Embodiment Design (reference: Pahl & Beitz Chap.7)

By now, in the design process, should have:

- Concept
  - Final picks on working principles for each subfunction
  - Rough overall arrangement (layout)
- Logic behind the concept (this logic could be amended, adjusted, or rearranged as more design information is discovered in the embodiment phase, and so the logical path to the design needs to be clean and clear)
  - Customer Requirements
  - Engineering Characteristics
  - Engineering Design Specification
  - Functional Decompositions (possibly several)
  - Morphological Matrix of Working Principles

Next step is Embodiment Design, in which the rough Concept is clarified into workable systems, components, and features.

Note that Embodiment Design is not Detail Design. Detail Design is (i.e., Embodiment Design is not):

- Final CAD of parts, assemblies; surface dimensioning and tolerancing
- Detail manufacturing and parts purchase plan
- Precise material selection
- Surface finishes and tolerances
- Documentation for manufacturing, operation, maintenance
- Regulatory filings

The point of Embodiment is to bring the design to just short of this final detailed description, so that the effort of Detail Design is only applied to the right systems, components, and features (i.e., re-detailing effort is minimized).

Embodiment Design is:

- Product Architecture
  - Arrangement into modules
  - Layout (with subassemblies and critical components)
- Configuration Design
  - Initial Sizing (idealized analysis)
  - Design process for parts
- Parametric Design
  - Final sizing (numerical analysis or model test)
  - Dimensions and tolerances
  - Make assemblies work
Note:
The concept, while selected, is still open. Embodiment brings new ideas, constraints, and means for assessment. When these come to light, work back through the concept logic to support the new path.

Also:
Some detail design topics are so important (i.e., design drivers) that they should be covered in embodiment
**Method 1** (Dieter & Schmidt) – best for more open-ended design problems (form is completely unknown) – more adapted to product architecture and configuration design

**Steps**

- **Product Architecture**
  - Functional schematic – accomplishment of functions and accompanying flows of:
    - Force
    - Motion
    - Energy
    - Material
    - Information
  - Clustering – grouping into modules
  - Layout of modules
    - Bus – standard connection to an intermediary interface
    - Slot – individualized connection to an intermediary interface
    - Sectional – modules directly connected
  - Interfaces and module performance
  - Functional requirements for module
  - Layout within module
  - Components of module
  - Interfaces with other modules/buses
  - Performance/evaluation models
    - Analytical
    - Computational
    - Physical
  - Note: after each step, check and modify all upstream steps to maintain flow of design logic

- **Configuration design**
  - Process
    - Module requirements
      - Constraints
      - Flows
      - Product life cycle needs
      - Human interfaces
      - Intermodule connections
    - Consider combination of modules
    - Consider standardization of modules
    - Refine & patch overall configuration
    - Iterate and re-configure (or re-architect, or re-concept) if there are too many problems
    - Analyze for functional factors (e.g., simple beam theory, Bernoulli’s equation)
    - Develop alternatives (substitute, combine, decompose, magnify, minify, rearrange)
    - Avoid bending stresses
Results
- Define standard parts
- Define special purpose parts
- Define standard assemblies (could be used as subassemblies of components)
- Define overall assembly and special purpose subassemblies
- Parametric design (more detailed modeling and analysis)

HP1200C inkjet printer – Product Architecture

Functional Structure:

Modularization:
Tentative physical decomposition:

- **Product:** Printer
  - **Paper Handling System**
  - **Ink System**
    - **Ink Print Cartridge**
    - **Carriage Mechanism**
  - **Chassis**
  - **Base**
  - **Electronics**
    - **Fan/Vents**
    - **Filter**
    - **Housing**
    - **Input Paper Tray**
    - **Hertzian Paper Index Mechanism**
    - **Output Paper Tray**
    - **Switch**
    - **Power Supply**
    - **Printer Controller & Display**

Rough geometric layout:

- **Print Cartridge and Carriage**
- **Paper Handling System (Index and Advance Mechanism)**
- **Chassis**
  - **Output Paper Tray**
  - **Input Paper Tray**
- **Base**
Method 2 (Pahl & Beitz) – best for high domain knowledge/highly constrained design problems – more adapted to configuration and parametric design

- Steps
- Rules
- Principles
- Guidelines

Steps (Progression of design logic – progression of events will iterate and run back and forth up and down this list – Same steps for: Product Architecture; Configuration; Parametric)

1. Identify those requirements that drive physical form
   a. Those EC’s that drive the physical form of the design
   b. Less form-critical elements can be added on later, or covered by form-modification

2. Identify spatial constraints
   a. Like where it has to go
   b. Or side that it is loaded on
   c. Or center of gravity limitations

3. Size main function carriers - Analysis

4. Make a scaled layout
   a. Maybe hand-drawn (to scale, with a straight-edge)
   b. Maybe CAD (can be simplified CAD – blocks and blobs instead of detailed components)

5. Make several possible layouts
   a. Different embodiments to meet same concept
   b. Different ways to give physical form to the same concept
   c. Significantly different – idea is to find new arrangements (and maybe better), not just do the exercise
   d. Try TRIZ to generate different ideas
   e. Record logic behind each embodiment alternative
Figure 7.100. Systematic variation of the structure of an automatic teamaker (after [7.280]), investigating the configuration of the water kettle, the tea container and the teapot.
6. Fill in means for functions so far neglected
7. Fill in means for auxiliary functions
8. Make a more detailed layout with the above sort of filled in, then adjust as necessary
9. Make a really more detailed layout (by now it really has to be in CAD)
   a. Note that you still have several concept alternatives!
   b. Check back up the chain of steps
      i. Does everything still look good?
      ii. Could anything be better?
10. Now evaluate
    a. Embodiment alternatives v. EC’s (analysis) and v. CR’s (logical)
11. And choose
    a. Quantitative decision (matrix, or matrices)
12. Deeper evaluation of chosen embodiment
    a. What bothers you? → fix it.
    b. Be critical
    c. Gather outside input
    d. Maybe a formal review
13. Examine possible failure modes (what if _____ happens?). Then improve the embodiment (make sure improvement does not inhibit some other function!)
14. Parts list (generic, but try to specify what is most important, and address the build/buy question)
15. Final embodiment
    a. Layout (arrangement) drawings
    b. Define functions of each module and critical component (with drawings as necessary)
Rules (things to keep to while following each step; i.e., applying disciplined design methodology – try to avoid too much ‘seems right’)

1. Clarity
   a. Of function, working principle, layout, safety, ergonomics, manufacturability, assembly/transport, operation, maintenance, recycling
   b. Of sequence of actions (mechanically, what happens next, and why does it have to be that?)
   c. Repeatable
   d. Of location-fixing (six degrees of freedom)
   e. Of statical determinacy (equivalent strain)
      i. If rigid, do not over-constrain
      ii. If flexible, do not under-attach

![Diagram of bearing arrangements]

Figure 7.4. Basic bearing arrangements: a) Locating and nonlocating arrangement: left-hand locating bearing takes up all the axial forces, right-hand sliding bearings permit unimpeded axial movement due to thermal expansion; accurate calculations are possible. b) Stepped bearing arrangement: the axial loading of the bearings depends on the preload and thermal expansion and cannot be clearly determined; a modification is the “floating arrangement” in which the bearings are provided with axial clearance; in that case, thermal expansion is possible to a limited extent but there is no precise shaft location. c) Spring-loaded bearing arrangement: here the disadvantages of the stepped bearing arrangement are largely eliminated, though the constantly applied axial load may reduce the bearing life; forces resulting from thermal expansion can be determined by spring force deflection diagrams; the shaft is located precisely provided the axial force $F_s$ acts only towards the right or does not exceed the preloading $F_p$. 
Figure 7.6. Avoiding double fits: a Tapered shaft-hub connection with interference (shrink) fit. The simultaneous axial location against the shaft collar and the taper seat creates a double fit: the radial pressure due to the interference fit cannot be determined. The right solution would be to use either a taper without a shaft collar or to use a cylindrical seat with a shaft collar. b Supported linear slide using a guiding sleeve in a housing. The simultaneous location of the housing at two points complicates the assembly process. A possible solution is shown in the figure on the right. c Spring clip of such a length that the lower end touches the tube at the same time as the pressure point touches the tube. The user will not be able to determine whether the clip is blocked by the tube or whether the spring force has to be overcome. The correct solution is shown in the figure on the right.
Figure 7.5. Combined rolling-element bearing. a Transmission path of radial forces not clear; b combined rolling bearing with the same elements as in a, but clear identification of the transmission paths of the radial and axial forces

Figure 7.7. Combined shaft–hub connection achieved by means of shrink fit and key: an example of not applying the principle of clarity
2. Simplicity
   a. “Simplificate and add lightness” – Ed Heinemann
   b. Similar to clarity – directness of action
   c. Least complex
   d. Tried and true
   e. Make the design as dumb as it can possibly be and still function (KISS; also information axiom in axiomatic design methodology)
   f. Check function, working principle, layout, safety, ergonomics, manufacturability, assembly/transport, operation, maintenance, recycling
3. Safety
   a. Direct safety
      i. Keep accident from happening
      ii. Fail safe
      iii. Redundant
      iv. Visible condition
      v. Evaluate risk, reliability, availability, cost
      vi. Safety of operator, society, environment
   b. Indirect safety
      i. What if {breaks, loosens, slips, rusts, etc.}? 
      ii. What is the next safety barrier item (in the chain of failure)?
      iii. Warnings are not legally sufficient defense against claims of
           negligent product design
      iv. Testable failure chain strategy
   c. Of function, working principle, layout, safety, ergonomics,
      manufacturability, assembly/transport, operation, maintenance, recycling

Figure 7.16. Fastening of components: the covering of the bolted connection maintains function and prevents broken
parts migrating in the event of bolt failure
Figure 7.20. Layout of a quick-action valve. In the event of a drop in oil pressure \( p \), the spring force, the flow pressure on the valve face and the weight of the valve act together to guarantee the rapid closure of the valve.

Figure 7.22. Protective devices employed to protect against excessive pressure build-up in pressure vessels: a two safety valves (not safe against common faults); b safety valve and shear plate (principle redundancy)
**Principles** (procedures – subject to which Rules are applied while following each Step)

1. Force transmission (flow of force through module; transfer of force between modules; sufficient material to carry force)
   a. Principle of uniform strength (along entire force path)
      i. Stress ∝ strain = ∆l/l
      ii. Chain breaks at weakest link = greatest stress = greatest strain
      iii. Less stress (strain) in one part/feature means more ∆l (and stress) somewhere else
      iv. Strength uniformity in all of the stress modes:
         1. Axial
         2. Transverse
         3. Bending
         4. Twisting (torsion)
   b. Principle of direct transmission (minimize change in direction of force)
      i. Shortest path – for constant strain, less ∆l, less material, less weight, less misalignment, less vibration
      ii. No (abrupt) changes in force direction
      iii. Avoid bending stress (generally less than tensile/compressive strength, as long as compressive stress does not lead to buckling)
   c. Principle of matched deformation (matched flexibility)
      i. Avoid stress concentration
      ii. Avoid fatigue
      iii. Example – torque steer

*Figure 7.32.* a Shaft–hub connection with strong “force flowline deflection”. Torsional deformations of shaft and hub in opposite sense ($\psi =$ angle of twist). b Shaft–hub connection with gradual “force flowline deflection”. Torsional deformations of shaft and hub in the same sense
Figure 7.27. Supporting a machine frame on a concrete foundation: a very rigid support due to short force transmission path and low stress on the baseplates; b longer force transmission path, but still a rigid support with tubes or box sections under compression; c less rigid support with pronounced bending deformation (a stiffer construction would involve the greater use of materials); d more flexible support under bending stresses; e very flexible support using a spring, which transmits the load in torsion. This can be used to alter the resonance characteristics.
d. Principle of balanced forces (stability)
   i. Reduce reaction loads with symmetric and opposing force elements
   ii. Reduce friction loads with symmetric and opposing motions

Figure 7.35. Fundamental solutions for balancing associated forces, illustrated via a turbine, helical gears and cone clutch
2. Principle of division of tasks
   a. Some components/features carry multiple functions/subfunctions
      i. Different functions may push component/feature design in different directions
      ii. Might be better to use separate components/features for each subfunction instead
      iii. One design feature for every functional requirement satisfies the independence axiom of axiomatic design methodology
   b. Some components/features cannot meet a function (say strength) without exceeding a constraint (say size)
      i. Function may be divided between multiple identical components/features
      ii. Requires either equivalent stiffness or automatic deformation adjustment
      iii. Multiple identical design features satisfies the least information axiom of axiomatic design methodology
   c. Division of tasks increases manufacturing and assembly cost, and reduces reliability – performance gain must be worth it.
3. Principle of self-help
   a. Operating forces push structure together (instead of pull it apart)
   b. Reaction to operating forces is fail-safe
   c. Leads to improved contact area
      i. More heat transfer, friction, sealing
      ii. Less stress concentration
   d. Parameter – range of operating forces
      i. Normal loads
      ii. Emergency loads
   e. Self-protecting – alternate load path engages an overload (hopefully, engagement is gradual)

Figure 7.49. Layout of an inspection cover. $I =$ initial effect; $O =$ overall effect; $p =$ internal pressure
4. Principle of stability (disturbances self-reduce)
   a. Stress-strain
   b. Thermal deformation
   c. Wear
5. Principle of bi-stability (disturbance causes excursion to 2\textsuperscript{nd} stable state)
6. Principles for fault-free design
   a. Simple manufacture and assembly, with loose tolerances
   b. Design out faults
   c. Clarity – working principles are insensitive to disturbance
   d. Balance – disturbances trigger balanced reactions

Figure 7.61. Piston in cylinder, tilted due to a disturbance, after [7.225]: \(\text{a}\) resulting pressure distribution produces an effect that increases the disturbance (unstable behaviour); \(\text{b}\) resulting pressure distribution produces an effect that opposes the disturbance (stable behaviour)

Figure 7.64. Taper roller bearings in which the shaft heats up more than the housing: \(\text{a}\) thermal expansion leads to increased loading and hence to unstable behaviour; \(\text{b}\) thermal expansion leads to reduced loading and hence to stable behaviour
Figure 7.76. Location of inner casings in outer casings: a arrangement of guides does not allow for expansion: oval deformation of the housings can cause guides to jam; b arrangement allowing for expansion: guides lie along symmetry lines, no jamming with oval deformation.

Figure 7.78. Connection by means of a steel stud and aluminium flange (7.200): a stud endangered because aluminium flange has greater expansion; b incorporation of Invar expansion sleeve with a coefficient of expansion close to zero helps to balance the relative expansion of flange and stud.
Guidelines (checklist of things to watch out for, in making a “well-engineered” design)
Known as “Design for X”, where X is:

1. Thermal expansion
   a. Often caused by friction - Avoid letting more expansion lead to more friction
   b. Over-constrained case
      i. Expansion = stress
      ii. Stress = deformation
   c. Sufficiently-constrained case
      i. Sliding constraint on general path – slider must pivot
      ii. Sliding constraint on line of part symmetry – need not pivot
   d. Relative expansion
      i. Static
      ii. Transient

2. Creep and relaxation
   a. Creep at high temperature and/or load
      i. Reduction in modulus of elasticity
         1. Steel > 300°C
         2. Polymer > 100°C
      ii. Plastic strain (lattice deformation over time at > 0.75\(\sigma_{yield}\))
      iii. Surface creep
         1. Like scraping off material
         2. Pins should always be shorter than the holes they go in
   b. Relaxation (creep in response to pre-load)
      i. Loss of spring coefficient
      ii. Loosening of bolted joints (bolt clamping pressure)
   c. Design considerations
      i. Allow excess strength in joints
      ii. Provide cooling
      iii. Direction of creep should not lead to jamming mechanism
3. Corrosion
   a. Types
      i. Atmospheric – exposure to electrolyte (usually water)
      ii. Transition – region of gas/liquid interface
      iii. Bimetallic – galvanic current through electrolyte
      iv. Stress – accelerated by static or fluctuating stress
      v. Motion – accelerated by electrolyte motion
   b. Effects
      i. Local pitting
      ii. Stress concentration
      iii. Uniform reduction in thickness
      iv. Sludge deposit
   c. Design
      i. Prevention
         1. Drain moisture traps
         2. Low surface area
         3. Insulate (against condensation)
         4. Low liquid flow rates (< 2 m/s)
         5. Less susceptible material
      ii. Resistance
         1. Surface coating (i.e., paint)
         2. Surface treating (shotblasting, nitriding)
         3. Sacrificial anodes
      iii. Tolerance
         1. Thicken
         2. Design for uniform life
         3. Inspectability
Free surface corrosion

Uniform corrosion

Indentation corrosion

Cavity corrosion

Crevice corrosion

Contact corrosion

Bimetallic corrosion

Deposit corrosion

Stress corrosion

Stress corrosion

Fatigue corrosion

Static tensile stress

Alternating stress

Abrasion corrosion

Erosion corrosion

Cavitation corrosion

Surface stress with micro-movement

Flow abrasion

Local pressure with implosion

Selective corrosion within the material

Intercrystalline corrosion

Separation corrosion

Ni, Al

Zn

Zinc separation

Nickel separation

Porosity of cast iron

Figure 7.91. Types of corrosion
Figure 7.92. Drainage of components susceptible to corrosion: a design of bases encouraging and impeding corrosion; b wrong and right arrangement of steel sections; c brackets made of channel section with drain-hole

Figure 7.93. Examples of welded joints: a susceptible to crevice corrosion; b correct design, after [7.260]; c crevice-free welding of pipes, also improves resistance to stress corrosion cracking
4. Wear
   a. Types
      i. Adhesive – self-forming particles
      ii. Abrasive – micromachining by particles
      iii. Sanding/polishing/honing – a little wear is good
   b. Design
      i. Stress reduction
         1. Less normal force
         2. More interfacing area
      ii. Choose resistant materials
      iii. Lubricate wear surfaces
      iv. Replaceable wear surfaces
      v. Inspectability
      vi. Graceful failure of mechanism

Figure 7.94. Increased corrosion at the transition from the gaseous to the liquid state, after [7.260] due to concentration of the medium in the region of the water line of a vertically arranged condenser. This can be remedied by raising the water level.
5. Ergonomics
   a. Anthropomorphy
      i. Human variability range: 5\textsuperscript{th} percentile female $\rightarrow$ 95\textsuperscript{th} percentile male (see data tables on course website)
      ii. Accommodate whole range
      iii. Accommodation may require machine adjustment
      iv. Static: stowage of human body (fit, comfort, safety, vision)
         1. Seat size
         2. Seat support (points, stiffness, capacity)
         3. Body containment
         4. Sightlines to environment
         5. Sightlines to displays & controls (& readability)

\textbf{Figure 7.99. Application of a body template to evaluate the sitting position in a truck, after [7.70]}
v. Dynamic: reach envelop, body part arcs, passage planes, grip and support points, tactile cues
   1. Control actions (definitions of tasks)
   2. Control reach
   3. Access to stowage
   4. Control visual and tactile cues
   5. Ingress/egress (entire path)
   6. Delethalization (removal of injury sites)
   7. Hazard egress (from degraded structure)
   8. Maintenance actions

b. Biomechanics - anthropometry plus:
   i. Comfort (of action)
   ii. Strength (@ machine interface)
   iii. Speed (@ machine interface)
   iv. Accuracy (reliability)
   v. Endurance (repeatability)

---

Fig. 5.4 Arm strength for the 5th percentile man. Note: 90° is straight down from the shoulder; 180° position is straight forward from the shoulder. [5.14]
6. Aesthetics (understandable, fewer shapes, organized, fit for function)
   a. Variables
      i. Structure
      ii. Form
      iii. Color
      iv. Graphics
   b. Metrics
      i. Identifiable function
      ii. Suited to function
      iii. Usability
      iv. Perceived value
   c. Process
      i. Overall shape related to function
      ii. Harmony of sub-shapes
      iii. Consider design from outside to in (as opposed to functional design from inside to out)
      iv. Bring Industrial Design in early
<table>
<thead>
<tr>
<th>Embodiment Guidelines</th>
<th>Wrong</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Select an expression</strong></td>
<td>Vertical three-phase AC motor</td>
<td>Stable, compact</td>
</tr>
<tr>
<td>Provide a recognisable and uniform expression</td>
<td>Unstable, top-heavy</td>
<td>Light, easy to handle</td>
</tr>
<tr>
<td>Iron:</td>
<td>Heavy, immobile</td>
<td></td>
</tr>
</tbody>
</table>

| **Structure the overall form** |                                |                                |
| Structure in a identifiable way | Vacuum pump                    | Box shape                      |
| Divide into clearly distinguishable areas | Steering device                | Clear arrangement L-shape      |
|                                    | Unidentifiable                 |                                |

**Figure 7.101.** Embodiment guidelines for aesthetics: expression and structure
<table>
<thead>
<tr>
<th>Embodiment Guidelines</th>
<th>Wrong</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unify the form</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimise the number of different forms</td>
<td>Generator</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rope winch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Closed structure</td>
<td></td>
</tr>
<tr>
<td><strong>Aim for similar forms and contours</strong></td>
<td>Bearing</td>
<td></td>
</tr>
<tr>
<td><strong>Adjust lines</strong></td>
<td>Air conditioner</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Confusing, inhomogeneous</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Block form</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer form</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7.102.** Embodiment guidelines for aesthetics: form
<table>
<thead>
<tr>
<th>Embodiment Guidelines</th>
<th>Wrong</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Support using colour</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Match colour to form</td>
<td><img src="image1" alt="Wrong" /></td>
<td><img src="image2" alt="Right" /></td>
</tr>
<tr>
<td>Reduce colours and material differences</td>
<td><img src="image3" alt="Wrong" /></td>
<td><img src="image4" alt="Right" /></td>
</tr>
<tr>
<td>Choose one main colour supported by complementary colours</td>
<td><img src="image5" alt="Wrong" /></td>
<td><img src="image6" alt="Right" /></td>
</tr>
<tr>
<td><strong>Complement with graphics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use uniform styles for fonts and graphic symbols</td>
<td><img src="image7" alt="Wrong" /></td>
<td><img src="image8" alt="Right" /></td>
</tr>
<tr>
<td>Unity expression</td>
<td><img src="image9" alt="Wrong" /></td>
<td><img src="image10" alt="Right" /></td>
</tr>
<tr>
<td>Adjust size, form and colour of the graphics to the other forms and colours</td>
<td><img src="image11" alt="Wrong" /></td>
<td><img src="image12" alt="Right" /></td>
</tr>
</tbody>
</table>

*Figure 7.103. Embodiment guidelines for aesthetics: colour and graphics*
7. Production
   a. Metrics
      i. Part/subassembly is fool-proof to produce successfully
      ii. Quality control measures are measureable
      iii. Clarity of part allows for reconfiguring
   b. Issues
      i. Design of the production process (material flow through machines and stations)
      ii. Subdivision (modularization) for production
      iii. Assembly sequence
   c. Construction categories
      i. Differential construction (many pieces)
      ii. Integral construction (one big part)
      iii. Composite construction (permanent assembly)
      iv. Building block construction (interchangeable parts with other subassemblies)
   d. Design for production guidelines
      i. Casting
      ii. Sintering
      iii. Forging
      iv. Extruding
      v. Bending
      vi. Machining – turning
      vii. Machining – boring
      viii. Machining – milling
      ix. Machining – grinding
      x. Stamping or laser-cutting
      xi. Welding
   e. Material selection
      i. Applicability of production procedures & tools
      ii. Ability to handle, store
      iii. Measureable quality control
      iv. Commercial availability
   f. The big question: build or buy?
      i. Buy if you can
      ii. Build if you must
8. Assembly
   a. Actions
      i. Storage
      ii. Handling
         1. Identify
         2. Orient
         3. Pick up
         4. Move
      iii. Positioning
         1. Place
         2. Align
      iv. Joining
      v. Adjusting
      vi. Securing
      vii. Inspecting
   b. Assembly environment
      i. Run size
         1. One-off
         2. Batch
         3. Continuous
      ii. Responsibility
         1. In-house
         2. Farmed-out
      iii. Labor
         1. Unskilled
         2. Skilled
   c. Automation
      i. Hand-made
      ii. Semi-automatic
      iii. Fully automatic
   d. Guidelines
      i. Layout for assembly
      ii. Assembly interfaces
      iii. Elements of assembly interfaces
9. Maintenance
   a. Measures
      i. Monitor
      ii. Assess
      iii. Service (fill, clean)
      iv. Inspection
      v. Repair
         1. Failure repair
         2. Preventative repair
            a. Interval
            b. Condition
   b. Guidelines
      i. Identical part lives
      ii. Self-balancing
      iii. Self-adjusting
      iv. Standard components
      v. Easy access & disassembly
      vi. Low part count, simplicity
      vii. Low tool count, simplicity
      viii. Clear manual, maintenance points labeled
      ix. Maintenance procedures safe and ergonomic

10. Test
    a. Function, performance, operations, life
    b. Vibration, moisture, heat
    c. Strength, strain, failure
11. Removal
12. Dismantling
13. Recycling (recover and reuse raw material)
   a. Green design
      i. Less material
      ii. Less exotic materials
      iii. Prefer repurposed parts and materials
   b. Green manufacturing
      i. Less raw material wastage
      ii. Repurposing of wastage
      iii. Less process material
      iv. Less contamination of process material
   c. Processing the waste stream
      i. Crush
      ii. Cut
      iii. Separate
         1. Mechanical
         2. Chemical
         3. Magnetic
         4. Buoyant
d. Guidelines
  i. Ease of disassembly (like maintenance)
  ii. Ease of removal
  iii. Ease of transport
  iv. Separability of material
  v. Objective of recycled material
  vi. Inhibit corrosion and decay
  vii. Provide recycling guide
14. Remanufacture
15. Disposal
  a. Transport
  b. Stability/toxicity
16. Reliability (lack of availability)
17. Durability
18. Risk of accident or failure
  a. Risk of uncertain analysis
  b. Risk of uncertain environment (or loads, or conditions)
  c. Risk cannot be entirely removed or even minimized – some level of risk must be accepted
  d. Generally technical risk is inversely proportional to commercial risk
  e. Guidelines
    i. Design for “what if”
    ii. P&B recommend – start with the cheapest solution, leading to market acceptance and compilation of service history, and then adjust to more robust solution if necessary
19. Adaptability (repurposing, variations in use environment)
  a. Process standards (ISO 9000, test standards)
  b. Design standards (ASME Boiler Code)
  c. Part standards (ANS screw thread)
  d. Most are voluntary (though certification is offered)
  e. Some are statutory (FAA)
  f. “If the rules don’t fit, break ‘em – but be damn sure you’re right” – Ed Heinemann
21. Distribution
  a. Packing
  b. Shipping