Do Not Optimize, Solve the Problem – Development of Critical Thinking Skills in DFM Small Projects

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Abstract

This paper describes activities, requirements and assessment techniques used in small projects in Design for Manufacturing course. The projects are assigned to teams of 3 to 7 students, and the vast majority of work is done in class under specific time constraints. The team size and time constraints for each problem on hand try to imitate real work environment of time-constrained meetings that must end with producing solutions. Successful realization of the projects requires knowledge of wide range of physical, chemical, and to some extend, biological effects. A strong emphasis is put on process of defining goals and objectives, and critical description of present state of design or process, including product liability. A particular emphasis however is put on knowledge of scientific principles which may provide idealistic solutions to the problem at hand. Knowledge of engineering principles of problem solving and evaluation of possible solutions is emphasized in activities related to closing of each project.

Results of up to date projects point at several perennial problems, such as: formulation of engineering contradictions and solving them, development of metrics as well as choice of tools and procedures to evaluate final solutions. These problems were observed in almost all students and groups. The process of formulating and solving engineering contradictions proved to be the one requiring most guidance on part of course instructor. Some in-class exercises designed to improve student’s ability in defining core of engineering problem are described in the paper. Intentionally, computational skills are not emphasized in the projects. Solutions aiming at optimization of the present design are forbidden. Some proven approaches to enhance group outputs are also described in the paper.

1. Introduction

“The simpler the better” is preached in engineering schools all over the world. Easy to say, but how to make students’ minds follow that path of thinking when the vast majority of their engineering learning effort is spent on learning mathematical principles with a goal of using them for optimization and numerical assessment. Consequently, the students are examined and graded almost exclusively on performance that is based on the mathematical knowledge, memorization of procedures and data. Despite its abstract nature, mathematics based engineering knowledge is easily quantifiable, and there is a lot of historical experience available in teaching it. On the other hand little learning time and grading effort is accorded to development of creativity, inventiveness and learning logical methods of designing. It is somewhat understandable, since the latter group is difficult to quantify, elusive in teaching and in assessment of student learning.
It is interesting and ironic at the same time, that almost all engineering breakthroughs, historically significant designs were achieved by using creativity and knowledge-based logic, not by optimization-based refinement of existing designs. So how is the engineering and technology education faring in the process of teaching of finding core of a problem and solving it in a methodical way that enhances chances of creating best solutions (not optimal solutions for the existing state of matter)? Results of one study assessing deficiency gaps between industry expectations and students' proficiency level in the matter of Product Realization Skills (PRS) ranked: problem solving, DFM and system approach to design as the top 3 deficiencies. Another study found technical arrogance as one of the top engineering weaknesses among engineering graduates. Yet another study found glorification of Hi-Tech complicated solutions, disrespect for effective Low-Tech solutions, avoidance of contradictions in problem solving and drive to optimize existing solutions as some of the major weaknesses of engineering graduates and senior students in fields of mechanical, manufacturing and industrial engineering. Engineering contradiction is defined as a state of design parameters in which improvement to one parameter of the system deteriorates another parameter. In other words, the system cannot be fundamentally improved while using these two parameters. Any improvement achieved by optimization, leads to a compromise in influence of these two parameters.

It is completely unrealistic to expect that engineering and technology education should mold inventors. Perhaps the best measure of how difficult it is to come up with a true invention is provided by analysis of over 2 million patents done by developers of Theory of Inventive Problem Solving (TRIZ). Only 1% of the patents were based on a major scientific discovery, 4% based on field of discovery external to the scientific field of patented application, 18% based on existing technical system, while the remaining 77% were minor inventions or repackaged existing solutions. So over three quarters of the inventions are not real inventions, they are not even innovative solutions. Engineer is not a synonym for inventor, but rather for creator. However, since for the most part engineering education does not loose sight of the fact that The Best Solution is The Ideal Solution, it is definitely worthwhile to teach what steps to take to arrive at The Best Solution.

2. Lean Manufacturing Principles and Successful Designs

Since about 1960’s in Japan and late 1980’s in the USA, Lean Manufacturing principles revolutionized approach to the entire process of fabricating a product. In its core is a quest for elimination of waste not only on production floor level, but across entire organization. Ten Primary Wastes can be described as:

1. Overproduction
2. Waiting of a part or a resource for the next processing step
3. Motion – unnecessary movement of employees and other resources
4. Processing
5. Defects (products and processes)
6. Inspection
7. Inventory (too high or too low)
8. Transportation of products or resources
9. Re- (repetition, redoing, rework, etc.)
10. Disposal

Translating the above 10 wastes into the realm of product design and process design:
1. Overdesign
2. Complex functioning of the design, slow acting
3. Unnecessary product functions that require additional resources
4. Processing required to make the product but not justified by its function
5. Errors at any stage of PRP
6. Inspection required/designed into the product or its production instead of robust mistake-proofed solutions
7. Inventory of consumables enabling proper functioning of design (too high or too low inventory)
8. Transportation of products or resources (for design functioning, and product fabrication and assembly)
9. Repeated optimization instead of problem solving solutions
10. Disposal of the used up product or consumables that enable the product to function properly

Design process has a lot in common with manufacturing process; therefore successful designs should have minimal content of the above wastes. Also, in the production phase, manufacturing must have processes that are capable of producing the products to design specification. Manufacturing must work closely with product design during the development process to:

- Ensure that engineers understand manufacturing limitations and modify their designs as practicable to minimize or outright eliminate chances of errors in manufacturing
- Prepare tooling and methods to be ready for consistent manufacture when the product is released for manufacturing

All of the above is really about avoiding expected and unexpected problems during product manufacturing. As the next two figures show, choosing robust solutions and elimination of problems early during design process is least costly in the long run.
Figure 1. A typical relationship between costs of correcting a design error at different phases of Product Realization Process. Numerical values are not for a specific project but for comparison purposes only.

A progression of costs similar to the one shown in Figure 1 is true for most manufacturing processes, whether new ones under development or existing ones during improvement. For novel and fast growing technologies the relationship may be even steeper due to a large number of unknown problems lying ahead. Figure 2 shows how likelihood of product defects increases with an increase of difficulty and inefficiency of manual assembly (low values of DFA index characterize designs inefficient from manual assembly stand point of view). It is typical of such designs to be complex and require working against basic physical principles, e.g. gravity, symmetry; instead of using them to the advantage.

Figure 2. Dependence of product reliability on product design characteristics described by Manual Assembly Efficiency. The higher the percentage the better the design. Based on data gathered by Motorola.
A recent study on best practices conducted by the PMDA (Product Development & Management Association) indicates that companies with the most successful new product development programs have the below common characteristics:
- Have more up-front activities at the beginning of the development process
- Do more up-front thinking and less tweaking once an idea is implemented
- Strive for simplification since simple systems are less prone to failures, and give fewer opportunities to tweak
- Define goals:
  - If a goal is to keep an existing production process under control, then a mix of SPC/SQC and managerial procedures may be a solution (however costly and failure prone)
  - If a goal is to avoid mistakes and not to waste resources on quality control, then solution aiming at avoidance of mistakes is in order. A proactive system designed using underlying physical principles is in order, and the simpler one the better one.

The important issue in today’s dynamic industries is not a development of a single successful product or process, but continuous development of successful products. The deeply intertwined metrics for successful products and for a successful organization are: their value to customers, quality and engineering or/and financial efficiency.

The above can be summed up in 3-point design mantra:
- Product/process executes tasks necessary from final product point of view.
- Product/process does not execute tasks unnecessary from final product point of view.
- Developmental goals are ideal solutions not optimized (compromised) ones.

3. Design Improvements - What Are They?
3.1 Basic Types of Design Improvements

There is usually more than one possible solution to any engineering problem. Improvements to non-performing products and processes may be brought about by:
1. cosmetic improvements: betterment, optimization or ruggidization of already implemented solutions
2. fundamental improvements: implementation of new solutions or even innovations that are almost always innovative in the matter of application of physical and chemical principles to the problem at hand

The above mentioned cosmetic improvements are usually achieved using mathematics and statistics based tools. On the other hand, the fundamental improvements are primarily achieved by using principles of the surrounding physical world (very few abstract descriptors as it is in the case of cosmetic improvements). It is interesting to notice, that successful engineering designs are achieved by using both types of improvements, but ground breaking designs are achieved almost uniquely via fundamental improvements. More thoughts and some examples related to that matter can be found in various publications.
Well engineered products and processes have the right set of physical principles as a core of their design. Therefore, the improvements have a big chance of being implemented because they are conceptualized at the stage of functional analysis, at the beginning of design process (closer to the left in Figure 1 and closer to the right in Figure 2). With progression of design process, fundamental improvements start resembling more of fundamental changes – closer to the right in Figure 1, which results in products depicted with low Manual Assembly Efficiency as shown in Figure 2. As a result, when design process is fairly advanced, to keep costs in check, a multitude of cosmetic improvements is usually used. That underscores the importance of beginning the design process right; starting with functional analysis of the problem on hand, defining goals, assumptions, constraints, contradictions and benchmarking already available solutions.

3.2 Teaching How To Come Up With Design Improvements

It is very common that, while solving a problem, engineers do not try to find the root of the problem, but concentrate efforts on optimizing existing solutions which may not be based on the most suitable principles. That seems illogical, since using correct physical principle tends to give a simple and robust solution. On the other hand what could be the right solution is often beyond the reach of the particular problem solver working on it, or it is deemed too costly to pursue or implement. In 1716 Frenchman Mr. Gautier wrote an interesting observation in his “Text on Bridges”. He was the first to complain in writing about scientists of the day, who had no interest in practical matters, e.g. arches in bridges. Little over three decades later, structured training in science and its practical applications began with establishment of Ecole Nationale des Ponts et Chaussées in Paris in 1747. Since it was established to train engineers for French army, purely technical knowledge with view of military use only was considered the core of engineering education at the Ecole. A scientific base of military engineering knowledge was also delivered to the élèves during limited classroom sessions. Accounts of teaching problem solving to its élèves are limited to in-field training/apprenticeship with an experienced military officer.

Teaching of creativity and inventiveness is strongly related to the way engineers (also engineering students and in general students showing engineering aptitudes) think in action. How engineers think as compared to other professionals has been described by several authors, e.g. . These references do not explain though what makes engineers think creatively and how to build on it. The below described short projects, completed almost entirely in classroom with functional analysis and subsequent brainstorming as the most important parts of the exercise try to invoke unrestricted thinking and expression of ideas in small groups of students.

4. The Short Projects

During analysis of various types of project problems, the ones well suited for Mistake-Proofing improvements were judged as the most powerful tool in conveying and practicing “the simpler the better” approach to designing parts and processes. This is attributed to the fact that superior Mistake-Proofing solutions easily stand out from inferior ones. Projects assigned to groups of 3
to 7 people were solved almost entirely in class. All the problems called for Mistake-Proofing solutions, hence for some form of invention and not for optimization of the existing solution. A good knowledge of natural effects (primarily physical, and occasionally also chemical) is required in order to understand the problem and come up with feasible solutions. This type of projects gave multiple opportunities to repeat the design process even though in a much abbreviated form.

4.1 Short Introduction

Before the projects, students are introduced to the basics of Mistake-Proofing. Best error avoidance techniques giving robust process solutions are in order:

1. make error impossible to make by design
2. use error detection and automatically stop erroneous action
3. use error detection and alarm operator (active signals)
4. use status displays (passive signals)
5. use checklist (additional activity)

The students are asked to aim at the highest level of Mistake-Proofing and to find ideal solutions.

4.2 Examples of Projects

First projects are very simple (example in Figure 3). To avoid a processing problem one needs to alter tooling to take advantage of asymmetrical geometry. A variation of the first project allows for changing part design to help the process by adding an asymmetrical feature and designing tooling that takes advantage of this feature (Figure 4). Following projects also involve use of asymmetry and symmetry. To eliminate insertion problem of wrong orientation of the part, either asymmetry or symmetry is added (Figure 5). The changes to the feature serve no functional purpose for the part. Their only function is to mistake-proof the assembly process. Later projects are more complex, requiring knowledge of physical effects, and capability of using them for finding solutions (example and one of solutions in Figure 6). Other variations of this problem include: containers with high L/D ratio, containers with low L/D ratio, conical containers, glass containers, and square containers.
Figure 3. Example of initial problem for short project. Mistake-Proofing by using existing geometry. Large hatched circles illustrate datum simulators, small black circles illustrate pins for mistake-proof insertion. (a) part can be inserted in any way, (b) use of existing part feature to change fixture to provide mistake-proof insertion (use of tab on right).

Figure 4. Mistake-Proofing by changing design geometry. Large hatched circles illustrate datum simulators, small black circles illustrate pins for mistake-proof insertion. (a) part can be inserted in any way, (b) added non-functional but non-harmful feature (rounded pocket on top) and its use to change fixture to provide mistake-proof insertion.

Figure 5. Mistake-Proofing by changing design geometry. (a) part can be inserted using either end: correct on left, incorrect on right, (b) one feature is changed to provide insertion asymmetry and no need to change the fixture, (c) both features are made alike providing insertion symmetry and no need to change the fixture – addition of non-functional although non-harmful feature.
Figure 6. Example of more involved problem. (a) Upside down container needs to be taken out of the conveyor belt. (b) Mistake-Proofing by using existing geometry of the object and changing surrounding environment. Advantage is taken of the geometry along with physical effect of degrees of freedom and gravity. Vibrating flat bottom gutter with a notch that will cause upside down container to fall off.

4.3 First Solutions

Groups quickly produce first solutions. As a rule however, these solutions have one or more of the below listed common characteristics (shortfalls):

1. addition of Hi-Tech infrastructure, e.g. sensors and computer driven actuators
2. lack of consideration for simplification of the given design
3. lack of problem definition
4. lack of translation of the defined problem into physical effects
5. effort to personalize the problem (blame an operator)
6. effort to find the blame upstream in the process and fix that
7. ardent avoidance of finding contradictions in the present design

All of these characteristics result in shortfall in delivering improvement-minded designs. With the exception of simple problems based on geometric features (present vs. absent or symmetrical vs. asymmetrical), the first solutions provided by project groups are always nothing more than cosmetic improvements. One important observation (not quantified yet): groups that have a member with more than a decade of industrial technical/engineering experience come up with subsequent solutions that use some physical effects pertinent to the design or process, and have traits of simplification. These solutions are usually conceived by these technically more mature students who draw from a number of examples seen in industry.
4.4 Student Learning

The simpler the better had to be reminded constantly, even after completion of few exercises. Easy problems were solved first, than degree of complexity or a possibility of many different solutions increased. Each group was required to produce a written report containing abbreviated documentation of problem solving, and above all, sketches. The documentation was subsequently used for in class presentation and had to address the following:

1. current problem(s)
2. goals of the process or functional requirements of the part
3. constraints
4. contradictions
5. evaluation criteria for new design
6. evaluation of solutions and their comparison (Pugh method or Weighted method or Dominic method)
7. choice of the best solution

One of the most daunting teaching tasks is to motivate students to prove that their solution has shortcomings, list them and look for a better (simpler or more robust) solution. It is like asking for development of lack of self-confidence and continuous self-doubting. That does not bring ‘feel good’ reward and is often taken personally. How to explain, and better yet convince, that one should not abandon searching for an ideal solution?

**Best Solution = Ideal Solution**

Multiple opportunities to repeat the design process, even though in a much abbreviated form, increase buying into the rigors of conceptual design work and needs of keeping at least a small documentation and ability to convey one’s idea to the rest of the group.

4.5 Group Dynamics

The team size and time constraints for each problem on hand try to imitate real work environment. Project groups were between 3 and 7 people. Group leaders usually emerged quickly, some just bossed around with their solutions. The best remedy for such behavior seems to be the requirement of semi-formal hand written report addressing earlier mentioned 7 points for each solution. Peer learning as observed was very good because every solution was acceptable, but each group had to have at least two people to agree to every presented solution. The time restrictions of 10 to 30 minutes for problem analysis plus brainstorming and evaluation of solutions, proved to be a positive factor in enhancing students’ focus on defining cause of the problem. It proved also to be a good opportunity to practice quick notation of the possible solutions and convincing explanation to other group members. As expected, requirement of abbreviated documentation was a double edged sword: good for registration and explanation of ideas, but after few solutions have been reached, it became detrimental in searching for new ones (“we have quite a few so far, let’s document them nicely and stop thinking about new ones” was
heard all too often in the classroom).

5. Summary

By nature, most humans are creative and some are inventive. Therefore, exposing students to variety of problems, scientific, technical and logical, allows for practicing methods of seeding creativity and finding solutions giving fundamental improvements. Problems used for the short projects were dealing primarily with manufacturing process and were easy to understand. Design problems requiring Mistake-Proofing were the easiest to understand and envision goals of the projects. The simpler the solution the more robust the process needs little explanation which makes design goals rather obvious.

No equipment was needed to run the projects. Groups were able to generate multiple solutions very quickly. Observation from running multiple back-to-back short projects, showed some development of design skills of at least half of the class population. Requiring ‘the simpler the better’ solutions and forbidding optimization as the ultimate improvement method (or worst yet, an ultimate goal) had to be constantly reminded during the first projects, and less often during subsequent ones. Requiring simple solutions has demonstrated in these short projects to foster drive for creative solutions.

Successful groups did not have a dominant leader with all the answers. Most creative students were the ones with very good hands on technical skills (most likely due to the fact that most of the projects dealt with failures of production processes using some type of a mechanical system).

Vast majority of students considered that type of peer learning very stimulating.

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