A Process for Design Engineering

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Abstract

The American Institute of Aeronautics and Astronautics Design Engineering Technical Committee has developed a draft Design Engineering Process with the participation of the technical community. This paper reviews similar engineering activities, lays out common terms for the life cycle and proposes a Design Engineering Process.

Introduction

At the April 2003 Design Engineering Technical Committee (DTEC) meeting, several people expressed a desire to begin working toward a consensus opinion concerning a process for design engineering. Open forum discussions were planned beginning with the fall meeting at the American Institute of Aeronautics and Astronautics (AIAA) Space 2003 conference. [Tam 2004] The DETC Chairman, Kent Longenecker, established this charter:

> [development of] a baseline or current state Design Engineering Process starting at product or part concept inception and ending with product or part definition release. The ultimate goal of this effort is to create a lean Design Engineering Process Standard including minimal requirements definition, system and functional interaction, design and product manager tool attributes and process efficiency measurement approaches.

The DETC Design Process Subcommittee is leading this activity. The Charter of the Subcommittee includes "improvement of the Entire Design Engineering Process" and "Continuous Improvements in the Processes Used by Industry." The Mission includes three guiding topics:

- Pursue Design Integration as a Systems-Oriented Approach to Improving the Design Engineering Process
- Develop Cost Modeling Information Suitable for Use in Teaching Design Engineering in the Classroom and in Projects
- Address the Concern that Increased Computer Use and Reliance on Analytical Tools Results in a Loss of Physical Judgment in Design Outcomes

Such a process has many aspects, but the intention is develop a time ordered series of activities that make up the elements of doing Design Engineering. The appropriate activities will be contingent upon the industry, organizational practices and period in the development of the product.

The relative importance of an activity will also vary. Some activities may be deemed critical and must be done. Others amount to good advice. The opinions vary based upon personal experience, organizational practices and type of product.

In engineering process development, there is always a great deal of concern about over specifying the activity of design, thereby limiting the ability of design engineers. The general understanding today is that certain activities can be agreed upon that, in a given professional setting, are important to do. It gets more difficult to be very specific about how to do them, since the details of engineering practice vary significantly by discipline and industry. Often there are regulatory requirements that provide sufficient details in critical situations. As James Martin, the EIA-632 Working Group Chairman, says: "Processes not Methods or Tools."

Further, it is recognized that many of the activities in design are not sequential but concurrent and overlapping in a given design period. By nature, processes are most easily described as a sequence of steps, but this concurrent nature is usually spelled out in supportive text.

Design engineering is an engineering activity that requires a variety of technical and managerial skills. For most organizational activities, several people will be involved in the engineering design of a particular product. Small groups may be 5 to 15 people, each contributing a variety of skills. Larger groups might be 100 people. Quite often, design is a hierarchical activity where subgroups contribute assemblies to a larger design activity.

The leader of the design activities may vary in time and in responsibility. Usually there will be a manager in charge of the business aspects of the product's development. Financial and administrative staff may support the business activities of larger projects. The design lead may be a design engineer, a project engineer, or system engineer. Design leadership may rotate through engineering specialties depending upon the design issues, industry or organization structure. Engineering specialists such as structural and thermal engineers will usually support the design team.

The Life Cycle

The long scale temporal aspects of product development, utilization and retirement are described in terms of the Life Cycle. Life Cycles cover the beginning when a need is recognized and a development activity is approved. The development period is often several stages or phases of definition, design, and testing. A fabrication period covers production, an operational period covers the usable life of the product, and retirement covers the product's phase out and disposal.

These vary by product and industry. During operations, there might be concerted life extension or refurbishment period where the products are updated, rebuilt, or otherwise modified in lieu of transitioning usage to a new product. A particular product rarely exists in isolation, but is part of a family or series of related products. Together, the family of products might shift from an incumbent to a successor, with overlapping development and deployment phases. Retirement and disposal may be a significant phase where materials are recovered or wastes are reprocessed, or the product may be naturally lost or consumed and unavailable for retrieval.

Enterprise-based life cycles are described as having five distinct functional phases: (1) assessment of opportunities, (2) investment decision, (3) system concept development, (4) subsystem design and pre-deployment, and (5) deployment/installation, operations, support, and disposal. [EIA-632] These are established by the external environment, for example by market cycles or government agency directives, and are not generally based on engineering efforts required for development.

Alternately, a life cycle is a period of time, organized into phases, that begins when a product is conceived and ends when the product is no longer available for use. [SEI 2002] A product life cycle will vary with industry and organization, but could consist of the following phases: (1) concept/vision, (2) feasibility, (3) design/development, (4) production, and (5) phase out.

The Design Engineering Process under consideration here will be focused on the development phases of the product life cycle. There will be consideration for all phases during design, such as producibility or user acceptance. The initial process definition covers the activities following the need definition and approval to proceed with design through to initial adoption by users, leaving the design activities in life extension or refurbishment phases to be added in subsequent updates. It is during the time from approval to adoption that the general product concept is created, the details of connections, joints and material are examined, and the means and methods of fabrication are devised. Simulation and testing, whether for design exploration or design verification, are to be included as supporting activities, although only to a depth reflecting usage not necessarily execution.

This design development period is generally organized into similar phases where the design fidelity increases, uncertainties are reduced and attributes of the product are established. For parts of the aerospace industry, there are usually three design phases known as Conceptual Design, Preliminary Design and Detail Design. In other areas, there may be a Concept Development Phase followed by an Engineering and Manufacturing Development Phase. In industries where products are fielded and upgraded in a more incremental fashion, there may be a single design phase followed by a field implementation and deployment phase.

A primary contribution of the design engineering process definition activity may initially be understanding this common Life Cycle framework. The adopters should find a significant clarity in these results as an organizing principle in an apparently unstructured field. Inside the varying industry life cycles, a given design period will likely have a very standardized activity list. This is the level of detail that participants are driving toward. This is where recognizable activities that are familiar on a daily or monthly basis are to be found. Furthermore, this is the level where improvements in common practice are most likely to be rooted.

A Design Phase

Periods or phases in the development period, as noted above, are variously known by descriptive names such as Conceptual Design and Detail Design. Similar activities exist in each, but the level of detail or specificity generally increased in later phases. This is a natural consequence of the developmental nature of this product activity. Complex, large or innovative systems might take 5 years or more from concept development to initial fabrication, while systems or major subsystems with significant heritage might take 2 to 3 years in development.

Design phases are well described by activities performed and design data products produced by the end of the phase. [Blanchard 1998, Forsberg 1996] Project management speaks of phase transition gates and transition criteria. Design reviews that end a design period are the gates in that successful completion is a prerequisite for beginning the subsequent phase. Further, the team can be sent back to revisit design elements deemed unsatisfactory in the review and return for an incremental or delta review. The phase transition products are described by Blanchard as baselines with specific content and level of detail.

Phase: Conceptual Design

> Phase Gate: Conceptual Design Review
> Design Product: Functional Baseline (system specification) and Design-to Package
> Design Activities: requirements analysis; evaluation of feasible technology applications; selection of technical approach.

Phase: Preliminary Design

> Phase Gate: Preliminary Design Review
> Design Product: Allocated Baseline (development, process, product and material specifications)
> Design Activities: requirements allocation; trade-off studies; synthesis; preliminary design.

Phase: Detail Design

> Phase Gate: Critical Design Review
> Design Product: Product Baseline (process, product and material specifications) and Build-to Package
> Design Activities: Subsystem design; development of engineering models; verification of manufacturing and production processes.

EAI-632 speaks of the stages of maturity for the design specifications. [EIA-632] They evolve through three stages: conceptual, initial and established. Conceptual specifications are used to show feasibility of a higher-level product. Initial specifications are used to direct lower-level developments of subsystems. Established specifications provide guidance to testers, provide a basis for negotiation of engineering changes, and enable configuration management of solution definitions.

Design Activities

As postulated, these design periods have several activities in common although the level of detail, size of the team, breadth of considered alternatives, and accuracy varies. The activities are not thought of as sequential steps in a process, but rather concurrent and iterative activities pursed in the act of determining the eventual design specifications.

1. Prepare a management plan and attend to the business activities of schedule, finances, staffing and communication.

2. Determine and analyze requirements and prepare design problem statement.

3. Design the product.

4. Analyze the product design through engineering analysis, simulation and/or test.

5. Review the design prior to completing the design phase. If the review indicates further design activity in this phase is required prior to proceeding, replan the task and revisit the design activities until successfully passing further reviews.

The design team will require support from various disciplines in accomplishing the activities. In some organizations, the business aspects may be handled by a manager who is not an active engineering design contributor. In organizations with an existing systems engineering group, the system engineering team may develop the mission and system level requirements, leaving lower level requirements to be derived and handled by the design team. When considering critical materials for the product, the design team may bring in a materials and processing specialist and when sizing the major structural elements, a loads and external forces specialist may be needed.

A variety of technical disciplines may be involved depending upon the way the organization has broken down the work. For example, the mechanical design might be separated from the electronics design, or the software development might be partitioned off to a separate activity. As a result, the mechanical team might need specialists for mechanisms or lubrication, while the electronics team will need specialists in integrated circuit design or RF transmission and reception. Such partitioning might lead to use of specific techniques such as developing and managing interface definitions.

As a result, further definition of the design activities will lead to context and product specific activities in these key technical areas. For example, it might be that the general activity of risk assessment leads to a failure modes and effects analysis in some electronics organizations, but other organizations find that fault tree analyses are more appropriate. The process definition will establish a guideline for organizing the activity descriptions at this level.

EIA-632 breaks System Design into two processes: Requirements Definition and Solution Definition. [EIA-632] In activities list above, Determine and Analyze

Requirements and Design the Product could be carried out with the EIA-632 processes. EIA-632 has a process called Systems Analysis in the Technical Evaluation Area which could guide Analyze the Product and EIA-632 has a Technical Management area with processes for Planning, Assessment and Control which could guide Plan and Execute the Activity. Finally, Review the Design is covered by Technical Reviews in the Assessment Process.

The SEI CMMI collects these design activities into the Engineering Process areas. [SEI 2002] Of the six process areas, Requirements Development and Technical Solution are most relevant. The planning and management activities are covered under Project Management process areas.

These five activities, then, have good support in two other major process definition efforts that are quite relevant to the industry.

Process development must proceed cautiously in the area of design since there is significant concern for impacting creativity in this area. There are design texts that provide design techniques, but these are recommendations not prescriptions. [Dym 1999] This is probably an accurate reflection of design, or our state of understanding design, in that few methods work universally.

Conclusion

There is a wealth of information describing the activities needed to support Design Engineering. [Blanchard 1998, EIA-632] Current practice is for each organization to tailor their process from the general knowledge base to fit their needs and circumstances. See [Linick 2004] for one example. The activity descriptions broadly cover the engineering practices in product development and don't provide discipline specific methods or tools.

Implicit in discussing a Design Engineering Process is the broader subject of managing processes and managing organizational development. The process definition needs a context statement concerning the using organization's process development and management practices. This will supply an interpretation of the Design Engineering Process in terms of formality, rigor and implementation.

Design Engineering activities take place in the design and development portions of a product development lifecycle. While the number and depth of design phases varies, the following activities are to be included in a phase.

1. Prepare a management plan and attend to the business activities of schedule, finances, staffing and communication.

2. Determine and analyze requirements and prepare design problem statement.

3. Design the product.

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5. Review the design prior to completing the design phase. If the review indicates further design activity in this phase is required prior to proceeding, replan the task and revisit the design activities until successfully passing further reviews.

The Design Engineering Technical Committee will open a period of discussion to refine the process definition and move toward adoption of an initial process.

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