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ICT Innovation – Spring 2015

MSc in Computer Science and MEng Telecom. Engineering

EIT Masters ITA, S&P,SDE

Lecture 07 – Robust Design

Prof. Fabio Massacci

Robust Design and Quality in the Product

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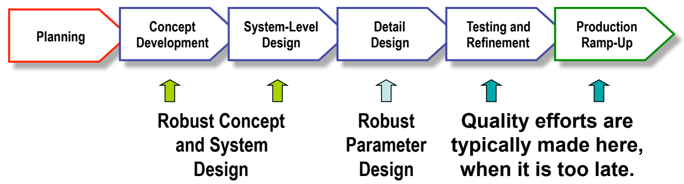

Goals for Designed Experiments

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- **Modeling**
  - Understanding relationships between design parameters and product performance
  - Understanding effects of noise factors
- **Optimizing**
  - Reducing product or process variations
  - Optimizing nominal performance

Esercise: the gun shooter

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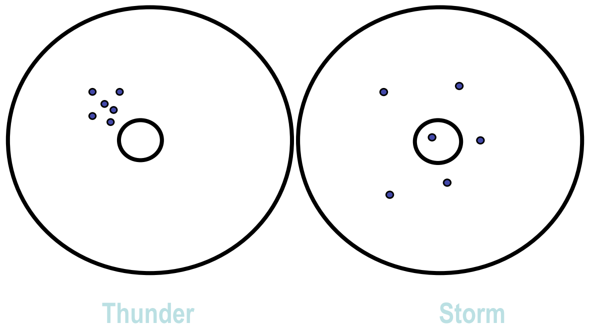
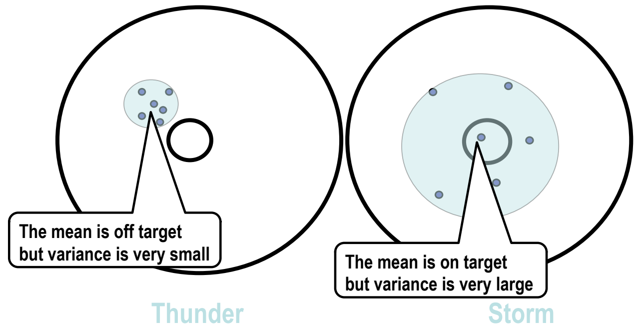
- **Testing a laser-guided rifle**
  - Thunder
  - Storm
- **Experiment**
  - Ask 6 soldiers to take aim and shoot
  - Identify best gun
- **Decide what to do in response**

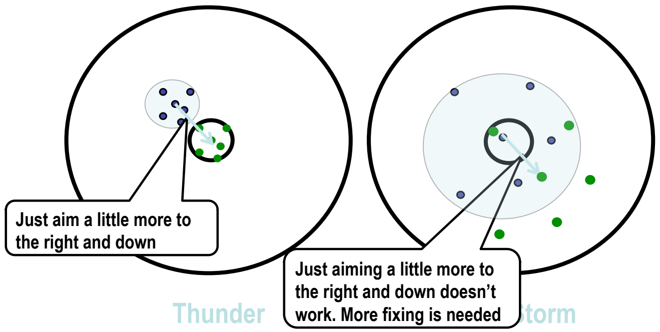
Who is the better target shooter?



Who is better? Mean vs Variance



Who is better? Mean vs Variance



Robust Designs

- A robust product or process performs correctly, even in the presence of noise factors
- e.g. shooters (aka users)
- Noise factors may include:
  - parameter variations
  - environmental changes
  - operating conditions
  - manufacturing variations

Response to Factors: linear

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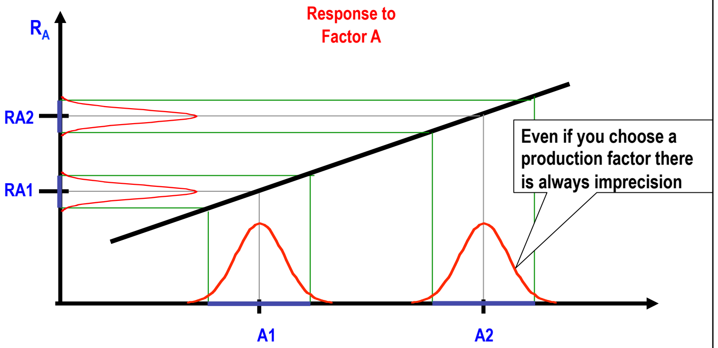

Can chose Factor A between A1 and A2
- **No difference in Variance**
- **Difference in Mean (R2 > R1)**

Response to Factor: Exponential/Power Law

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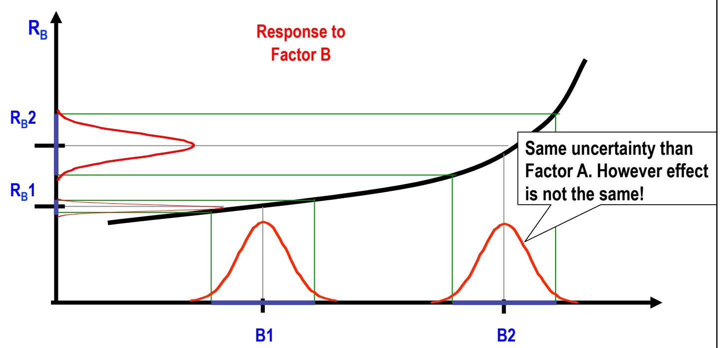

Can chose Factor B between B1 and B2
- **Difference in Variance**
- **Difference in Mean (RB2 > RB1)**

Exploiting Non-Linearity to Achieve Robust Performance

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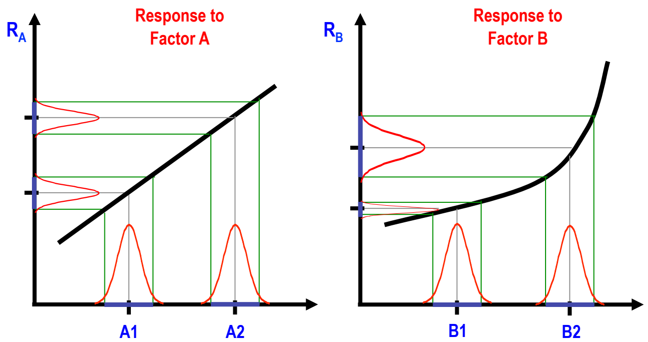

Response = $R_A(A) + R_B(B)$
What level of factor B gives the robust response?
How do we use factor A?

Robust Designs

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- **A robust product or process performs correctly, even in the presence of noise factors**
- **e.g. shooters (aka users)**
- **Noise factors may include:**
  - parameter variations
  - environmental changes
  - operating conditions
  - manufacturing variations
- **How do we find the robust design?**

Robust Design Procedure
Step 1: Parameter Diagram

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- Step 1: Select appropriate controls, response, and noise factors to explore experimentally.
- Control factors (input parameters)
- Noise factors (uncontrollable)
- Performance metrics (response)

Robust Design Example:
Seat Belt Experiment

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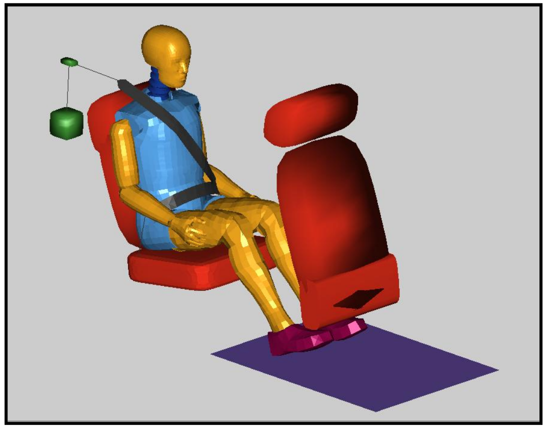

The "P" Diagram

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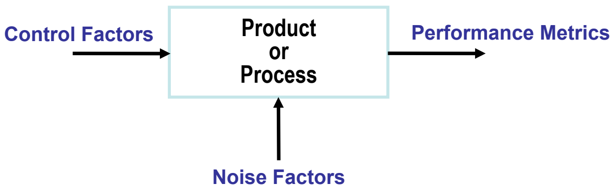

Parameter Diagram

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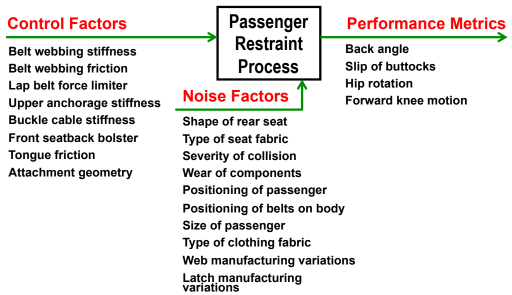

Example: Brownie Mix

- **Control Factors**
  - Recipe Ingredients (quantity of eggs, flour, chocolate)
  - Recipe Directions (mixing, baking, cooling)
  - Equipment (bowls, pans, oven)
- **Noise Factors**
  - Quality of Ingredients (size of eggs, type of oil)
  - Following Directions (stirring time, measuring)
  - Equipment Variations (pan shape, oven temp)
- **Performance Metrics**
  - Taste Testing by Customers
  - Sweetness, Moisture, Density

Robust Design Procedure
Step 2: Objective Function

Step 2: Define an objective function (of the response) to optimize.

- **maximize desired performance**
- **minimize variations**
- **target value**
- **signal-to-noise ratio**

Types of Objective Functions

Larger-the-Better e.g. performance $\eta = \mu^2$	**Smaller-the-Better** e.g. variance $\eta = 1/\sigma^2$
Nominal-the-Best e.g. target $\eta = 1/(\mu - t)^2$	**Signal-to-Noise** e.g. trade-off $\eta = 10\log[\mu^2/\sigma^2]$

Robust Design Procedure
Step 3: Plan the Experiment

- **Step 3: Plan experimental runs to elicit desired effects.**
  - Use full or fractional factorial designs to identify interactions.
  - Use an orthogonal array to identify main effects with minimum of trials.
  - Use inner and outer arrays to see the effects of noise factors.

Experiment Design: Full Factorial

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- Consider k factors, n levels each.
- Test all combinations of the factors.
- The number of experiments is nk .
- Generally this is too many experiments, but we are able to reveal all interactions.

Expt #	Param A	Param B
1	A1	B1
2	A1	B2
3	A1	B3
4	A2	B1
5	A2	B2
6	A2	B3
7	A3	B1
8	A3	B2
9	A3	B3

2 factors, 3 levels each:

$n^k = 3^2 = 9$ trials

4 factors, 3 levels each:

$n^k = 3^4 = 81$ trials

Experiment Design: One Factor at a Time

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- Consider k factors, n levels each.
- Test all levels of each factor while freezing the others at nominal level.
- The number of experiments is 1+k(n-1).
- BUT this is an unbalanced experiment design.

Expt #	Param A	Param B	Param C	Param D
1	A2	B2	C2	D2
2	A1	B2	C2	D2
3	A3	B2	C2	D2
4	A2	B1	C2	D2
5	A2	B3	C2	D2
6	A2	B2	C1	D2
7	A2	B2	C3	D2
8	A2	B2	C2	D1
9	A2	B2	C2	D3

4 factors, 3 levels each

$1+k(n-1) =$

$1+4 \times 2 = 9$ trials

Experiment Design: Orthogonal Array

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- Consider k factors, n levels each.
- For every pair of factors each level of one factor is paired with all levels of the other factors
- The number of experiments is order of (k-1)n.
- This is the smallest balanced experiment design.
- Trade-off effects and interactions are confounded.

Expt #	Param A	Param B	Param C	Param D
1	A1	B1	C1	D1
2	A1	B2	C2	D2
3	A1	B3	C3	D3
4	A2	B1	C2	D3
5	A2	B2	C3	D1
6	A2	B3	C1	D2
7	A3	B1	C3	D2
8	A3	B2	C1	D3
9	A3	B3	C2	D1

4 factors, 3 levels each:

$(k-1)n =$

$(4-1)3 = 9$ trials

Using Inner and Outer Arrays

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- Induce the same noise factor levels for each combination of controls in a balanced manner

3 factors, 2 levels each:
L4 outer array for noise

4 factors, 3 levels each:
L9 inner array for controls

				E1	E1	E2	E2
				F1	F2	F1	F2
				G2	G1	G2	G1
A1	B1	C1	D1				
A1	B2	C2	D2				
A1	B3	C3	D3				
A2	B1	C2	D3				
A2	B2	C3	D1				
A2	B3	C1	D2				
A3	B1	C3	D2				
A3	B2	C1	D3				
A3	B3	C2	D1				

inner x outer =
L9 x L4 =
36 trials

Using Inner and Outer Arrays

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- Induce the same noise factor levels for each combination of controls in a balanced manner

This design is not balanced
F1 never tested with G1

This design is balanced
Check it out

				E1 F1 G2	E1 F2 G1	E2 F1 G2	E2 F2 G1
A1	B1	C1	D1				
A1	B2	C2	D2				
A1	B3	C3	D3				
A2	B1	C2	D3				
A2	B2	C3	D1				
A2	B3	C1	D2				
A3	B1	C3	D2				
A3	B2	C1	D3				
A3	B3	C2	D1				

Robust Design Procedure
Step 4: Run the Experiment

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- Step 4: Conduct the experiment.
- Vary the control and noise factors
- Record the performance metrics
- Compute the objective function
- Possibly more than one single run for each trial!
  - So total is (k-1) factors * n levels * m runs

Why More Than a Single Trial?

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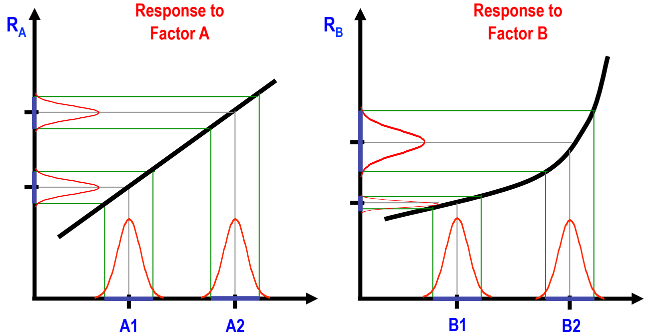

Seems obvious that there is a difference between linear and exponential effects
BUT we don't know if B is linear or exponential before running the experiment!

Why More Than a Single Run?

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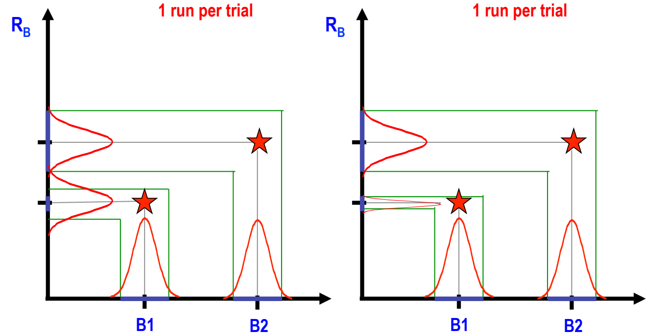

How can we tell which of the two effects is the real one?

Why More Than a Single Run?

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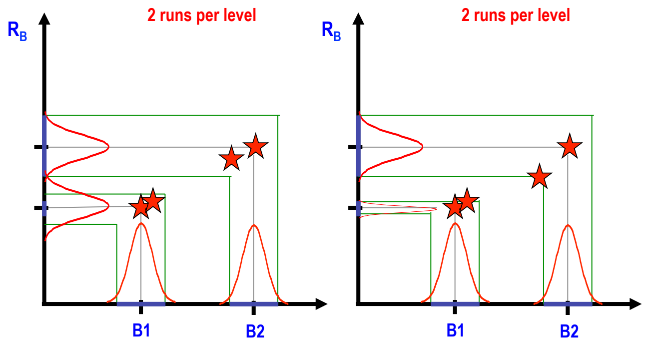

How can we tell which of the two effects is the real one?

Why More Than a Single Run?

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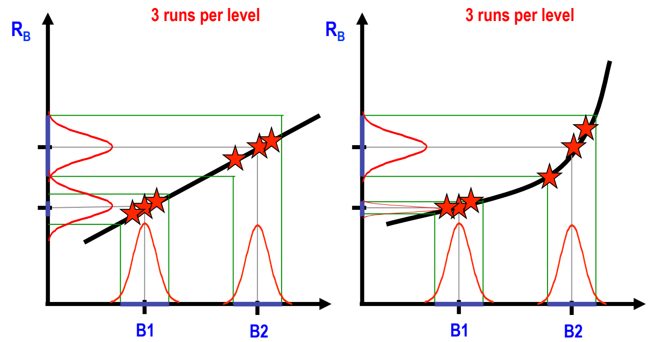

How can we tell which of the two effects is the real one?

Robust Design Procedure
Step 5: Conduct Analysis

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- **Step 5: Perform analysis of means and variance.**
  - Compute the mean value of the objective function for each factor setting.
  - Identify which control factors reduce the effects of noise and which ones can be used to scale the response. (2-Step Optimization)

DOE Plan and Data

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	A	B	C	D	E	F	G	N-	N+
1	1	1	1	1	1	1	1		
2	1	1	1	2	2	2	2		
3	1	2	2	1	1	2	2		
4	1	2	2	2	2	1	1		
5	2	1	2	1	2	1	2		
6	2	1	2	2	1	2	1		
7	2	2	1	1	2	2	1		
8	2	2	1	2	1	1	2		

	A	B	C	D	E	F	G	N-	N+	Avg	Range
1	1	1	1	1	1	1	1	0.3403	0.2915	0.3159	0.0488
2	1	1	1	2	2	2	2	0.4608	0.3984	0.4296	0.0624
3	1	2	2	1	1	2	2	0.3682	0.3627	0.3655	0.0055
4	1	2	2	2	2	1	1	0.2961	0.2647	0.2804	0.0314
5	2	1	2	1	2	1	2	0.4450	0.4398	0.4424	0.0052
6	2	1	2	2	1	2	1	0.3517	0.3538	0.3528	0.0021
7	2	2	1	1	2	2	1	0.3758	0.3580	0.3669	0.0178
8	2	2	1	2	1	1	2	0.4504	0.4076	0.4290	0.0428

Factor Effects Charts

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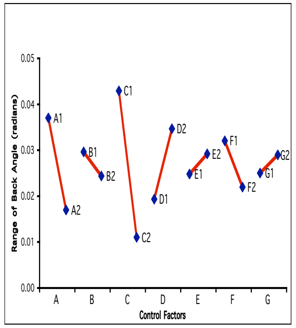

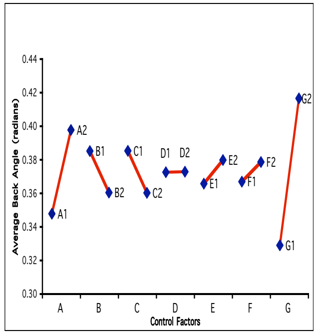

Robust Design Procedure Step 6: Select Setpoints

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- **Step 6: Select control factor setpoints.**
  - Choose settings to maximize or minimize objective function.
  - Consider variations carefully. (Use means or variance to understand variation explicitly.)
- **Advanced use:**
  - Conduct confirming experiments.
  - Set scaling factors to tune response.
  - Iterate to find optimal point.
  - Use higher fractions to find interaction effects.
- **Test additional control and noise factors.**

Confounding Interactions

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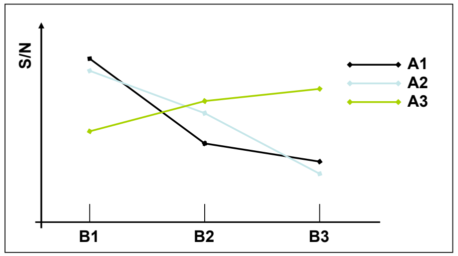
- **Generally the main effects dominate the response. BUT sometimes interactions are important. This is generally the case when the confirming trial fails.**
- **To explore interactions, use a fractional factorial experiment design.**



Adaptive Factor: Hill Climbing

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- Consider k factors, n levels each.
- Start at nominal levels.
- Test each level of each factor one at a time, while freezing the previous ones at best level so far.
- The number of experiments is nk+1.
- Since this is an unbalanced experiment design, you can stop anytime (you have no info anyway).
- Helpful to sequence factors for strongest effects first.
- In some cases it work well when interactions are present.

Expt #	Param A	Param B	Param C	Param D	Response	
1	A2	B2	C2	D2	5.95	
2	A1	B2	C2	D2	5.63	
3	A3	B2	C2	D2	6.22	A3
4	A3	B1	C2	D2	6.70	B1
5	A3	B3	C2	D2	6.58	
6	A3	B1	C1	D2	4.85	
7	A3	B1	C3	D2	5.69	C2
8	A3	B1	C2	D1	6.60	
9	A3	B1	C2	D3	6.98	D3

4 factors, 2 levels each:

nk+1 =

2x4+1 = 9 trials

Key Concepts of Robust Design

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- Variation causes quality loss
- Two-step optimization
- Matrix experiments (orthogonal arrays)
- Inducing noise (outer array or repetition)
- Data analysis and prediction
- Interactions and confirmation

References

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- Taguchi, Genichi and Clausing, Don
  "Robust Quality"
  Harvard Business Review, Jan-Feb 1990.
- Byrne, Diane M. and Taguchi, Shin
  "The Taguchi Approach to Parameter Design"
  Quality Progress, Dec 1987.
- Phadke, Madhav S.
  Quality Engineering Using Robust Design
  Prentice Hall, Englewood Cliffs, 1989.
- Ross, Phillip J.
  Taguchi Techniques for Quality Engineering
  McGraw-Hill, New York, 1988.

Paper Airplane Experiment

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Expt #	Weight	Winglet	Nose	Wing	Trials	Mean	Std Dev	S/N
1	A1	B1	C1	D1				
2	A1	B2	C2	D2				
3	A1	B3	C3	D3				
4	A2	B1	C2	D3				
5	A2	B2	C3	D1				
6	A2	B3	C1	D2				
7	A3	B1	C3	D2				
8	A3	B2	C1	D3				
9	A3	B3	C2	D1				

Textbook

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Product Design and Development
Karl T. Ulrich and Steven D. Eppinger
5th edition, Irwin McGraw-Hill, 2012

1. Introduction
2. Development Processes and Organizations
3. Opportunity Identification
4. Product Planning
5. Identifying Customer Needs
6. Product Specifications
7. Concept Generation
8. Concept Selection
9. Concept Testing
10. Product Architecture
11. Industrial Design
12. Design for Environment
13. Design for Manufacturing
14. Prototyping
15. Robust Design
16. Patents and Intellectual Property
17. Product Development Economics
18. Managing Projects