Teaching Design for Manufacturability:
the Historical Events, the Current Events and the Future Events

B. Lee Tuttle
GMI Engineering & Management Institute

Abstract:

A course entitled Design for Manufacturing was begun in the Spring of 1988 as a required course in the Manufacturing Systems Engineering program and an elective in the Mechanical Engineering program. This course represented to many a step backward in educational methodology since it incorporated a practicum (a workshop) during which students performed design and analysis exercises under the supervision of a preceptor. The course format has remained relatively stable over the past 8 years. However, the topics covered in the course have evolved with the understanding of the concepts of DFM/A. Further, the method by which each topic is taught has changed over these years. A historical perspective is drawn describing the paths trod in the evolution of this course in an effort to stimulate a discussion of both the topics and the methods for teaching DFM/A.

The present format of the course includes two lecture sessions per week and one two hour practicum session per week. In the present form the DFM/A course includes: DFM Methodologies Overview, Break-Even Analysis, Process Analysis, Design for Function, Design for Assembly Principles, BDI-DFA Manual Methodology, Creative Concept Development, Design for Automated Handling, Value Engineering, and Group Technology.

Historical Events:

The discussions of a course to integrate the functions of product design and manufacturing processes began in the Spring of 1985 when a new academic program called Manufacturing Systems Engineering was proposed at GMI. One of the hallmarks of the MSE curriculum was the integration of the various product and process functions under one engineering program hat. As appears to be the stamp of academia the process flow from concept to course took nearly two years. The format of the course from the beginning was two lecture hours per week and one two hour practicum session per week. The original lecture topics included

- DFM Methodologies
- Material/Process Interactions
- Value Analysis
- Design for Assembly
- Boothroyd-Dewhurst DFA
- Group Technology
- Future Directions for DFM

The original practicum topics included:

- Process Routing Analysis
- Product Redesign Term Project
- Function Analysis
- Creative Enhancement Techniques
- VANE Problem
- Peppy Robot Assembly Analysis
- BDI-DFA Exercise (2 sessions)
- Part Classification for GT
- Term project Presentations
The description of the evolution of the course is best approached by describing the three aspects of the course separately: (1) changes in the topics and methods of delivery in the lecture, (2) changes in the topics and delivery style in the practicum, and (3) changes in the elements of the term project.

Early Years - Lecture Format:

The original lectures were delivered in the traditional engineering (or university) style with the professor espousing the great learned knowledge to the masses. Since there was no textbook there were considerable notes to be recorded and many tedious definitions to be given. In the third year that the course was taught a series of programmed lecture modules were developed for each lecture topic. These modules contained the major definitions of terms, data tables, and some case studies of each tool. Each time that the course was taught the lecture modules were updated to incorporate the modifications in the direction of the course. Although the learning materials in the hands of the students had changed, the delivery style of the lecture remained basically the same as it has been traditionally done in engineering programs for years.

Early Years - Practicum Format:

In the beginning the practicum sessions operated in a very rough unstructured manner since the instructor nor any of his immediate colleagues had any experience operating such sessions. The practicum sessions were meant to be group activities in which the participants put into practice the various DFM/A tools that they had learned in lectures. (1) The first problem that arose was that in the absence of prepared practicum booklets, many topics needed to be “lectured” in the practicum sessions themselves, thereby reducing the time available to practice the application of the tools under controlled supervision. Of the 10 originally scheduled practicum sessions only 8 were actually completed. When the course was first taught there were 16 students (one practicum session). The first semester the practicum session was taught in the engineering graphics laboratory. Since this room was scheduled for many engineering classes, the DFM/A sample products had to be transported to the room for each practicum session. In order for the teams to work on the practicum assignments, they had to sign out the product at the end of the practicum session. For the first semester, the distribution of the weekly practicum products was not difficult since there were four copies of the product and only four practicum teams. In the second and subsequent terms that the course has been taught the enrollment had surged to 64 students (4 practicum sessions with four teams each). When students were assigned projects on a small product that was used in the practicum, there was chaos among the students trying to get and return the products to the professor so that other teams could use them.

At the end of the first year that the course was taught, several changes were considered for the practicum sessions:

1. A permanent design studio dedicated to DFM/A was needed to provide a home for the analysis products, a workplace for the teams outside the formal practicum sessions, and a display area for good and bad product/process examples.
2. The lecturing on the DFM/A tool needed to be moved up ahead of the application of the tool in the practicum session in order to get more work time in the practicum sessions.
3. A practicum booklet needed to be prepared for each DFM/A tool including an example of how the tool was used on a simple product.
4. A more effective means of providing feedback to the teams and sharing the concepts from each practicum session with all the students was needed.

Although none of these are difficult to develop, the implementation of all these concepts took several years.

Early Years - Term Project:

From the inception of the course it has embodied a term project in which teams of three or four students evaluated a current commercial product for Manufacturability and then redesigned it to improve manufacturability. Like the practicum and the lectures, the term project has evolved as the DFM/A tools being taught has evolved. The original concept of the term project was for the students to evaluate a product for manufacturing processes and assemblability and then to design a better way to manufacture this product. In the beginning the term project involved:

- Function Analysis
- Process Analysis
- DFA Analysis (Original)
- VE/DFA Redesign
The focus of the project at this time was to find the faults in the old design and to improve the manufacturability of that concept. Although the concepts of Creative Concept Generation were being taught in the lecture and practicum, the designs that resulted were linear modifications of the original concept driven by the DFA analysis.

At the end of the first two years that the course had been taught several changes were considered:

1. Finding a tool or method to get the students to think in terms of new methods for performing the operation of the product instead of mimicking the original design.
2. Improving the students’ ability to develop visual concepts of new product mechanisms.
3. A place to allow students to concentrate on redesigning a product where they could create their own team environment either quiet and calm or noisy and stormy.

Intermediate Years - Lecture Format:

The problem of getting the basic information on the DFM/A tools out to the student was approached by scheduling the lectures as front loaded in the term. The lectures were scheduled 3 times per week for the first five weeks, two times per week for weeks 6 to 9 and no lectures during weeks 10& 11. The lecture format embodied the application of further programmed learning modules embodying the basic factual information. The lecture sessions were now devoted to interactive applications of the various tools that appropriately lend themselves to such a learning style. Where interactive lecture sessions to demonstrate tools were not appropriate, the demonstrations of visual products illustrating the original product concept and the improved product concept was employed. Unfortunately, there still seemed to be topics that seeded appropriate only for conventional lecture presentation.

The original concepts employed in Value Engineering were seen to have a broader application to product design in DFM/A. Two of these tools: namely, Function Analysis and Creativity were removed from the Value Engineering lecture format and given a pedestal of their own. The original concepts of Function Analysis in Value Engineering were developed into what is called Design for Function. In DFF the design of the physical embodiment of the product is driven by the verbal product specification developed in the fiction evaluation (rather than function analysis). The concepts of Creativity were expanded to include further concept generation tools. The PUGH Concept Selection Matrix was introduced as a divergent thinking tool to focus inward toward the new product design. The ideas covered in Design for Assembly were separated into the underlying principles of DFA analysis with reference to the various systems employed through the years and a specific section devoted to the BDI-DFA manual system as one practical tool of DFA methodology. Due to the expanded coverage of the DFF, Creative Concept and DFA tools, the coverage in Design for Primary Process (Design for Manufacture) was dropped.

Intermediate Years - Practicum Format:

The practicum sessions immediately became more productive with the introduction of some of the DFM/A tools during the early lectures. After week three, the practicum sessions lagged the topics covered in the lecture. Each time that the course has been taught, more and more of the factual information on the application of the tools has been incorporated in print in the practicum booklets. Less and less time is spent each week of the term “lecturing” on the tools in the practicum. Further progress in removing the “lecturing” from the practicum sessions was made by adding an appendix to each practicum booklet that included an application of that tool to a simple product as performed previously by some students. Although this provided a practical example for the instructor to reference, this added to the maintenance work for the design studio because each time that the DFM/A tools changed then that appendix had to be updated in detail. In an effort for the students to think visually, an exploded assembly sketch has been included as a requirement for all practicum assignments even if it is not critical to the assignment.

A formal practicum session on the application of three tools to Creative Concept Generation was incorporated into the practicum sessions. Previously, this material had only been covered in the lecture. (2) A practicum booklet was prepared on the application of the Pugh Concept Selection Tool to the selection of early product concepts. However, no formal practicum was devoted to the application of this tool. The feedback to the design teams was now given at the beginning of the practicum and incorporated in the DFM/A Sketchbooks that was displayed in the DFM/A studio. The DFM/A Sketchbooks is a book of current and recent past student assignments available to all design terms for consultation during the completion of a assignment and for feedback after an assignment was completed. The products used each week could be left in the DFM/A studio when the practicum sessions were not in session without other students taking them.
used each week could be left in the DFM/A studio when the practicum sessions were not in session without other students taking them. Since the DFM/A studio was dedicated to the teaching of this one course, the products, DFM/A tool spreadsheets, and product displays could be accessible to all groups throughout the day for performing the assignment for that week. Alternately each team could sign out the products for the night or weekend, work on the tool application for that week outside, and return the product to the studio without the need to locate the instructor for product check in.

In the intermediate years, most of the changes seemed successful. However, some changes still seemed needed:
1. Students seemed to be struggling to implement the tools even though there was a current solution to the tool in the practicum assignment.
2. Explanations of how the DFM/A analysis tool would drive the next design iteration was lacking.
3. Students still seem reluctant to share the contributions of others toward the understanding of the application of the tool.

Intermediate Years - Project Format:

The term project followed the evolution of the tools being taught in the lecture and the practicum sessions. Incremental changes occurred each year in the function analysis, process analysis, Design for Assembly analysis, phases of the project as the details of the applications of these individual tools changed. However, the VA/VE-DFA Redesign phase began a major change about four years ago. After reviewing many term projects, it became evident that the use of the DFA tool was driving the redesign into the same mechanism with fewer parts. This redesign phase was expanded to include a second product concept that embodied a different mechanism than the original product to perform the product function.

Although the project seemed to follow the evolution of the DFM/A tools, there were still several major challenges in the Redesign Phase.
1. How to get the teams to make the paradigm shift from the embodiment of the old design mechanism to the new mechanism.
2. How to get the teams to really try the creative concept tools in the creative redesign phase.
3. How to evaluate the effective use of the creative concept tools in the redesign stage of the product.

Current Years - Lecture Topics:

Unfortunately, most of the lecture presentations are still lectures. The topic of Function Analysis has been replaced with the Design for Function approach to concept development in an effort to drive the next product design away from the physical manifestation of the old product. (3) The Function Analysis lecture of definitions has been replaced with a semi-interactive lecture on the development of the functions of several sample products. The Boothroyd Dewhurst Design for Assembly tool is introduced by an interactive group analysis of a simple product. A new topic of “How do we perform Engineering Design?” has been introduced to guide the application of the various DFM/A tools being taught throughout the course. The coverage of Value Engineering is now only a review of the contributions of the methodology to the evolution of DFM/A and a description of the process as a total problem solving process. The principle contributions of VE to DFM/A (namely Function Analysis and Creative Thinking) have been given separate tool functions by themselves and are covered early in the term now so that the project teams can use these tools in their project redesign.

Unfortunately, most topics still seem to be best covered for the majority of students through the traditional lecture format. Many students seem very uncomfortable developing the concepts of the DFM/A tool themselves. They feel that some authority figure must still give the knowledge to them. They are opposed to developing knowledge themselves.

The challenges ahead for the lectures seem to be:
1. Developing more interactive learning exercises for the students in the DFM/A tools.
2. Developing students who participate in the learning experiences.
3. Redefining some topics such as Group Technology so that they are focused to drive the design of the product rather than as a stand alone tool of analysis.

Current Years - Practicum Topics

The coverage in the practicum sessions has been realigned so that the tools that will be needed in the term project are practiced at the beginning of the course. The tools that are not directly used in the term project are covered at the end of the course when hopefully the students are fully involved in their term project.
The feedback is given verbally and visually at the beginning of the practicum session on the prior assignment. This is reinforced and enhanced by the display of the various solutions to the previous tool on the DFM/A studio walls. Since the introduction of the “solution of the week” display, students have begun to take pride in seeing their solution recognized by the instructor as “good”.

The practicum sessions now employ a “warmup exercise” for each tool utilizing a simple product that is displayed in the DFM/A studio. The “warm up exercise” is completed during the introduction practicum session, each team presents their vision of the correct application of the practicum tool, and a feedback is given by the instructor on the correct application of the tool. Although the correct application of the tool is given in the appendix of the practicum booklet, there is a great inertia in the minds of students to read and absorb the information in the practicum booklets.

The instruction of each DFM/A tool is ended with an example of how it is employed in the DFM/A process for the design of a product with emphasis toward the term project products.

The current format for the practicum sessions includes the following exercises.

- Term Project Function Specification
- Process Operations Evaluation
- Analysis of Function
- Function Structure Diagrams
- Assemblability Evaluation by Manual Assembly
- Creative Concept Generation Tools
- Pugh Concept Selection Matrix
- Design for Assembly (Manual Methodology)
- Assemblability Evaluation Methodology

Current Years - Term Project:

The direction of the term project has changed considerably in the past few years. The emphasis has gone from the use of one DFM/A tool to the use of three important tools.

The project now begins with a broader definition of the product specification developed from the perspective of the Design For Function tools at the product level and the Subfunctional group level. When the product specification is approved, the DFM/A team has both a visual specification of the current product to use in the DFA tool and also a verbal specification of the product to use with the DFF tool.

The phase of the project originally known as the “VA/VE-DFA Redesign” has evolved considerably into what is now known as the “Creative Concept Generation” phase. Currently, the team develops one product level concept using the DFA tool at the product level. Concept development proceeds upward from the bottom of each subassembly through the final assembly to the product level. The result of the operation of this tool on the product concept is a new concept that is the same mechanism as the original product but with fewer parts.

The team then returns the DFA tool to the tool box and takes out the DFF tool and the creative concept generation tools. The product specification in the first Subfunctional Group (SFG) is expanded and studied. Once satisfied with the product definition at the SFG level, the team uses one or more of the Creative Concept Generation tools to generate a number of concepts for this SFG that are different from the original method. When the divergent thinking has ceased, they change caps and use the Pugh Concept Selection Method. After developing appropriate SFG criteria from the functions and the manufacturability metrics, the team uses the Pugh selection tool to converge on the top three concepts for the first SFG. Once concepts for the first SFG are selected, the team repeats the DFF process for the remaining SFGs. When the top three concepts in each of the SFGs have been selected, the team then assembles a product level concept utilizing one of the top three ideas from each of the SFGs. A second DFF driven redesign concept is then developed at the product level by combing one of the top three ideas not previously used from each SFG. Once three concepts have been developed at the product level, the team again develops appropriate criteria based on product functions and manufacturability metrics for a Pugh selection matrix. The team then selects the “best” product concept which is further defined visually, in a disassembly sketch showing all parts and verbally, in the function specification for each part. From this point, the team analyses the “best” product for the manufacturability metrics that were examined on the original design.

In addition the teams are evaluated today on the “process” of applying the DFM/A tools as well as the “product” of using the DFM/A tool. For example, students are advised early in the term that part of the evaluation of the “Creative Concept Generation” phase will be the measurement of how well they use the creative tools to generate concepts. During the Creative Concept Generation practicum, they are introduced to the four metrics that will be used to evaluate their creative effort in the design project: Fluency, Flexibility, Elaboration and...
Originality. The evaluation of the Pugh Concept Selection tool at both the SFG level and the product level considers how well they defined the function criteria at the each level and how well they defined the manufacturability criteria at each level.

The current term project which focuses on the evaluation of an old product concept, and the generation of three improved product concepts, and the manufacturability evaluation of one new product concept includes the following phases:

Function Specification
Process Evaluation
DFA Analysis
Creative Concept Generation (Selection)
DFA Analysis (Redesign)
Process Evaluation (Redesign)
Function Specification (Redesign)
Comparison of New to Old Design

Achievements

The development of the lecture/practicum/project methodology of teaching DFM/A has provided several positive accomplishments:
1. The concept of “design” being the “reengineering” of an old product into the same but modern product has been eliminated in most manufacturing engineers.
2. Many engineering students are recognizing the places to use and the need to use “creative tools” (Divergent Thinking) in their product design.
3. All Manufacturing Engineers now have at least five creative concept generation tools and one concept selection tool in their design toolbox.

Challenges:

Although there seems to be a millennium of space between the first DFM/A term project performed in 1988 and that performed in 1995, there are still some challenges remaining for instruction in DFM/A.
1. Engineering students still see mainly analysis, particularly analysis using a computer, as the “real” engineering work. They must still learn that new concept generation is an important engineering skill.
2. Student engineers still have difficulty finding a “metric” for product design issues such as “eye appeal”, “ease of use”, Recyclability”. Most engineers try to avoid these issues since they can’t equate them.
3. Although they do try to use the concept generation tools to generate new designs, they are not skilled enough to define the subfunctional groups of the product in such a manner as to facilitate and stimulate the generation of new product concepts.
4. Students are still unaccustomed to learning from peers and developing knowledge themselves. A major revolution in post secondary and secondary education will need to occur before this form of learning can occur effectively in this course or any other engineering course.

References:

B. Lee Tuttle

Dr. B. Lee Tuttle is Professor & Program Director of Manufacturing Systems Engineering at GMI Engineering & Management Institute. He has a B. S. in Mechanical Engineering from Worcester Polytechnic Institute, and an M. S. and Ph.D. in Metallurgy from the Pennsylvania State University. He involved in the development of educational experiences at the undergraduate and graduate level in Engineering Materials, Manufacturing Processes, Design for Manufacturability and Assemblability, and Engineering Design. He is an active member of ASEE, AFS, ASM, ASME, and CEF.