Design 4: Teaching Materials for the 4th Year Design Course

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This is a compilation of notes I have made for the USM Mechanical Engineering Design 4 course. Many other excellent resources are available for the various topics within the course, and this is simply presented as a rough framework for the individual professors to work with in teaching this course. It is my hope that this material will be added to and expanded upon by all the professors involved in the 4th year design course.

Overview

The course provides an overview of the mechanical design process. Students should be able to analyze a given mechanical design problem using standard engineering principals, taking the initial specifications to a conceptual design, developing a detailed design and proposing a well defined solution including manufacturing, assembly and testing details. The student should be familiar with and be able to appropriately apply tools such as the decision matrix, and FMEA as well as the typical mechanical analysis (ie. strain, power) and other aspects such as cost, and environmental concerns. The student will be required to communicate details of mechanical designs both written and orally. Students will be required to write reports, give presentations, answer questions en vivo and design an informational poster. Material presented in this course will be predominantly in the form of "case studies" applying the various design techniques to real-world problems in order to help build insight into the design process. The class will consist of lecture, group discussions and individual/group work sessions as well as poster, and oral presentations both individually and in groups.

Course Outline

Introduction to Design 4

Course explanation, expectations and grading scheme
Engineering Communications: Writing guide and public speaking

Steps in the Design Process

- Identifying the customer
- Problem Statement
  - Identifying the Constraints
  - Identifying the Criteria for Evaluation of Solutions
- Data gathering
  - Customer Side Data
  - Literature Search
- Analysis
  - Modeling and Data Analysis Tools
- Developing Ideas for a Solution
  - The Decision Matrix (eg. On Excel)
  - Failure Mode and Effect Analysis (eg. Automotive Electrical Power Connector)
  - Testing: How will the solution be evaluated
    - Develop the test schedule BEFORE fabricating the solution
  - Optimization (eg. OmniluX Blade Design)
  - Design for manufacturability / Industrial Design (Symmetry, common components)
- Prototyping and Fabrication
- Testing
  - Modification and feed back to design/fabrication process
- Volume Production
- Continuous Verification and testing
  - Statistical Process Control
  - Customer Feedback
- End Of Life Considerations

Additional Aspects

- Time Lining and Human Resource Management
- Costing
- Documentation
- Environmental Concerns

A Guide to Modeling for Mechanical Design

Often very simple models are useful early in the mechanical design process. Not every aspect of a design will require formal design, however many of the overall constraints can be refined with the use of appropriate models of the system. The models themselves should be based on sound application of the appropriate mechanical equations or principals. As the range of possible models is too large to completely describe all applicable models, we will give some general guidelines and examples.

One area which can easily be modeled is power and energy requirements. Obviously any device or process must obey the laws of conservation of energy, and the efficiencies of various mechanical/electrical components can be determined or estimated.

For example, if we are designing a machine for testing automotive tires (a tire dynamometer) several of the important parameters are known simply by defining the kind of vehicle/tire to be used. Given a vehicles speed, we can determine the tires rotational speed from its diameter. If the tire is to run on a large roller, we then have a relationship between the rotational speed of the roller, and the tire. Additionally if the vehicles power is known, and we assume there are 2 drive tires accepting ½ of the power each, we can determine how much torque is applied to the tire, and thus the roller. If the power to be applied directly to the tire, the dynamometer will be responsible for absorbing that amount of power. The power absorption device can be directly connected to the roller of the dyno, but more likely it will require gearing to increase the speed for easier absorption. The ratio can be determined from the specifications of the absorbing device, eg. Generator, which will have a rated power vs. speed curve. Further refinement of the model can include things such as the tire losses (ie. the amount of power lose to tire/surface heating during power transmission, approximately 5 to 10%) and gearing losses (typically assumed to be ~2% per stage). This model can easily be prepared in a spread sheet or other calculation environment and aid in the selection of appropriate gearing rations, roller diameters, and generator power ratings, as in the excerpt below:

Tire Dynamometer Modeling Calculations

Input Data (Knowns)		
Tire Diam	80	cm
Engine Power	20	kW
Wheel Power	10	kW

Parameters (Adjusted in the model)		
Vehicle Speed	80	kph
Roller Diameter	200	cm
Tire Power Loss	8	%
Gearing Ratio	3.5	
Gear losses	2	%
Generator Power	15	kW (max)
Generator Speed	1500	rpm

Output Parameters		
Vehicle Speed	22.22	m/s
Tire Speed	531	rpm
Tire Torque	180	Nm
Roller Speed	212	rpm
Roller Torque	450	Nm
Tire Power Loss	0.8	kW
Gearing Pow. Loss	0.2	kW
Generrator Power	9	Kw (actual)
Gen Speed	1576	rpm
Gen Torque	55	Nm

Cells in YELLOW are Inputs

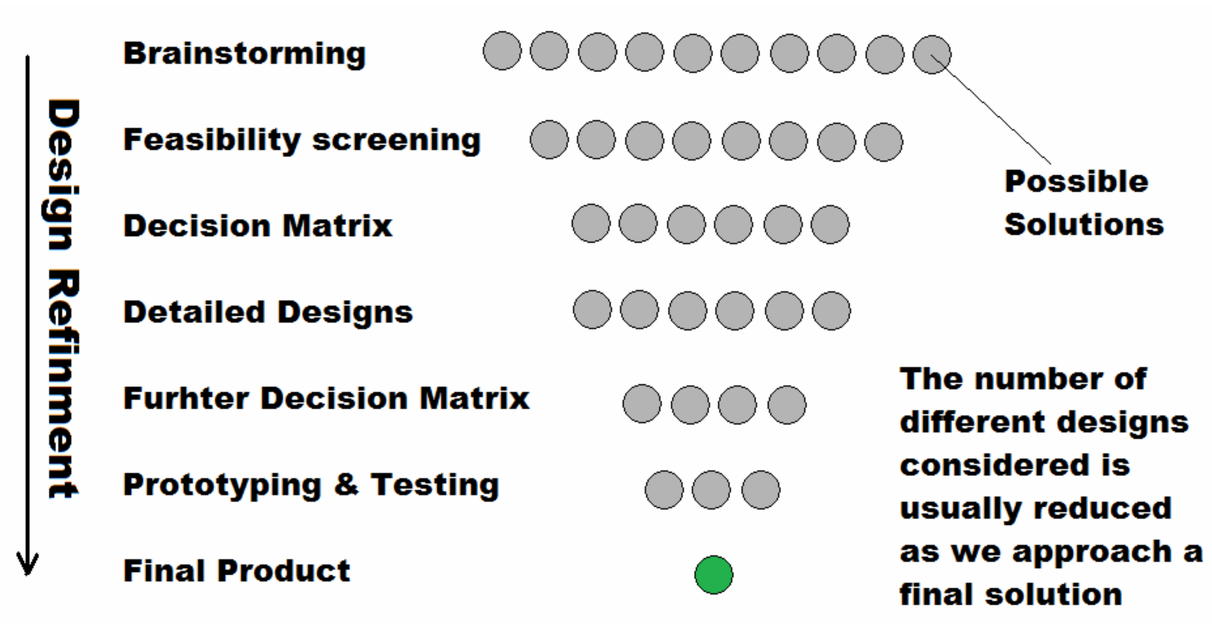
RED numbers are calculated based on Inputs

In the above example the tire diameter and engine power are taken as knowns. From this we calculate wheel power as ½ of the engine power. The Vehicle speed and roller diameter are inputs. Along with the other inputs these are used to calculate the vehicle speed in m/s, tire speed and torque, roller speed and Roller torque. Tire and gear losses are taken directly from the wheel power and the appropriate loss percentages. Finally given a generator rating (power and speed) we can estimate what gearing ratio is required to get the generator operating at its rated speed and torque. The gearing ratio, roller diameter or other parameters can be adjusted to confirm where the system will operate (ie. generator speed, power and torque).

Other areas which are readily modeled are things such as mass flows (conservation of mass), dynamics (mass, acceleration, velocity, displacement), solid mechanics (stress, strain, force, area, fatigue life, …) and etc.

A Guide to Decision Matrices

The decision matrix is a common tool in mechanical engineering design. It is a formalized way of deciding which is the best option for a given need out of several possibilities. There are a number of variations of this concept, here is the basic form.



Through the design process a large number of possible solutions (top) is gradually reduced down to a single solution for the final product (bottom). The decision matrix is an important step in this process.

Steps in Creating a Decision Matrix

1 Clearly define the decision that needs to be made.

2 List the criteria for evaluating the possible solutions. Things such as costs, weight, fatigue life, strength, corrosiveness, toxicity, benefits or whatever is appropriate for your specific part or assembly.

3 Assign a weight to each of the criteria. Higher numbers indicate the criteria is more important.

4 Make a 2-dimentional matrix with the criteria in the first column, the weights in the 2nd column and the possible options (solutions) in the upper row from the 3rd column onwards. Reserve a row at the bottom for the final evaluation score.

5 Fill in the decision matrix by evaluating who well each possible solution fulfills each criteria. Some like to use a 10=point scale (10 being the best possible fulfillment of the criteria, 0 = worst), but often it is easier to evaluate a reduced scale (eg. 3 = good, 2 = ok, 1 = poor, 0 = lousy). Be consistent with your evaluating scores!

6 Calculate the final score for each possible solution by summing the solution's scores multiplied by the weight for each criteria.

The option with the highest score is deemed to be the best, however this technique should only be used as a general guide. If the scores are widely disparate, ie. the highest score is much higher than the next closest score, it is likely that the result of the decision matrix evaluation is the right one. If several of the scores are close it is likely that further investigation is required. This is because although we are using a "linear" scale for the scoring of the possibilities a score of 2 may not indicate that it is twice as good as a score of 1.

Examples

Here is an example: Choosing a technique to go from one floor to another in a building. This decision will be made for 2 possible scenarios; in a mall and in an individual house.

The criteria for selection are the initial cost of installation, maintenance (cost or effort), ease of use, speed of conveyance, and floor area occupied. The possible solutions being evaluated are an Elevator, stairs, a walking ramp, a ladder or a pole (for sliding down). Obviously the weights of each of the criteria will be different for each application.

Here we'll use a score of 5 to signify the best fulfillment of the criteria, and 0 for the worst.

Floor-to-Floor access in a Mall

Here we assign a high weight to the factor of ease of use, because the mall will profit from having people accessing the 2nd floor. Cost is less of an issue, through still important.

Mall Floor Access	Weight	Elevator	Escalator	Stairs	Ramp	Ladder	Pole (slide)
Cost	2	1	2	4	4	5	5
Maintenance	3	2	2	3	4	2	4
Usability	5	4	5	3	3	1	0
Speed	3	1	3	2	3	1	0
Foot Print	2	3	2	3	1	5	5
Score	15	37	48	44	46	34	32

The best possible score would be the sum of the weights (15 in this case) times the highest evaluation, ie. 5, for a score of 75. According to this evaluation the escalator has the best overall score with a 48. The Ramp has the second highest overall score, 46, followed by the stairs at 44. Also you will note that the ladder and pole are in last place.

The stairs and the ramp are similar in construction, so many of their scores will be similar, but this analysis neglects finer details (such as: How long is the ramp? Is it designed for wheel chair access? It is linear, or a spiral?) Also the pole, while it will provide fast access for going down, it will be painfully slow for most people going up, so it received a zero in the "Speed" row.

One aspect this evaluation neglected is the volume of people that can be moved, and multi-story access. For multi-story access the elevator will obviously become more important. This analysis is, however, is good enough to highlight the face that in large malls you are most likely to see escalators as the major mode of floor-to-floor access.

Floor-to-Floor access in a House

In a house the cost and size are much more important factors. Here is how it effects our analysis, keeping the individual evaluations the same and just changing the weighting factors.

Home Floor Access	Weight	Elevator	Escalator	Stairs	Ramp	Ladder	Pole (slide)
Cost	5	1	2	4	4	5	5
Maintenance	2	2	2	3	4	2	4
Usability	5	4	5	3	3	1	0
Speed	3	1	3	3	3	1	0
Foot Print	4	3	2	3	1	5	5
Score	19	44	56	59	56	57	53

The maximum possible score now would be 95. For home use we can see that the stairs have the highest score, followed by the ladder. This does reflect the typical situation found in most homes.

Again care must be exercised when using this technique. According to this analysis ramps and escalators should be approximately equally as common for in-home use. While ramps are occasionally used for short flights, escalators are almost never found in homes.

Conclusion

The decision matrix is a valuable tool in the refining of a design. It can be used at several stages to eliminate less competitive designs or options, allowing you to focus further effort on the most likely to succeed designs. Once the number of options has been reduced to a reasonable number, more detailed designs can be investigated, prototyped and tested, ultimately leading to a single end-product.

However the student should keep in mind that the value of a decision matrix is only as good as the assumptions going into it. Often the values assigned in the decision matrix are "pulled out of the air", leading to incorrect final conclusions. Finally, as technologies advance, and more information is gained about the specifics of the problem and possible solutions, updated information should be used to re-evaluate the decision matrix and confirm that you are indeed headed in the right direction.

Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Anaylsis (FMEA) is a common tool in mechanical engineering design. The Goal of FMEA is to consider the possible failure modes very early in the design process, in order to design in fault tolerance and "fail safe" modes. There are many recourses on FMEA, this is just a brief review. I have broken FMEA down into the following steps: Determination of failure modes, Effects, Probability, Severity and Likelihood of detection, and finally the analysis of the FMEA matrix.

Determination of Failure Modes

The first, and most difficult step in FMEA is determining what the failure modes will be. We can focus on the systems functions, or go down to the individual component level. Initially FMEA should be applied to the overall system functionality, and later, as the design becomes clearer it can be reapplied at the component level.

Two ideas can help out identifying possible failure modes. First is that failure consists of: (1) not performing the desired function, or (2) performing any undesired function. The second concept is "Murphy's law" which states that "*Given enough time, any thing that can fail will fail.*" This means that ***any*** component, part, system or process will eventually fail.

For example the job of a breaking system in a vehicle is to stop the car when the break pedal is pressed. Looking at it another way its job is to NOT stop the car when the pedal is NOT pressed. Additionally any other undesired "side effect" should also be considered a failure. There for a failure can be defined as:

Possible Break System Failure Modes
Failure to stop the car when the pedal is pressed
Stopping the car when the pedal is not pressed
Causing unwanted effects: Loud screeching noise, Overheating, fire, leaking fluid…

Every component in the break assembly could also be looked at in the same way. For example the break shoes may grab or bind, causing harsh breaking, the pedal may require too much pressure (thus the use of power assist breaks), or the break shoes may wear out too fast…. Obviously when getting down to the component level there is a potential for a large number of failure modes.

Determination of Failure Effects

The effect of many failures may be obvious, but it still requires careful consideration. For example when thinking about the car's breaking system, a failure to break may simply mean the car takes longer to stop than expected, or that the car can not slow down at all. The effect of this could potentially be running the car off a cliff, or into a tanker truck full of gasoline parked in front of an orphanage next to a toxic waist facility. In this case the failure of the break system could cause a huge explosion, killing hundreds of people. Some less obvious failure effects could be something like a slow leak of hydraulic fluid. Eventually this will cause the breaks to fail, but typically breaking systems are "2-circuit" systems with diagonally opposed breaks on a common circuit. This, incidentally, is as a result of FMEA of break systems. Another effect of a leak could be to wet the break shoe or disk/drum with hydraulic fluid, reducing its effectiveness. This will cause an imbalance in the breaking force on the wheels, and can result in "pulling" to one side when breaking hard, or even cause the car to spin out of control during breaking. Other effects could be things like corrosion of paint on other components caused by the break fluid.

Estimation of Failure Probability

Again, in the absence of field data, the probability of failure is going to be an estimate. Some things should be considered: frictional joints wear out, guaranteed. Materials suffer fatigue failure at stress levels significantly below their yield point. Vibrations cause things to come loose, and rub, which causes wear. And it is always a good idea to remember that customers will always do crazy, ill-advised things with your products. With that in mind, let us examine the probabilities for our break system failure modes.

What is the probability that the break system will fail to stop the vehicle satisfactorily? The break shoes will definitely wear, but this will not lead immediately to total system failure. Instead it will cause a gradual reduction in break effectiveness, greater break pedal pressure, or a longer throw of the pedal before the breaks engage. In the case of extreme break shoe wear, the effected break will typically screech horribly, indicating that failure is occurring. Thus a total failure due to break lining wear is unlikely, but minor failure modes (too much pedal pressure, unwanted noise, break system pulling…) is almost guaranteed eventually.

Failure of the hydraulic break lines, eg. a puncture or rupture due to corrosion, is less likely than break shoe wear, but is more likely to cause a total system failure. Finally the pedal or mechanical linkage of the pedal (ie. pivot point) may wear, or fatigue, potentially resulting in total and immediate failure. The probability of this is related to the wear rate, and factor of safety of these components.

Sometimes probability will be broken down into the following obvious categories:

4 Probable Almost certain to occur, soon or often
3 Possible Will eventually occur
2 Unlikely Might happen given a long time
1 Very Unlikely Unlikely to ever happen

Estimation of Failure Severity

This is usually broken down into the following, obvious categories:

4 Catastrophic Causing fatalities or total loss of system
3 Severe Causing injuries or significant system damage
2 Marginal Causing minor annoyance, or damage
1 Negligible Anything less than the above

Estimation of Likelihood of Detection

This is important as undetected failures are more likely to cause further, secondary failures. Break lining wear generally does not result in tragedy because the wear becomes obvious long before causing catastrophic failure. If a vehicle is driven for a long time with warn-out breaks it will screech horrible, and gradually become less responsive. The relative amount of damage will increase slowly: initially the shoes would require replacement, next the drum/rotor might require turning, and eventually the assembly could require replacement. For a corrosion induced leak of hydraulic fluid the only warning might be a few spots of oil under the car, followed by very poor breaking, or total break system failure. This is much more likely to result in a catastrophic failure because it is less likely to be detected.

The FMEA Matrix

The exact scope of the analysis should be stated, and listed first including the specific parts, assembly or processes as well defined as possible. The matrix is formed with the failure modes form the 1st column, causes in the 2nd, effects in the 3rd, and Severity, Probability and Probability of detection in the 4th, 5th and 6th. The 7th column (Criticality) is calculated as the product of the Severity and Probability. Occasionally the probability of detection is used to calculate the criticality as well (less likely to be detected increases Criticality). Finally an 8th column is added for "Control Measures" being taken to avoid the given failure modes.

The Criticality is used to the rank the importance of the failure modes, and effort is apportioned appropriately.

FMEA EXAMPLE: Hybrid Vehicle Electrical Wiring

To illustrate the value of an FMEA analysis let's take a look at electrical hybrid vehicles. There are too many failure modes to consider, so we'll focus on just the high power electrical wiring and connections. Hybrid and electric vehicles require large amounts of electrical power for propulsion, so they therefore have high voltage, and high current power lines making their way around the inside of the vehicle. How can these fail?

1) The obvious failure modes are:

They fail to conduct the current properly (open circuit)
They fail by conduction current inappropriately (short circuit)

2) EFFECT: What could these failures cause?

Open Circuit:	Failure to accelerate car
	Failure to provide regenerative breaking
Short circuit:	Draining of battery power
	Destruction of power control components (over current)
	Fire

3) What is the probability of the failures?

Open Circuit: Pulling on wiring harness happens when components are replaced or serviced. Any accident could cause stress on the wiring by dislocating components. Vibration will loosen connections, and fatigue fail metal components. The probability is therefore taken to be ***Possible***. It won't happen immediately, but eventually it is inevitable.

Short Circuit: Again any of the above mentioned factors (maintenance, accidents) can cause short circuits. Additionally vibrations will cause wires to "chafe". This is a well documented failure mode in aircraft, where wiring harnesses subject to vibrations rub against aircraft structural components, wearing through the insulating coatings causing intermittent short circuiting. This may not happen immediately, but eventually it is almost certain to occur, therefore this failure mode also receives a ranking of ***Possible***.

4) Severity of Failure

We need to look at each of the effects to judge the severity of its effects. For each failure mode we can rank it as 1 for a Negligible failure, to 4 for a Catastrophic failure:

Open Circuit:

Failure to accelerate car	This is a major annoyance, Severity = 2
Failure to provide regen. breaking	Minor annoyance, Severity = 1

Short circuit:

Draining of battery power	Major Annoyance, Severity = 2
Destruction of power components	Major failure, Severity = 3
Fire	Catastrophic, Severity = 4

5) Likelihood of detection (prior to worst-case failure)

Any of these failures could spontaneously happen. An "open circuit" is most likely not going to be noticed until it occurs. Chaffing might be noticed, but it is unlikely unless the entire wiring harness underwent a careful inspection, which is unlikely. All of these we could rank as "unlikely to be detected" prior to failure. We could assign a number 4 to this (4 being unlikely to get detected prior to failure, 1 being easily detected) to these.

6) Resulting FMEA Matrix. Calculating criticality from the Probability times Severity we have the resulting matrix:

Failure Mode	Effects	Probability	Severity	Detectability	Criticality
Open Circuit	Failure to Acellerate	3	2	4	6
	Failure to Regenerate	3	1	4	3
Short Circuit	Battery Draining	3	2	4	6
	Power Component Destruction	3	3	4	9
	Fire	3	4	4	12

Clearly the short-circuit failures are the worst (highest Criticality rankings). What are appropriate control measures to prevent these kinds of failures?

Some of the answers spring directly from the analysis. For example, in step 3 when determining the probability of failures we mentioned several factors that can contribute to failures: pulling or tugging on wiring harness, vibrations and chaffing. Preventing these things by design can help us develop a more robust system.

To make the system immune to tugging or pulling, the wire connections should be made with bolted joints, or latching connectors (ones that can not simply be pulled apart). Bolted joints should have lock washers to prevent vibrations from loosening the connections

To prevent chaffing wires should be placed in conduits and held by tie-downs at reasonable spacing's. This will prevent the wires from moving, and if they do they will not rub directly against frame components. The tie-downs should be polymer (to prevent cutting of the wires) or perhaps polymer coated metal clips.

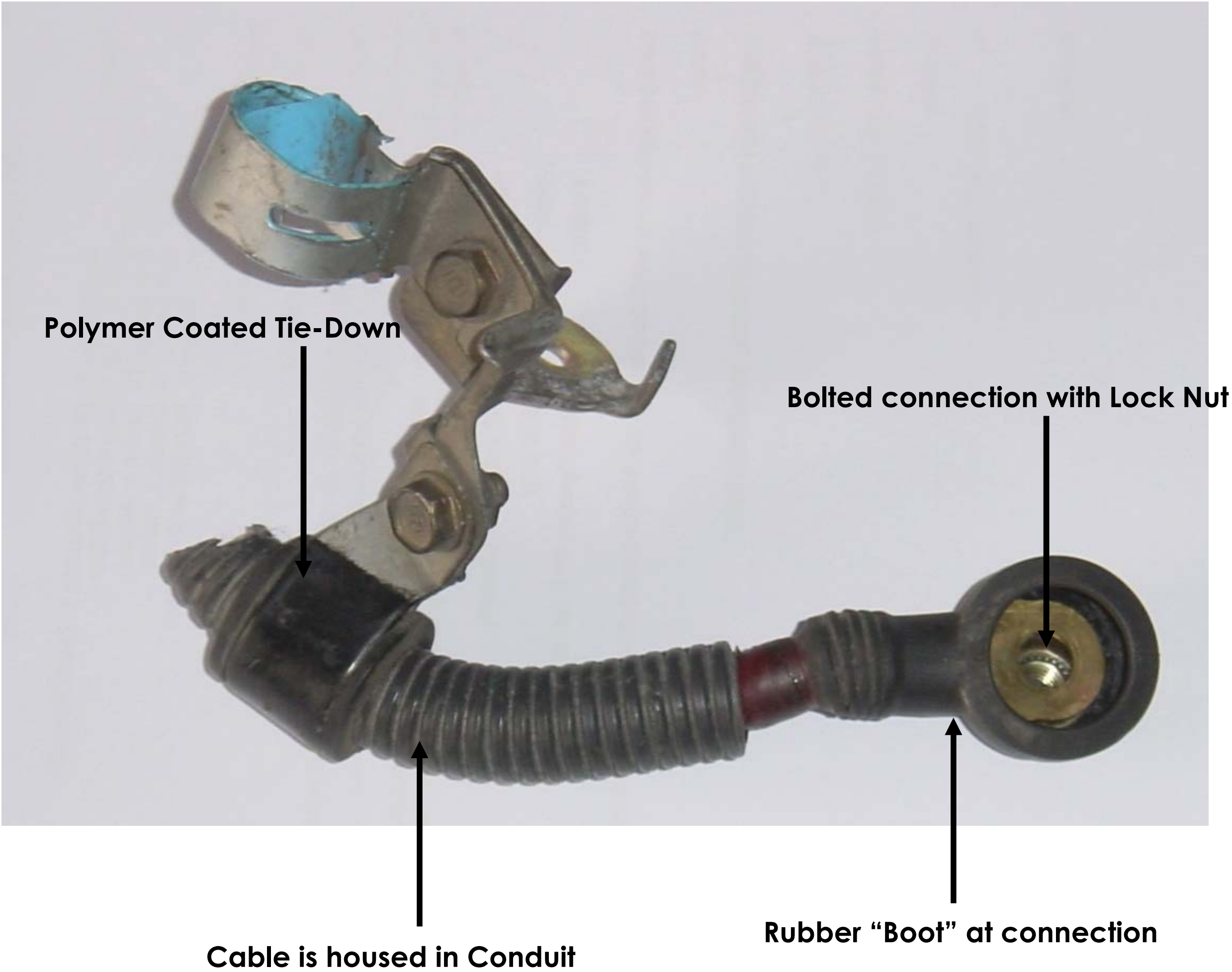
Additional measures to prevent short circuiting is could be to include rubber "boots" around any exposed wires or connections. Fusing the power lines is another good way to mitigate the negative effects of shorts when they do occur.

Entering this data into the matrix we might have something like the following:

Failure Mode	Effects	Probability	Severity	Detectability	Criticality	Control Measures
Open Circuit	Failure to Acellerate	3	2	4	6	Bolted Joints with Lock Washers. Latching Connectors.
	Failure to Regenerate	3	1	4	3	
Short Circuit	Battery Draining	3	2	4	6	Wires in Conduits, Polymer Wire Tie-doens, Boots at joints, Fuses in high current lines.
	Power Component Destruction	3	3	4	9	
	Fire	3	4	4	12	

Although this has been a very abbreviated example, the control measures listed in the right side of the matrix are exactly the same control measures you are likely to see in any automotive electrical power system, as evidenced in the fotograph of an automotive alternator power connection seen below.

Automotive Electrical Power Connection



Design For Manufacturability (DFM)

Design for Manufacturability is another well documented technique in Mechanical Design. Here are some pointers on designing parts and assemblies that are easy to make, and thus less expensive to manufacture, and maintain. There are a lot of sources of information on this, this is just a sampling. Basically it is all common-sense. It is best to “design in” manufacturability from the start, rather than to slip it in at the last minute. Consider the following as you generate your initial design concepts.

(The following section is taken from “DFM: Kenneth A. Crow, DRM Associates” with modifications)

1. Simplify the design and reduce the number of parts because for each part, there is an opportunity for a defective part and an assembly error. The probability of a perfect product goes down exponentially as the number of parts increases. As the number of parts goes up, the total cost of fabricating and assembling the product goes up. Automation becomes more difficult and more expensive when more parts are handled and processed. Costs related to purchasing, stocking, and servicing also go down as the number of parts are reduced. Inventory and work-in-process levels will go down with fewer parts. As the product structure and required operations are simplified, fewer fabrication and assembly steps are required, manufacturing processes can be integrated and lead-times further reduced. The designer should go through the assembly part by part and evaluate whether the part can be eliminated, combined with another part, or the function can be performed in another way. To determine the theoretical minimum number of parts, ask the following: Does the part move relative to all other moving parts? Must the part absolutely be of a different material from the other parts? Must the part be different to allow possible disassembly?

2. Standardize and use common parts and materials to facilitate design activities, to minimize the amount of inventory in the system, and to standardize handling and assembly operations. Common parts will result in lower inventories, reduced costs and higher quality. Operator learning is simplified and there is a greater opportunity for automation as the result of higher production volumes and operation standardization. Limit exotic or unique components because suppliers are less likely to compete on quality or cost for these components. The classification and retrieval capabilities of product data management (PDM) systems and component supplier management (CSM) systems can be utilized by designers to facilitate retrieval of similar designs and material catalogs or approved parts lists can serve as references for common purchased and stocked parts.

3. Design for ease of fabrication. Select processes compatible with the materials and production volumes. Select materials compatible with production processes and that minimize processing time while meeting functional requirements. Avoid unnecessary part features because they involve extra processing effort and/or more complex tooling. Apply specific guidelines appropriate for the fabrication process such as the following guidelines for machinability:

- For higher volume parts, consider castings or stampings to reduce machining
- Use near net shapes for molded and forged parts to minimize machining and processing effort.
- Design for ease of fixturing by providing large solid mounting surface & parallel clamping surfaces
- Avoid designs requiring sharp corners or points in cutting tools - they break easier
- Avoid thin walls, thin webs, deep pockets or deep holes to withstand clamping & machining without distortion
- Avoid tapers & contours as much as possible in favor of rectangular shapes
- Avoid undercuts which require special operations & tools
- Avoid hardened or difficult machined materials unless essential to requirements
- Put machined surfaces on same plane or with same diameter to minimize number of operations
- Design work pieces to use standard cutters, drill bit sizes or other tools
- Avoid small holes (drill bit breakage greater) & length to diameter ratio > 3 (chip clearance & straightness deviation)

4. Design within process capabilities and avoid unneeded surface finish requirements. Know the production process capabilities of equipment and establish controlled processes. Avoid unnecessarily tight tolerances that are beyond the natural capability of the manufacturing processes. Otherwise, this will require that parts be inspected or screened for acceptability. Determine when new production process capabilities are needed early to allow sufficient time to determine optimal process parameters and establish a controlled process. Also, avoid tight tolerances on multiple, connected parts. Tolerances on connected parts will "stack-up" making maintenance of overall product tolerance difficult. Design in the center of a component's parameter range to improve reliability and limit the range of variance around the parameter objective. Surface finish requirements likewise may be established based on standard practices and may be applied to interior surfaces resulting in additional costs where these requirements may not be needed.

5. Mistake-proof product design and assembly so that the assembly process is unambiguous. Components should be designed so that they can only be assembled in one way; they cannot be reversed. Notches, asymmetrical holes and stops can be used to mistake-proof the assembly process. Design verifiability into the product and its components. For mechanical products, verifiability can be achieved with simple go/no-go tools in the form of notches or natural stopping points. Products should be designed to avoid or simplify adjustments. Electronic products can be designed to contain self-test and/or diagnostic capabilities. Of course, the additional cost of building in diagnostics must be weighed against the advantages.

6. Design for parts orientation and handling to minimize non-value-added manual effort and ambiguity in orienting and merging parts. Basic principles to facilitate parts handling and orienting are:

- Parts must be designed to consistently orient themselves when fed into a process.
- Product design must avoid parts which can become tangled, wedged or disoriented. Avoid holes and tabs and designed "closed" parts. This type of design will allow the use of automation in parts handling and assembly such as vibratory bowls, tubes, magazines, etc.
- Part design should incorporate symmetry around both axes of insertion wherever possible. Where parts cannot be symmetrical, the asymmetry should be emphasized to assure correct insertion or easily identifiable feature should be provided.
- With hidden features that require a particular orientation, provide an external feature or guide surface to correctly orient the part.
- Guide surfaces should be provided to facilitate insertion.
- Parts should be designed with surfaces so that they can be easily grasped, placed and fixtured. Ideally this means flat, parallel surfaces that would allow a part to picked-up by a person or a gripper with a pick and place robot and then easily fixtured.
- Minimize thin, flat parts that are more difficult to pick up. Avoid very small parts that are difficult to pick-up or require a tool such as a tweezers to pick-up. This will increase handling and orientation time.
- Avoid parts with sharp edges, burrs or points. These parts can injure workers or customers, they require more careful handling, they can damage product finishes, and they may be more susceptible to damage themselves if the sharp edge is an intended feature.
- Avoid parts that can be easily damaged or broken.
- Avoid parts that are sticky or slippery (thin oily plates, oily parts, adhesive backed parts, small plastic parts with smooth surfaces, etc.).
- Avoid heavy parts that will increase worker fatigue, increase risk of worker injury, and slow the assembly process.
- Design the work station area to minimize the distance to access and move a part.
- When purchasing components, consider acquiring materials already oriented in magazines, bands, tape, or strips.

7. Minimize flexible parts and interconnections. Avoid flexible and flimsy parts such as belts, gaskets, tubing, cables and wire harnesses. Their flexibility makes material handling and assembly more difficult and these parts are more susceptible to damage. Use plug-in boards and backplanes to minimize wire harnesses. Where harnesses are used, consider fool proofing electrical connectors by using unique connectors to avoid connectors being miss-connected. Interconnections such as wire harnesses, hydraulic lines, piping, etc. are expensive to fabricate, assemble and service. Partition the product to minimize interconnections between modules and co-locate related modules to minimize routing of interconnections.

8. Design for ease of assembly by utilizing simple patterns of movement and minimizing the axes of assembly. Complex orientation and assembly movements in various directions should be avoided. Part features should be provided such as chamfers and tapers. The product's design should enable assembly to begin with a base component with a large relative mass and a low center of gravity upon which other parts are added. Assembly should proceed vertically with other parts added on top and positioned with the aid of gravity. This will minimize the need to re-orient the assembly and reduce the need for temporary fastening and more complex fixturing. A product that is easy to assemble manually will be easily assembled with automation. Assembly that is automated will be more uniform, more reliable, and of a higher quality.

9. Design for efficient joining and fastening. Threaded fasteners (screws, bolts, nuts and washers) are time-consuming to assemble and difficult to automate. Where they must be used, standardize to minimize variety and use fasteners such as self threading screws and captured washers. Consider the use of integral attachment methods (snap-fit). Evaluate other bonding techniques with adhesives. Match fastening techniques to materials, product functional requirements, and disassembly/servicing requirements.

10. Design modular products to facilitate assembly with building block components and subassemblies. This modular or building block design should minimize the number of part or assembly variants early in the manufacturing process while allowing for greater product variation late in the process during final assembly. This approach minimizes the total number of items to be manufactured, thereby reducing inventory and improving quality. Modules can be manufactured and tested before final assembly. The short final assembly lead-time can result in a wide variety of products being made to a customer's order in a short period of time without having to stock a significant level of inventory. Production of standard modules can be leveled and repetitive schedules established.

11. Design for automated production. Automated production involves less flexibility than manual production. The product must be designed in a way that can be more handled with automation. There are two automation approaches: flexible robotic assembly and high speed automated assembly. Considerations with flexible robotic assembly are: design parts to utilize standard gripper and avoid gripper / tool change, use self-locating parts, use simple parts presentation devices, and avoid the need to secure or clamp parts. Considerations with high speed automated assembly are: use a minimum of parts or standard parts for minimum of feeding bowls, etc., use closed parts (no projections, holes or slots) to avoid tangling, consider the potential for multi-axis assembly to speed the assembly cycle time, and use pre-oriented parts.

12. Design printed circuit boards for assembly. With printed circuit boards (PCB's), guidelines include: minimizing component variety, standardizing component packaging, using auto-insertable or placeable components, using a common component orientation and component placement to minimize soldering "shadows", selecting component and trace width that is within the process capability, using appropriate pad and trace configuration and spacing to assure good solder joints and avoid bridging, using standard board and panel sizes, using tooling holes, establishing minimum borders, and avoiding or minimizing adjustments.