Module VII: Design Optimization

Computer Aided Design & Analysis

1. Purpose and Application of Optimum Design

Design optimization is a systematic engineering process that seeks the best possible design solution by mathematically formulating the objective (e.g., minimum cost, weight, or energy) and various constraints (e.g., strength, manufacturability, safety). It is applied to:

- Improve **performance** (e.g., lighter, stronger, more efficient structures)
- Achieve **cost savings** and resource efficiency
- Enhance **product reliability**, safety, and quality
- Shorten development cycles by reducing the number of design iterations
- Balance trade-offs among conflicting requirements (like weight vs. strength or performance vs. cost)

Common applications include structural optimization in automotive/aerospace, mechanism efficiency in robotics, and process parameter tuning in manufacturing systems[1] [2] [3].

2. Primary and Subsidiary Design Equations

- **Primary Design Equation (PDE):**
  - Expresses the *main objective* or functional requirement for optimization—either a feature to be maximized or an undesirable effect to be minimized (like weight, cost, or power).
  - Example: For a shaft, the PDE might minimize weight given strength and rigidity requirements.
- **Subsidiary Design Equations (SDE):**
  - Equations expressing other functional requirements or constraints that must also be met but are not part of the main goal.
  - Typically include stress limits, deflection criteria, manufacturability, or safety factors in mechanical designs.
  - SDEs act as side conditions or relationships linking materials, geometry, and performance.

In practice, the primary equation defines the optimization goal, while subsidiary equations handle additional constraints that the design must satisfy for feasibility and acceptance[4] [5].

3. Limit Equations

- **Limit equations** mathematically define the permissible values or boundaries for design variables, often arising from material properties, physical constraints, or functional requirements.
- Examples:
  - Stress $ \leq $ Maximum Allowable Stress
  - Deflection $ \leq $ Acceptable Limit
  - Geometric features within specified maximum/minimum range

These equations ensure design safety and compliance, acting as constraints in the optimization process[6] [5].

4. Normal, Redundant, and Incompatible Specifications

Specification Type	Description	Example
Normal	All equations/constraints are consistent and mutually compatible; at least one feasible solution exists.	Maximum stress and deflection within allowable limits.
Redundant	Extra constraints do not affect feasible region or outcome—solution still exists and is the same.	Two similar deflection constraints, one stricter than the other.
Incompatible	Constraints conflict or are impossible to satisfy simultaneously—no feasible solution exists.	Strength requirement exceeds what is physically possible for the material or geometry chosen.

- Redundancy can add reliability checks or accommodate manufacturing variability, but too many or conflicting constraints (incompatible) must be resolved by revisiting specifications or relaxing certain criteria to reach feasibility.

5. Computer-Aided Design Optimization

Computer-aided design optimization integrates **CAD/CAE tools** with optimization algorithms to automate, simulate, and improve design performance under real-world constraints:

- **Process Integration:**
  - 3D CAD models are parameterized with design variables (dimensions, material choices, etc.)
  - Objective functions and constraints (based on PDE/SDE/limits) are implemented through simulation or mathematical models.
- **Optimization Algorithms:**
  - Gradient-based and non-gradient-based methods (e.g., Sequential Quadratic Programming, Genetic Algorithms, Bayesian Optimization).
- **Workflow:**
  1. Define variables, objectives, and constraints.

2. Computer simulates the effects of various combinations.
3. Algorithms search for the solution that best meets optimization goals while satisfying all constraints.

- **Benefits:**
  - Efficient exploration of large, complex design spaces.
  - Data-driven decision-making enhanced by simulation fidelity.
  - Rapid virtual prototyping, reducing need for physical trials [1] [2] [7] [8].

Popular CAE Tools for Design Optimization:

- ANSYS, Abaqus, Altair OptiStruct, Autodesk Fusion 360, Siemens NX, and MATLAB/Simulink.

Summary Table: Key Concepts in Design Optimization

Topic	Description/Role
Purpose of Optimum Design	Achieve best possible balance of performance, cost, and reliability
Primary Equation	Objective function—goal to maximize or minimize
Subsidiary Equation	Secondary constraints (stress, deflection, manufacturability, etc.)
Limit Equations	Boundaries for variable values (safety, material, geometry)
Normal/Redundant/Incompatible	Types of constraint relationships affecting feasibility
Computer-Aided Optimization	CAD/CAE-driven simulation/automation of design improvement

Effective design optimization ensures that engineering solutions are robust, feasible, and resource-efficient, leveraging computational power for rapid iteration, enhanced quality, and innovation across all fields of engineering design. [1] [2] [4] [8] [5]

⁂

1. https://en.wikipedia.org/wiki/Design_optimization
2. https://www.sciencedirect.com/topics/computer-science/design-optimization
3. https://www.sciencedirect.com/topics/engineering/design-optimization
4. https://www.rjwave.org/ijedr/papers/IJEDR2104019.pdf
5. https://www.scribd.com/document/862891240/CAD-Practical-8-1
6. https://www.scribd.com/document/144379110/Optimization-Methods-Lecture-India
7. https://2021.help.altair.com/2021/hwsolvers/os/topics/solvers/os/design_optimization.htm
8. https://arxiv.org/html/2403.08473v1