressed in writing.	

Figure 3 DESIGN ACTIVITIES, SKILLS AND OUTCOMES

<u>SKILLS</u>

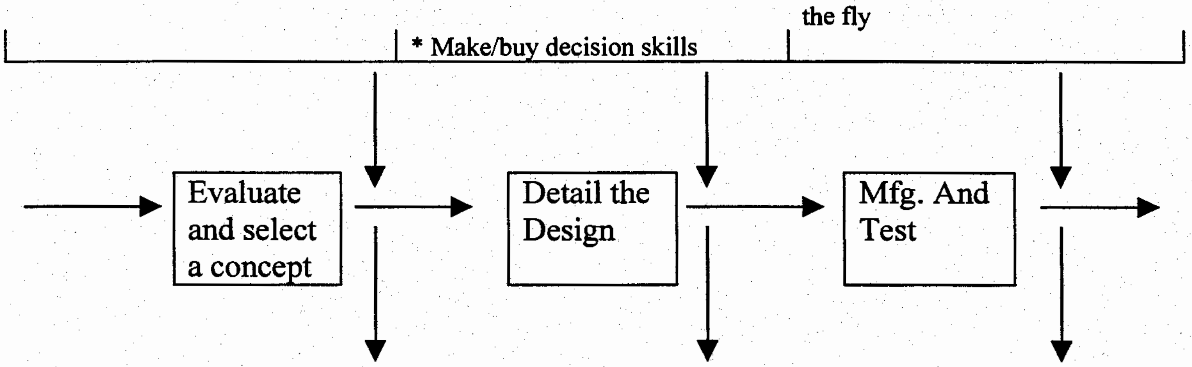
* Familiarity with modeling, analysis and computer based tools
* Recognize what modeling, analysis tools apply to estimate behavior and performance
* Able to build and test mock-ups for proof of concept
* Familiarity with scoring methods to compare concepts
* Familiarity with manufacturing methods
* Able to do rough costing

<u>SKILLS</u>

* Attend to detail
* Apply CAD tools
* Final Load/Stress/Thermal Analysis
* Specify component parameters (springs, shocks, bearings, etc.)
* Learn and apply established procedures, (i.e. bearing sizing)
* Hardware and material know-how – fasteners, matl. properties, etc.
* Able to seek assistance from experienced people
* Make/buy decision skills

<u>SKILLS</u>

* Define and schedule the needed operations
* Ordering parts and materials
* Operate tools
* Attention to detail
* Hands-on model building and fabrication experience
* Communicate with experienced professionals
* Able to recognize problems and propose "work around" solutions - final "decision" on the fly



<u>Outcome</u> is documented justification for selecting a concept to be detailed. It is to include:

* Estimate how the selected concept meets specs in technical terms using modeling and/or tests
* State how it interacts with other components
* Outline how it could be manufactured/purchased
* Outline costs
* Identify development problems ~ loading, stress analysis, etc.

<u>Outcome</u> is documentation that supports building, purchasing and assembly of the product, consisting of:

* Finished, scaled drawings of components to build
* Specification of purchased parts ~ part #, vendor, cost
* Assembly diagrams showing fits and tolerances
* Manufacturing plans in more detail, naming the sequence of needed operations
* Final analysis - refinement of the previous "evaluation" in light of problems discovered during detailing

<u>Outcome</u> is the system that meets the <u>specs</u> and fulfills the <u>need</u>

AND

A <u>Test Plan</u> to verify it meets the <u>specs</u> and <u>needs</u>

Figure 4 **SPIRAL MODEL OF THE DESIGN PROCESS**