Robust Design Methodology

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- Part 2: Understanding customers
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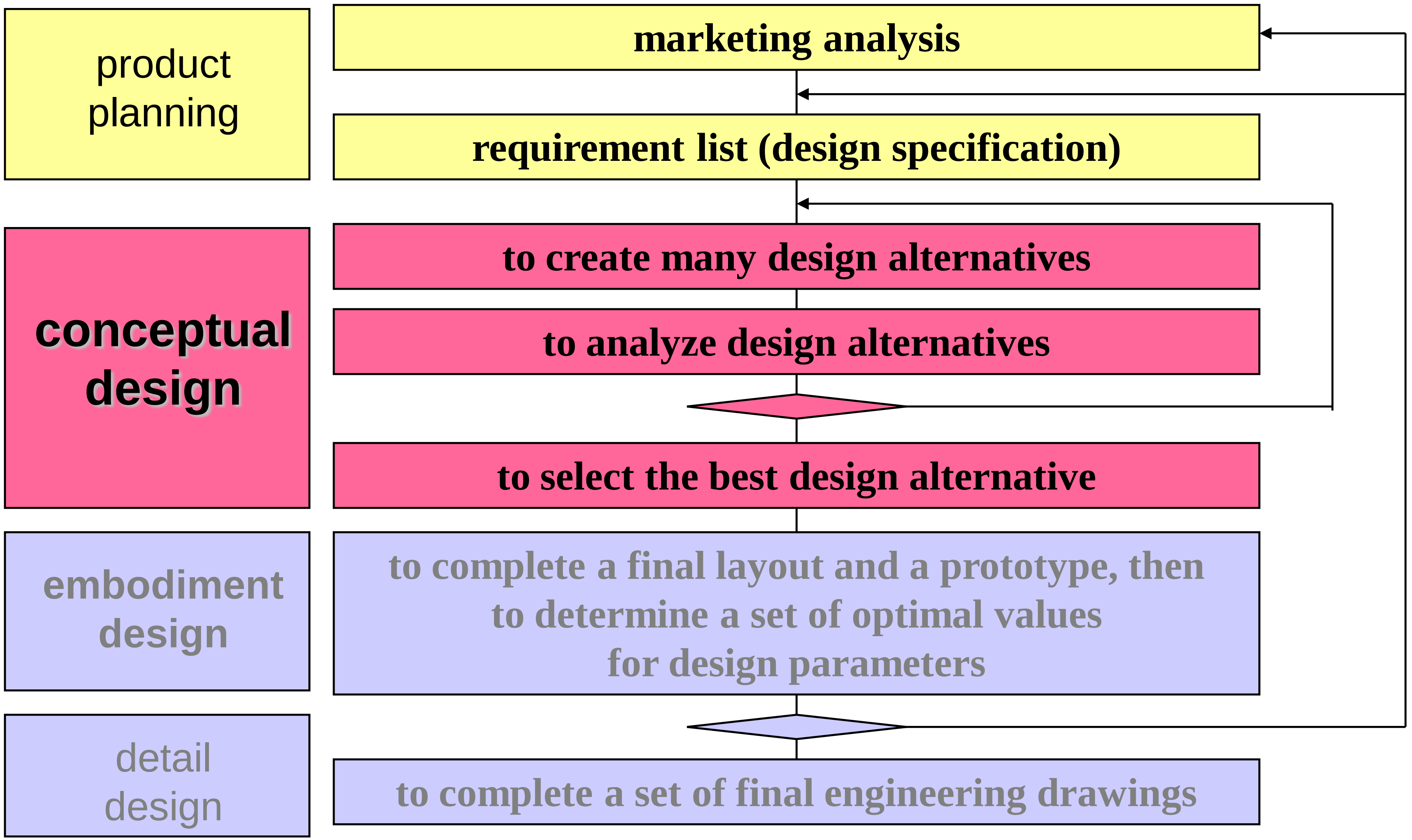
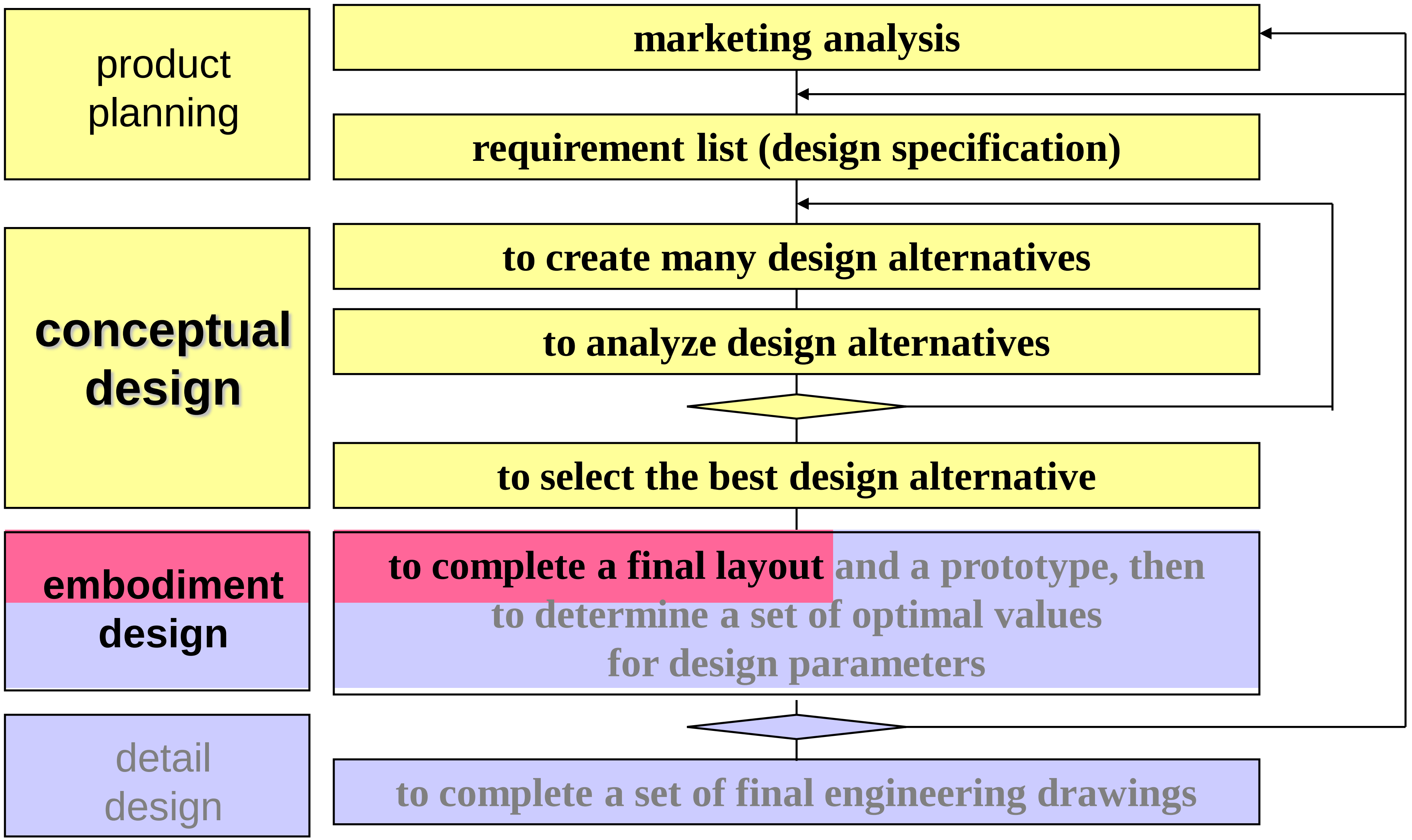
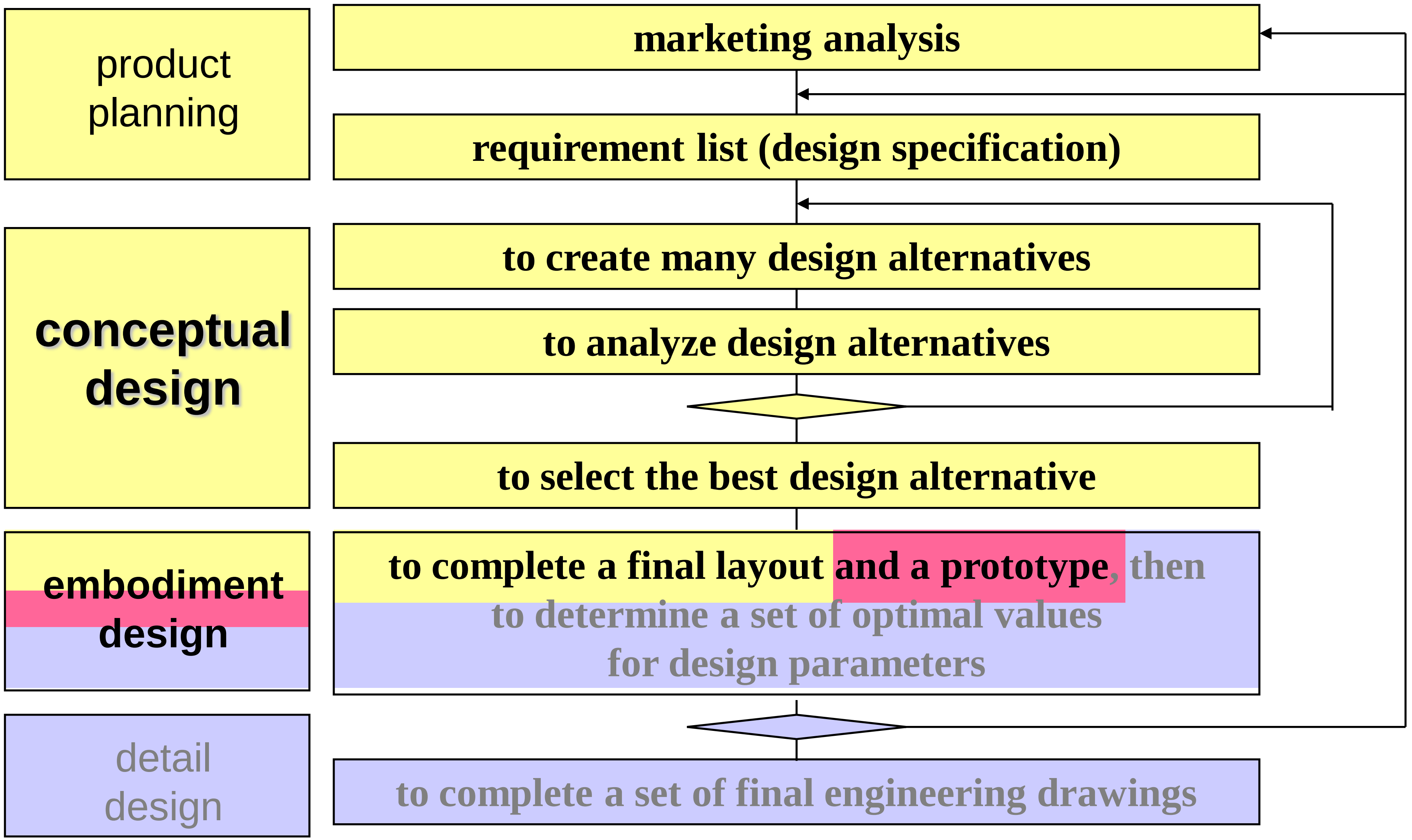
In the Design Review #1, your team will present the result of "conceptual design."



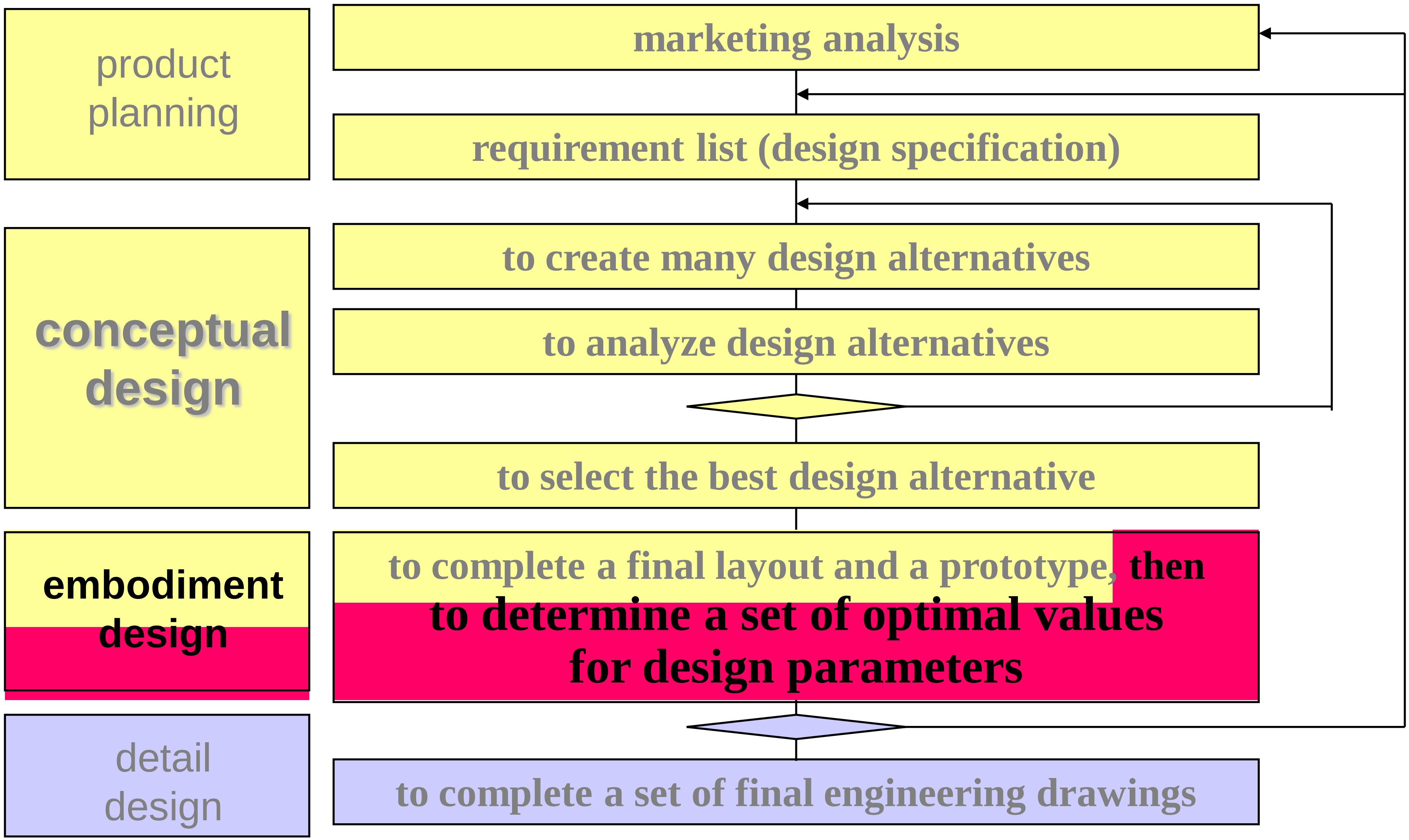
In the Design Review #2, your team will present the "final layout."



At the Final Exhibition, your team will present the "prototype."



In this lecture, I discuss "optimal design," which is not the scope of the GPD project.



Part 1:
The “true” concept of quality

My experience on passenger cars: which is the better quality car?

- **Toyota *Tercel***
  - **Wisconsin ('84 –'87)**
  - **0 - 50,000 miles**
  - **Replacement**
    - **A lamp bulb in the rear trunk (in 2.5 years)**
  - **Purchased it at $8,000, sold it at $5,000**

- **Daewoo *Lemans***
  - **Seoul ('87-'90)**
  - **0 – 30,000 miles**
  - **Replacement**
    - **Key unit (in two weeks)**
    - **Timing belt (at 15,000 miles)**
    - **Head lamp bulbs every year**
    - **Dashboard LCD backlight**
    - **Break pad**
    - **Noise from the frame**
  - **Purchased it at $10,000, donated it free.**

Then, why did the Daewoo dealer sell me the worse quality car?

- **Did they cheat me by selling me a car which did not pass the final quality inspection? No!!!**
- **Both Toyota and Daewoo dealers sell cars that passed required quality specifications.**

> *Daewoo*
>
> Quality Warranted
>
> **This car passed a series of final inspection procedures, which are strictly required by the company….**
>
> **Thank you…..**

The trap of the 'final quality inspection'…

- The Daewoo quality control inspector cannot find out at the time of inspection that
  - The key units will be stuck in two weeks.
  - The timing belt will be worn out at 15,000 miles.
  - The LCD back light will make trouble.
  - The break pad will produce squeaking noise.
  - Noise will be generated from the rear frame.
- A car which passes the final quality inspection does not guarantee the best "quality"???

“Final quality inspection” only means…

- That the car satisfies the required specifications within the given tolerance.

“True” quality cannot be measured directly by the manufacturer.

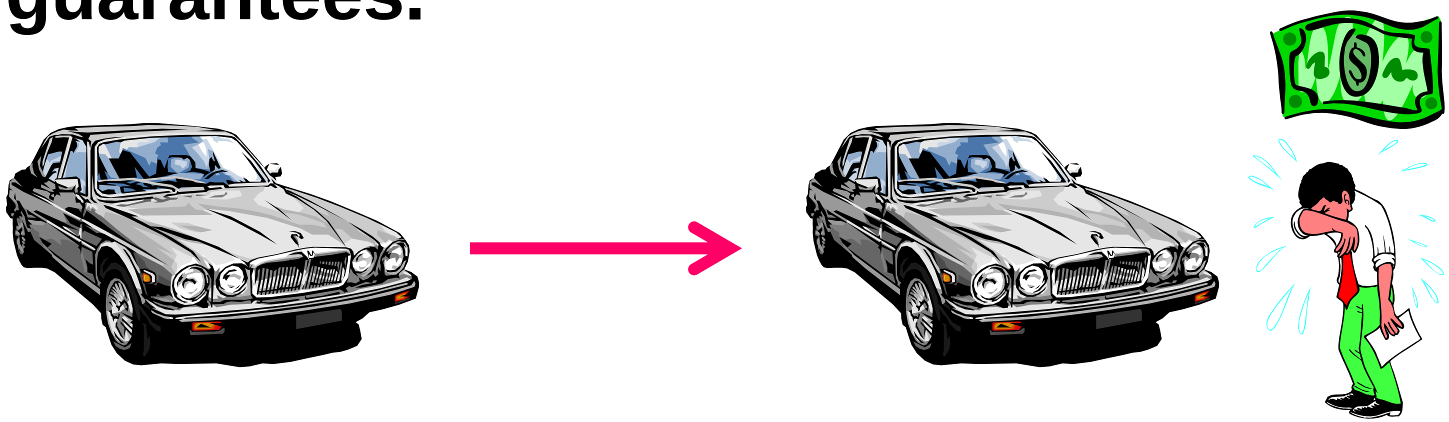
Total cost I paid for 5 years to use my Hyundai *Sonata-II* (5 year, 70,000km)

Running cost	gas: 200 full tanks x $60/tank	$12,000
Maintenance cost	engine oils: 14 times x $20 = $280 car wash: 60 times x $9 = $540 antifreeze: 2 times = $40 transmission oil: 2 times = $115 power steering oil: 1 time = $30	$1,005
Adjusting cost	break lining (2) & break drum = $132 exchange of three tires = $145 ignition plug & timing belt (2) = $315 engine gasket = $15	$607
Repair cost	battery exchange (2) & generator = $335 key unit = $52 power window (3) = $150 right headlight lamp = $10 throttle body exchange = $150 electric switch and wiring harness = $70	$767

Total cost = $14,379

What I most wish from my Hyundai *Sonata-II* is….

- **The *no change* of the mileage per liter as I am using it.**
  - **I do not care much about the initial mileage per liter, which the manufacturer guarantees.**



New car:
350km/70$

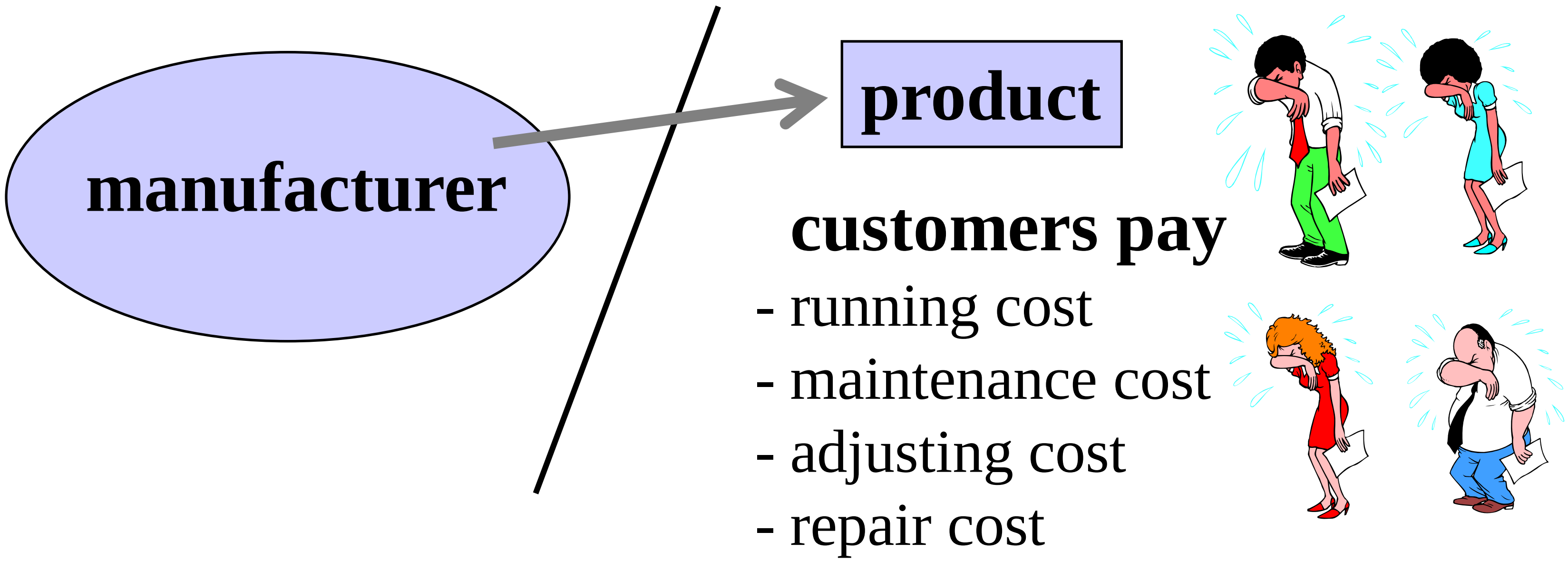
After one year:
250km/70$

The customer measures the "true" quality directly.

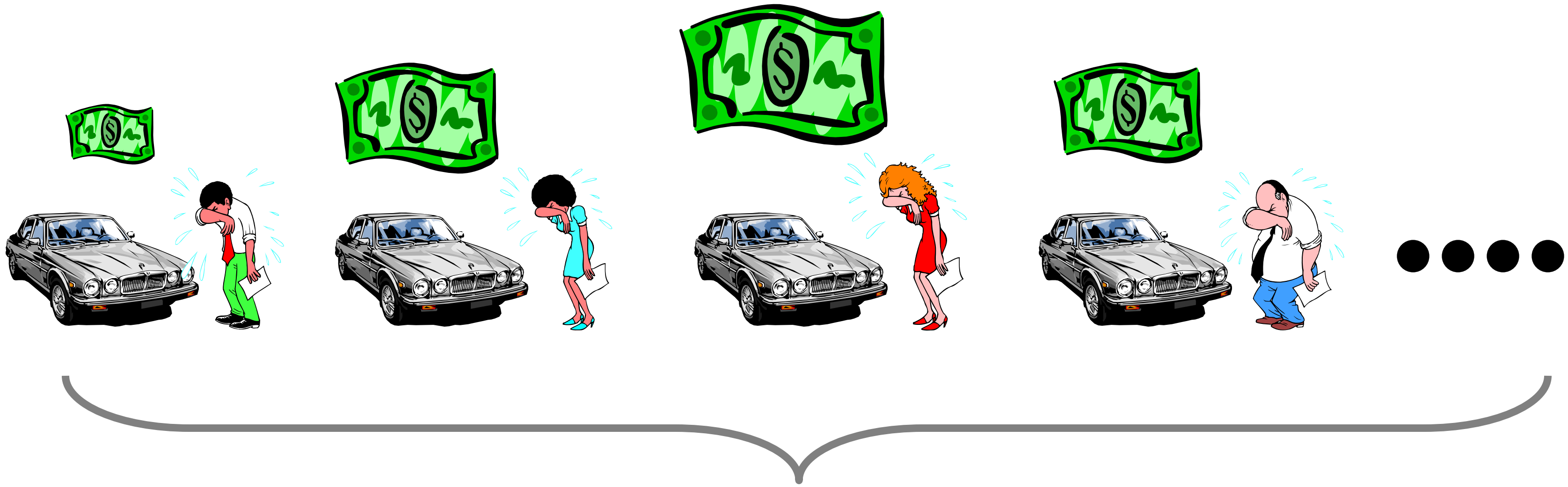
- I believe that my car has the best quality if the reduction of the mileage per liter is very small
- Because, I can save the total cost which I pay to use this car.
- This amount of the total cost is the true quality of the car.

"Quality" of the product is measured by money, not by specifications.

- True "quality" is the inverse of
  - The variation of initial functions, that is,
  - The total cost that customer must pay to use it.



Average ‘total cost’ per each product that customers pay to use it = “quality”



 = average total cost per each product

True ‘quality’ of the product

What the manufacturer must do is…

- **To design a product whose initial functions are not changed or, if changed, it should very little during the whole life cycle of the product.**
  - **Then, the product minimizes the total cost that customers must pay to use it.**
- **How? ➔ This is the topic of this lecture.**
  - **But, before that, we must understand customers.**

Part 2:
Understanding customers

"Do you really understand customers as a design engineer?"

Why do the initial functions of the product are changed?

Because customers are using it.

In what way, do the customers use the product?

- Customers use the product by their own way.
- Let's define "customer conditions" as "the method by which" and "the environment in which" the product is used by the customer.
- There are so many different types of customers.
- Therefore, "customer conditions" are extremely various beyond the engineers' imagination.

Customer conditions of the car

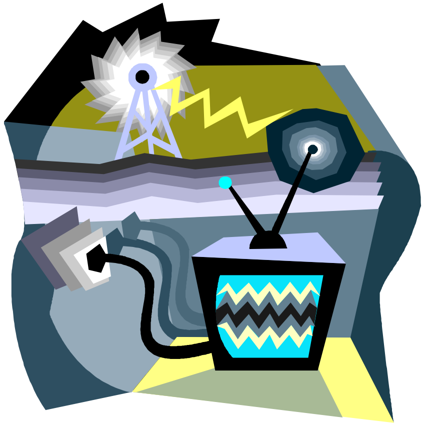
- Various drivers
  - Driving habit
  - Driving pattern
    - Distance
    - Driver's job
    - Driver's age
  - Weight it carries
  - Altitude
  - Highway or city roads ……
- Various environment
  - Road conditions
  - Temperature
  - Humidity
  - Wind velocity and direction
  - Rain and snow
  - Dust ……

The additional problem is…

- that those various customer conditions are extremely more severe comparing to the factory environment where the product is manufactured and tested.
  - Compare the customer conditions of a car with those conditions in the assembly plant.

Then, what about the TV?

- A TV is used at home. So, customer conditions are not severe than that in the plant?
- Customer conditions of the TV
  - Frequent channel change
  - Variation of the input voltage
  - Electric noise and shock
  - Connection to the external device (video, game device, camcorder, etc.)
  - Turned-on hours
  - Room temperature and humidity
  - Room brightness
  - Customer viewing angle



Do you really understand that customer conditions are severe?

- **Let's pick a simple product, for example, the spoon at the cafeteria.**
  - **What are the customer conditions of the spoon?**
  - **How severe are they?**

But, the most serious problem is that…..

- **Any manufacturer CAN NOT control or educate the customer to use their product properly.**
  - **"Warning: Please do not attempt to change channels so frequently. It might cause the problem to our TV."**
  - **"Never pump the acceleration pedal. Then, we cannot guarantee the initial mileage of our car."**
  - **"Please wash our spoon very smoothly. Otherwise, the surface of the spoon would be scratched so easily."**

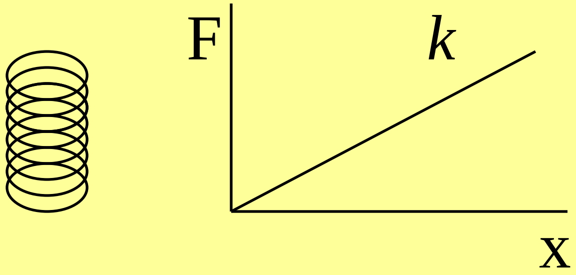
Therefore, professional design engineers must have the concept as follows:

- Even if so many different customers use my product in the most severe customer conditions,
- The initial functions of my product would not be changed, or if changed, it would be minimized.
- "Use my product by any way you wish. If the initial function of my product is changed, I will bet my whole life."

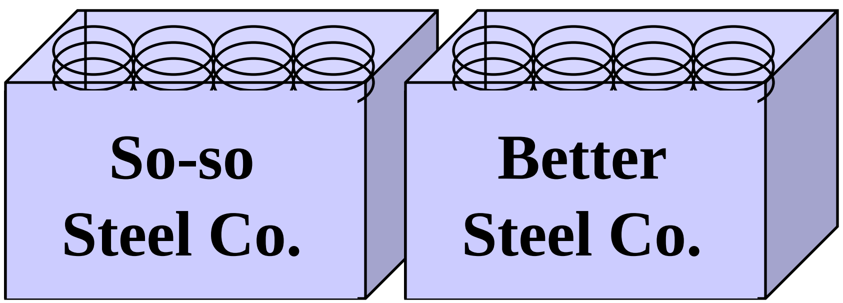
Then, how can you bet your life?

- If you really realize that something is true by your own experience, you can have the firm belief.
- You MUST check if the initial function of your prototype is really changed by applying the various and severe customer conditions to your prototype before you sell it to the customers.

Example #1: Which is the better quality spring?



$k = 10 \pm 5\%$ **kgf/mm**



2,000 suspension spring samples

Chief manager of Quality Control Dept.: "Bring them to the inspection room. Measure the spring constant and check if it satisfies the tolerance given on the drawing."

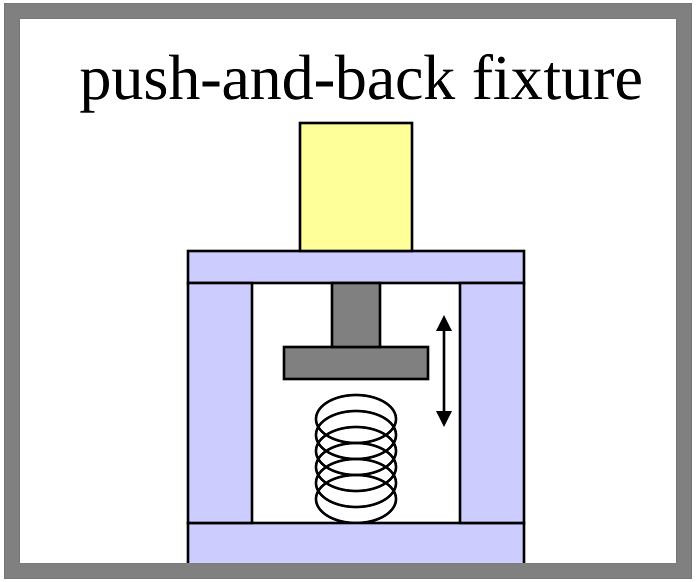
➔ Can he bet his life to find out the better quality spring?

The true "quality" of the spring

- Is not the tolerance satisfaction.
- How much will the initial function of the spring be changed under the various and severe customer conditions.
  - Function of the spring = elastic deformation from the external force
- You must measure the amount of spring deformation by really applying the severe customer conditions.

A test-bench has to be created to apply the severe customer conditions of the spring

- The typical customer conditions are
  - Ambient temperature: -30C and 70C
  - 10,000 push-and-back



heat chamber
that can apply the
-30C to 70C
environment

Now you can bet your life to find out the better quality spring.

- **Two typical severe customer conditions:**

N1: measure the deformation after 10,000 push-and-back in –30°C

N2: measure the deformation after 10,000 push-and-back in 70°C

- **Measurement results**

A Spring of the *So-so Steel*

	0	100	200 kgf
N1	-1.4	8.3	17.1 mm
N2	1.9	12.0	23.3 mm

A Spring of the *Better Steel*

	0	100	200 kgf
N1	-0.2	9.9	19.5 mm
N2	0.4	10.3	20.5 mm

What was wrong with the chief manager of the Quality Control Department?

The inspection room cannot represent the various and severe customer conditions.

How much better quality in number?

- **Signal-to-noise (S/N) ratio.**

$$\text{S/N ratio}: \ \eta = 10 \log \frac{1}{r}\left(\frac{S_\beta - V_e}{V_N}\right) \text{ dB}$$

- S/N ratio of the spring from *Extreme Steel* = -11.8 dB

- S/N ratio of the spring from *Nagoya Steel* = 2.4 dB

This means that the quality of the *Better Steel'*s spring is better than that of the *So-so Steel* by:

$$Gain = 10^{\frac{2.4-(-11.8)}{10}} = 26.3$$

You said that the quality is the total cost the customers pay to use it… Yes, it is…

- **In general, if the S/N ratio is higher by 14.2dB (that is in real number 26.3), then you can expect that the average total cost, which customer must pay to use it, would be reduced to:**

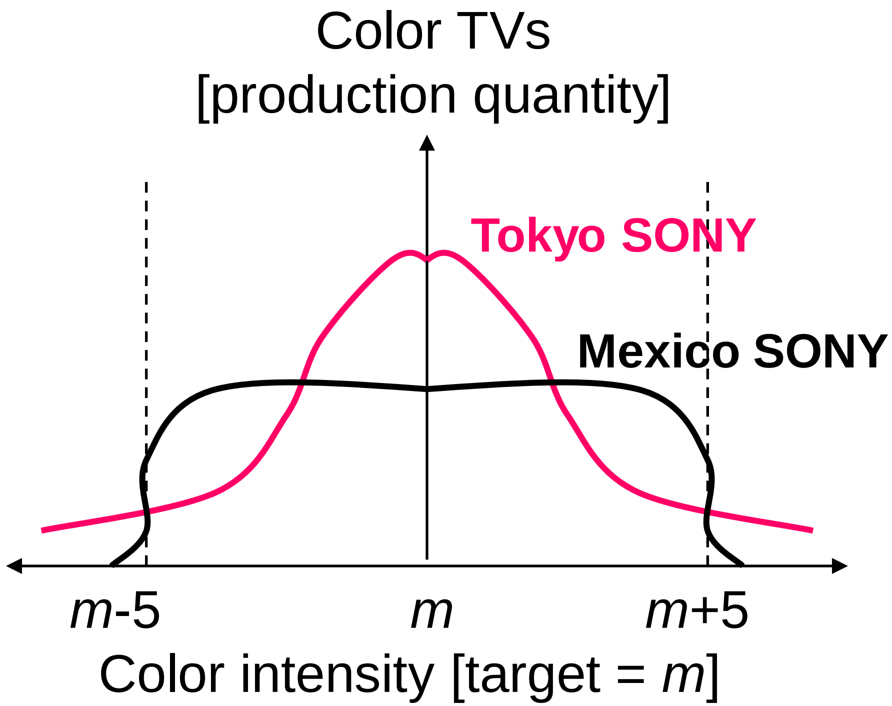
$$\frac{1}{26.3} = 3.8\%$$

"If the average total cost of the spring from the *So-so Steel* is 100$, then that of the spring from the *Better Steel* is only 3.8$."

- Dr. Taguchi -

Example #2: Does the zero defect plant produce the best quality products?

- **Which SONY plant produces less the defective color TVs?**
- **Then, is the Mexico SONY plant producing better quality TVs?**

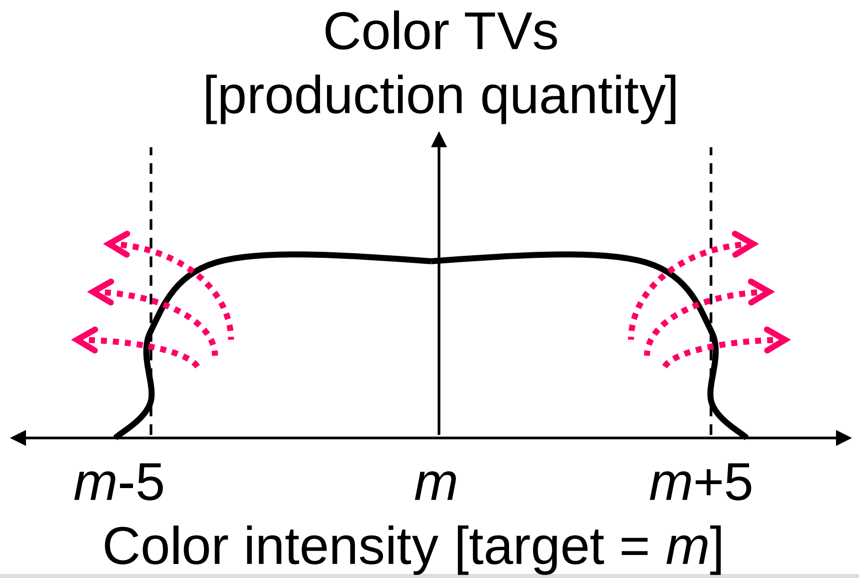


Tokyo SONY: normal distribution, σ = 1.667

Mexico SONY: equal distribution, σ = 2.887

Why are the Mexico SONY producing the worse quality TVs?

- **All TVs will undergo various and severe customer conditions after they are sold to the customers.**
- **Even if all the TVs from the Mexico SONY are passed by the quality inspection, the function of color intensity will be changed shortly after customers begin to use it since the color density of many TVs are near to the tolerance bounds.**



What should be improved?

1. **Minimize standard deviation, not the number of defective TVs.**

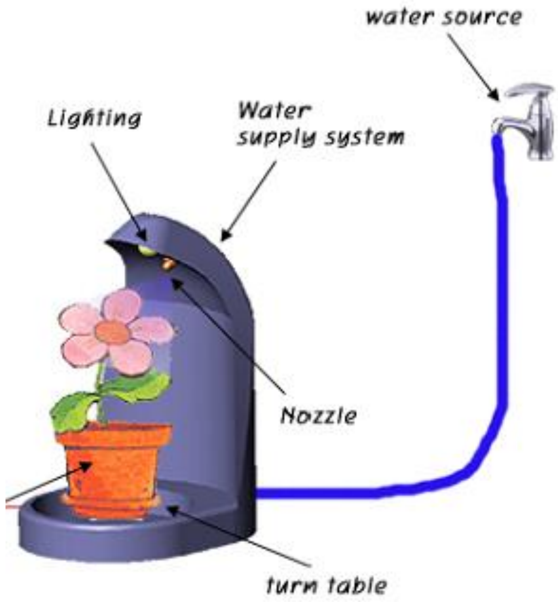
Tokyo SONY: normal distribution, $\sigma = 1.667$
Mexico SONY: equal distribution, $\sigma = 2.887$

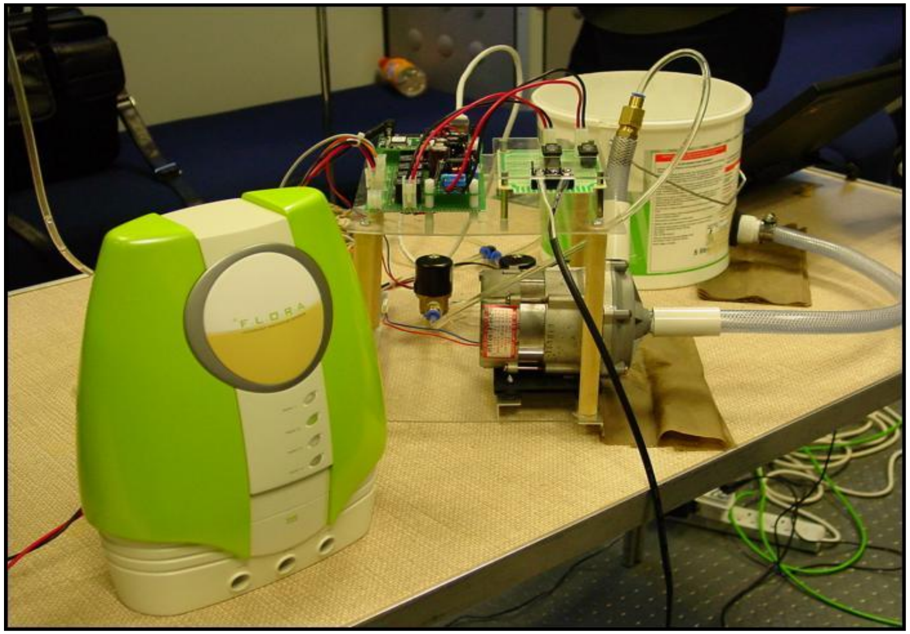
2. **Immediately redesign the TV.**
   - **which can minimize the variations of the color intensity, which is the indirect index representing the true quality.**
   - **How? → This is the main topic of this lecture.**

Part 3:
Robust design as the optimal design methodology

What is the working prototype?

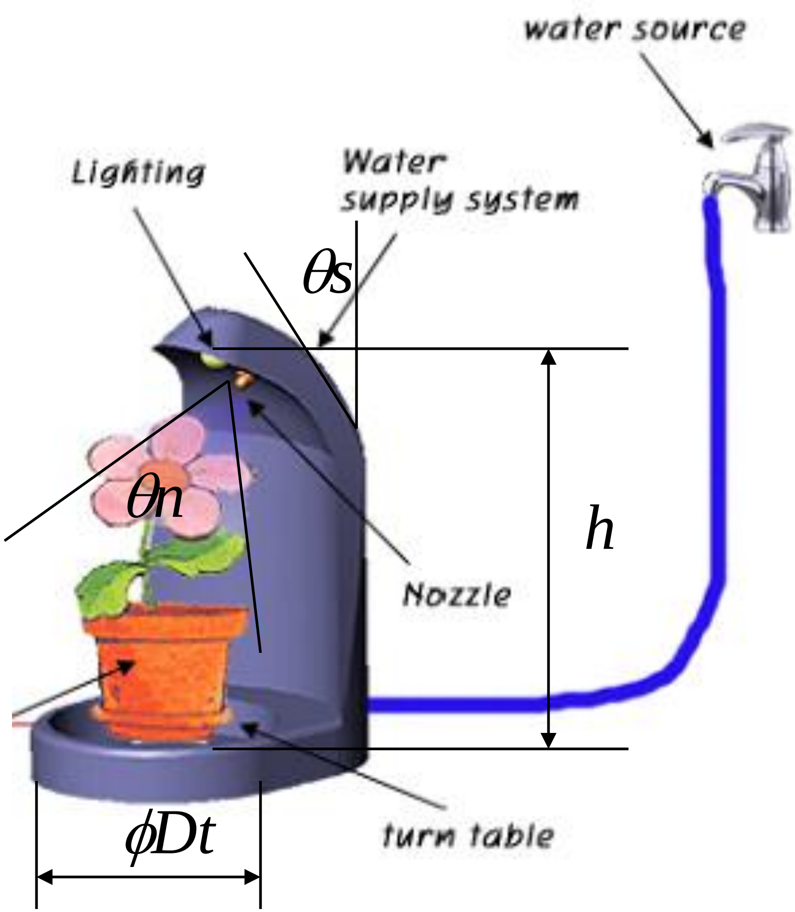
- **A sample product that can verify that all the required functions are realized under the given constraints.**





An internet-connected flower watering system (GPD 2001)

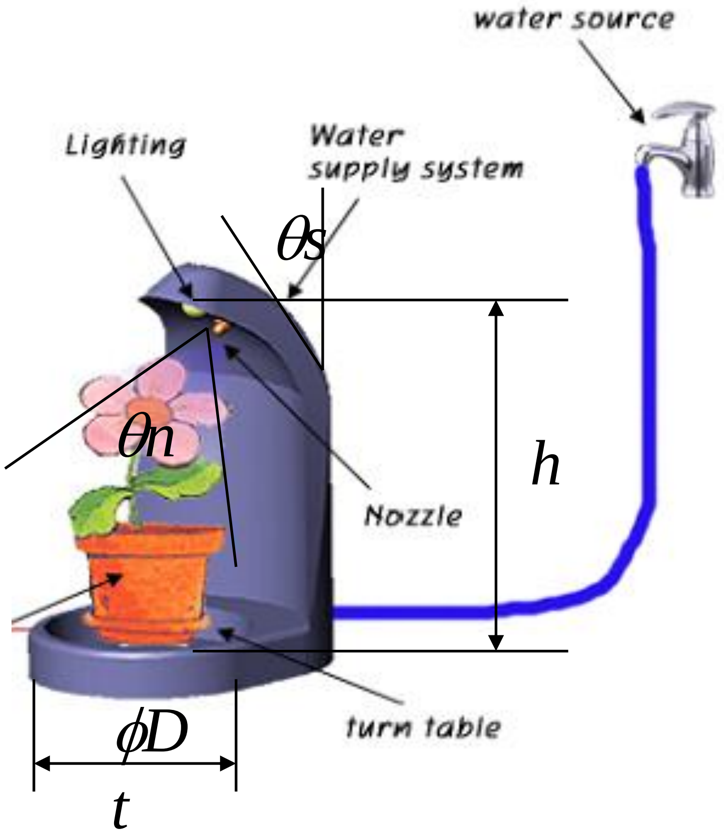
To make a working prototype,



- **You have to determine the values of each design parameters, which can realize the required function,**
  - **Function of the flower watering system:**
    - **to sprinkle water from the top of the flower and to make it flow into the soil.**

  ➔ Minimization of the water loss.

Let's assume that your initial values of each design parameters are as follows:



- **Nozzle**
  - diameter size *Dn = 1.0mm*
  - spray angle *θn = 30°*
- **Turn table**
  - rotational speed *ω = 12rpm*
  - diameter size *Dt = 200mm*
- **Case**
  - total height *h = 500mm*
  - slant angle *θs = 30°*
- **Hose**
  - type = *flexible*

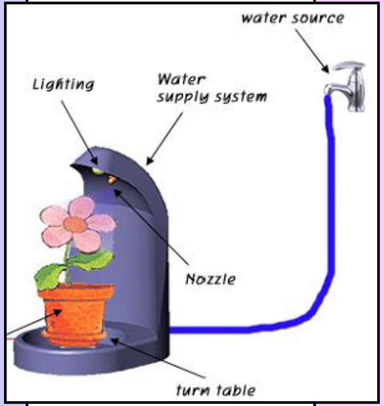
It works perfectly…..
Then, the mission is accomplished???

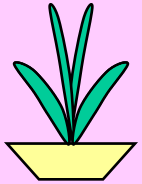
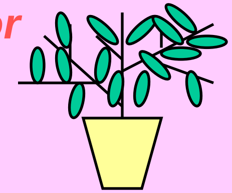
No, since the customer conditions also make the function of the prototype be changed.

- **Design parameters**
  → controllable

- **Customer conditions**
  → uncontrollable

- Nozzle
  - diameter size *Dn = 1.0mm*
  - spray angle *θn = 30°*
- Turn table
  - rotational speed *ω = 12rpm*
  - diameter size *Dt = 200mm*
- Case
  - total height *h = 500mm*
  - slant angle *θs = 30°*
- Hose
  - type = *flexible*



- Pressure of water source
  - pressure *Ps = 2 – 8 kgf/cm²*
- Plant and vessel types
  - types =  *or* 
- Ambient environment
  - temperature *T = {-15} – 40C*
  - Humidity *H = 0 – 95%*

You cannot set the customer conditions to your desired values.

So, finally, what you have to do is …

Find [*final values of design parameters*]

such that $\min |\Delta_H - \Delta_L|$

where

Δ_H = **function of the prototype at the extreme *high* values of customer conditions**

Δ_L = **function of the prototype at the extreme *low* values of customer conditions**

In case of the flower watering system,

Find [*final values of design parameters*]

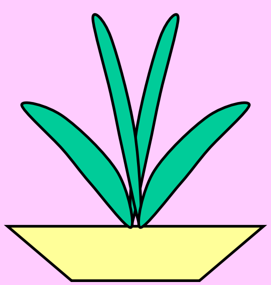
such that $\min |\Delta_{N1} - \Delta_{N2}|$

where

Δ_{N1} = **water loss of the system at the customer conditions N1**

Δ_{N2} = **water loss of the system at the customer conditions N2**

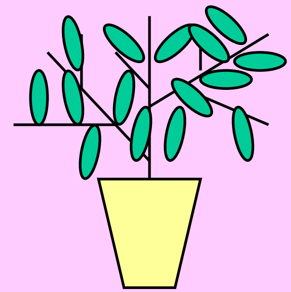
N1



with water supply pressure at 2 kgf/cm^2, -15C/5%

or

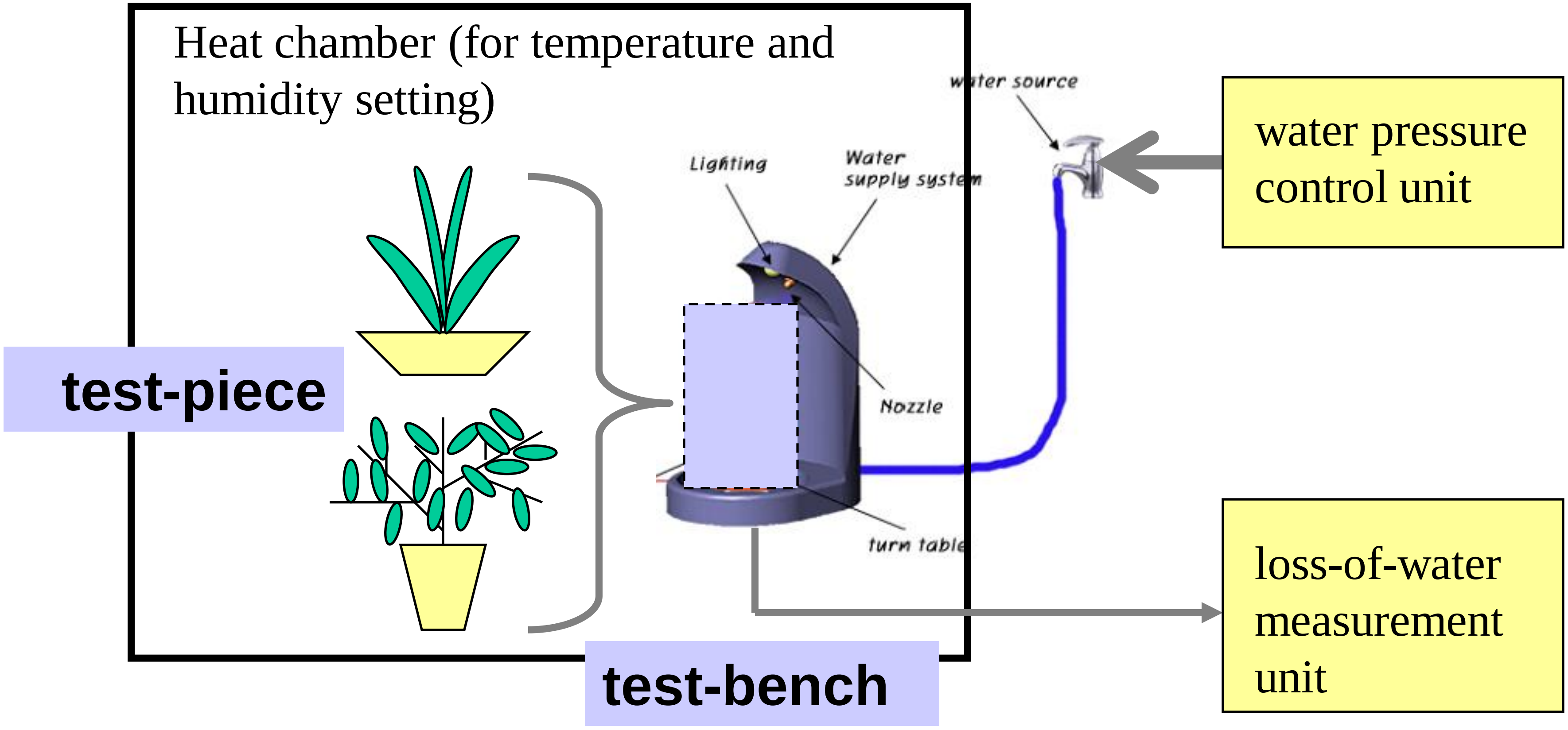
N2



with water supply pressure at 8 kgf/cm^2, 40C/95%

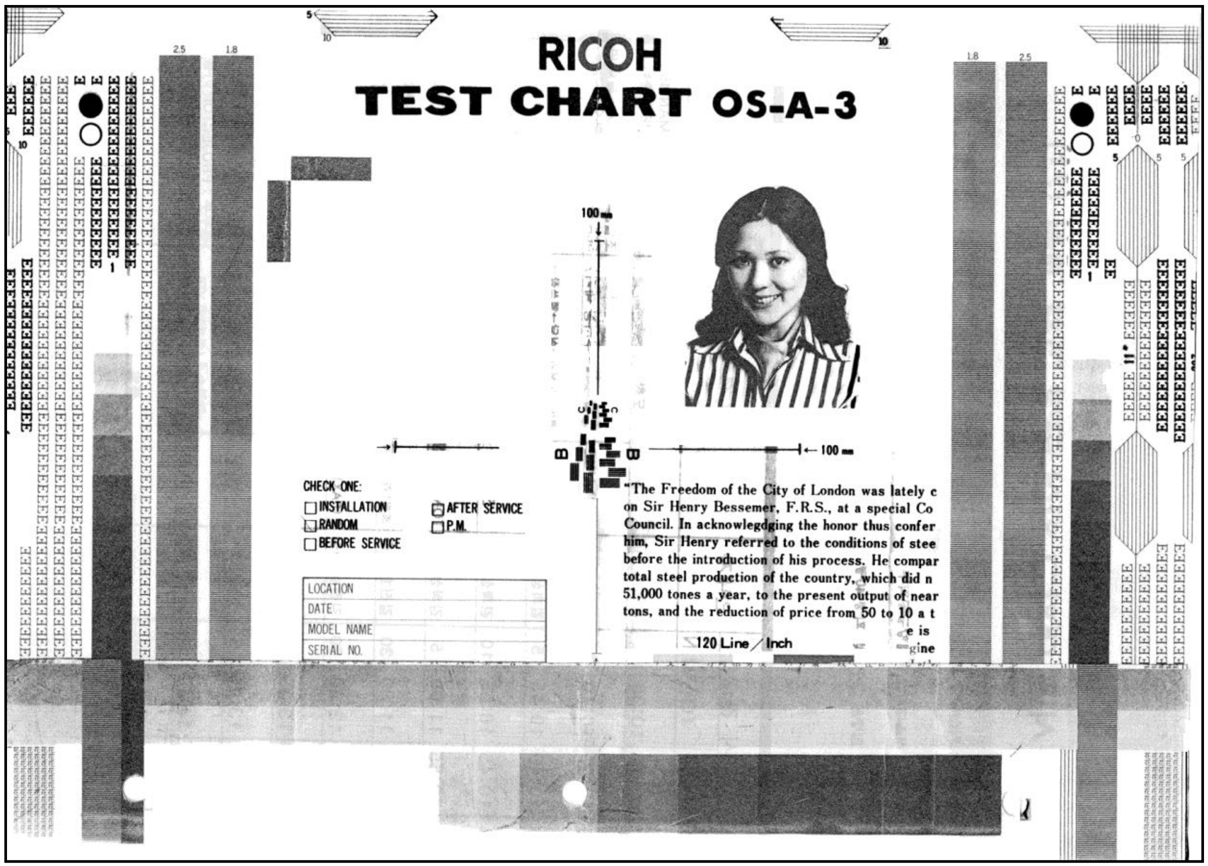
You have to create a test-bench and a test-piece to apply the customer conditions.

- **For the flower watering system**



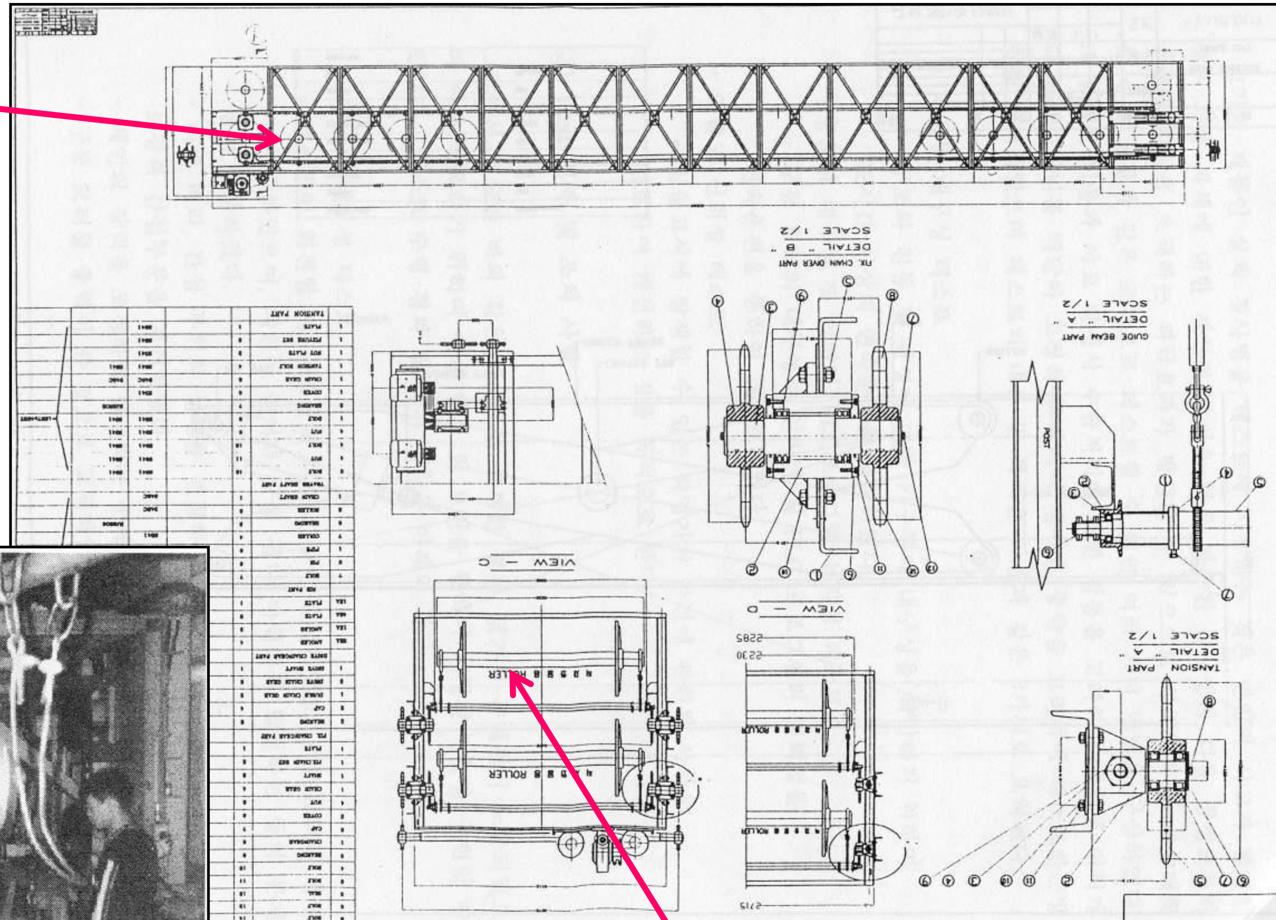
To create a test-bench and/or a test-piece is not that easy, actually, very difficult.

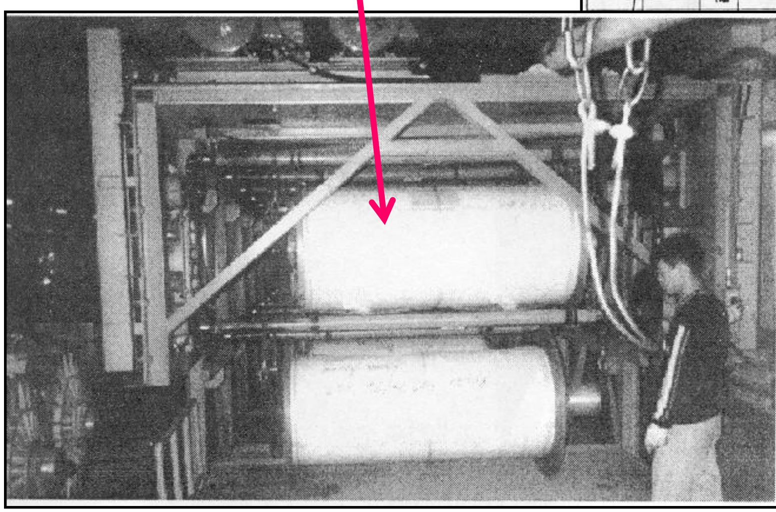
- **A test-piece to apply the customer conditions in case of copy machine**



A test-piece in case of the automatic storage and retrieval system (AS/RS)

a spool on which the textile thread is wound (1 ton = 1,000kg)

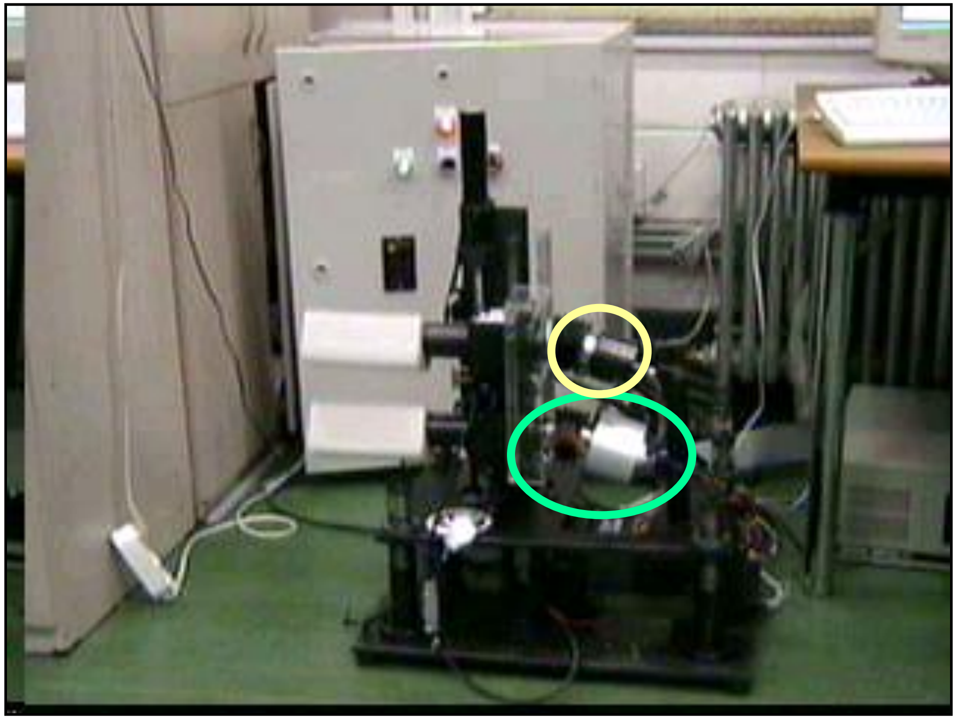




an empty spool

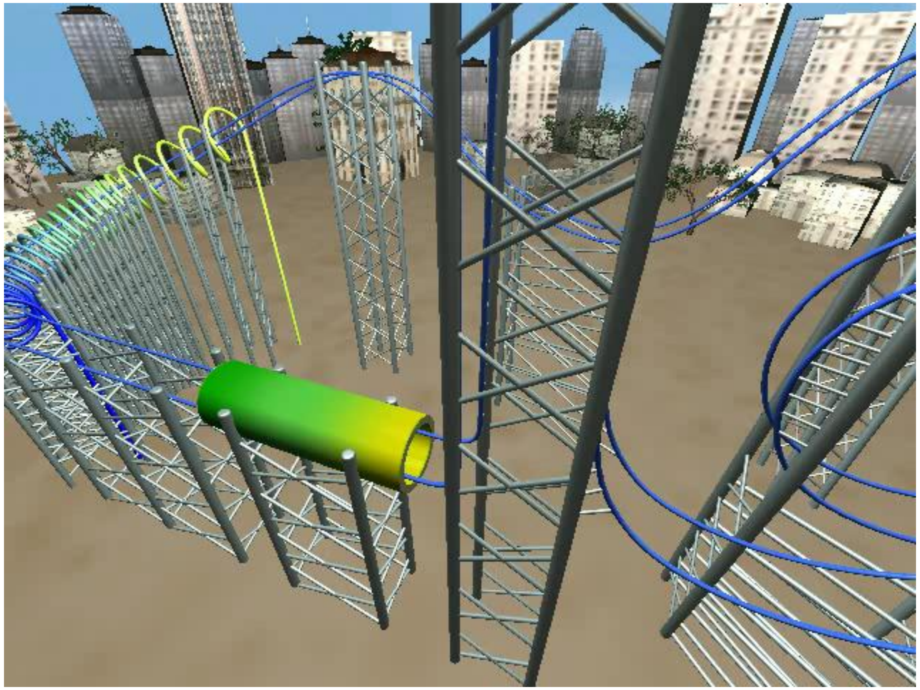
A test-bench for the slip-ring of the new concept motion simulator: *Eclipse-II*

- **For two slip-rings**
  - **Customer conditions: vibration, electric noise and link motion.**

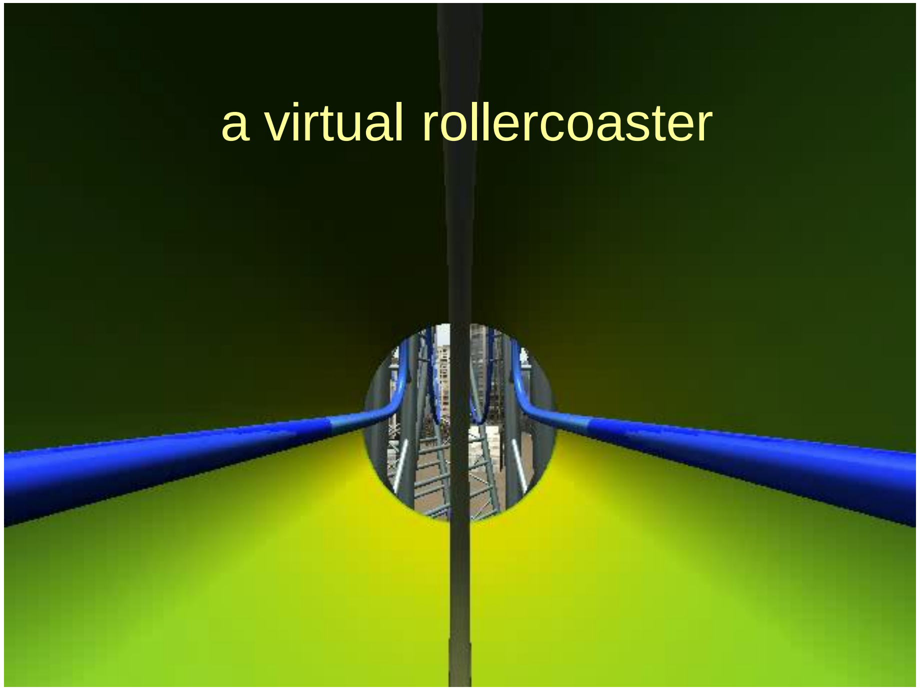


A test-piece path for the new concept motion simulator: *Eclipse-II*

- **For the simulated motions**
  - **Customer conditions: maximum workspace, velocity and acceleration**



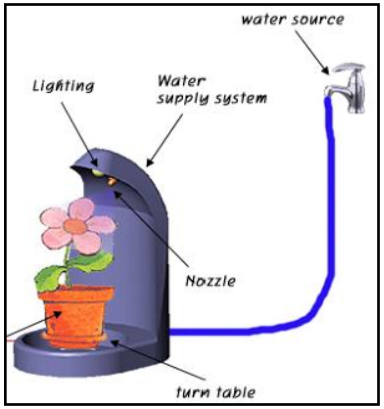
The image view by the observer



The movie clip to the rider

By using the test-bench, you execute a series of experiments for optimization.

- **Initial values of design parameters**
  - Nozzle
    - diameter size *Dn = 1.0mm*
    - spray angle *θn = 30°*
  - Turn table
    - rotational speed *ω = 12rpm*
    - diameter size *Dt = 200mm*
  - Case
    - total height *h = 500mm*
    - slant angle *θs = 30°*
  - Hose
    - type = *flexible*



- **Optimal values of design parameters**
  - Nozzle
    - diameter size *Dn = 0.7mm*
    - spray angle *θn = 40°*
  - Turn table
    - rotational speed *ω = 16rpm*
    - diameter size *Dt = 175mm*
  - Case
    - total height *h = 525mm*
    - slant angle *θs = 30°*
  - Hose
    - type = *rigid*

There are many sets of design parameter values, which can realize required functions.

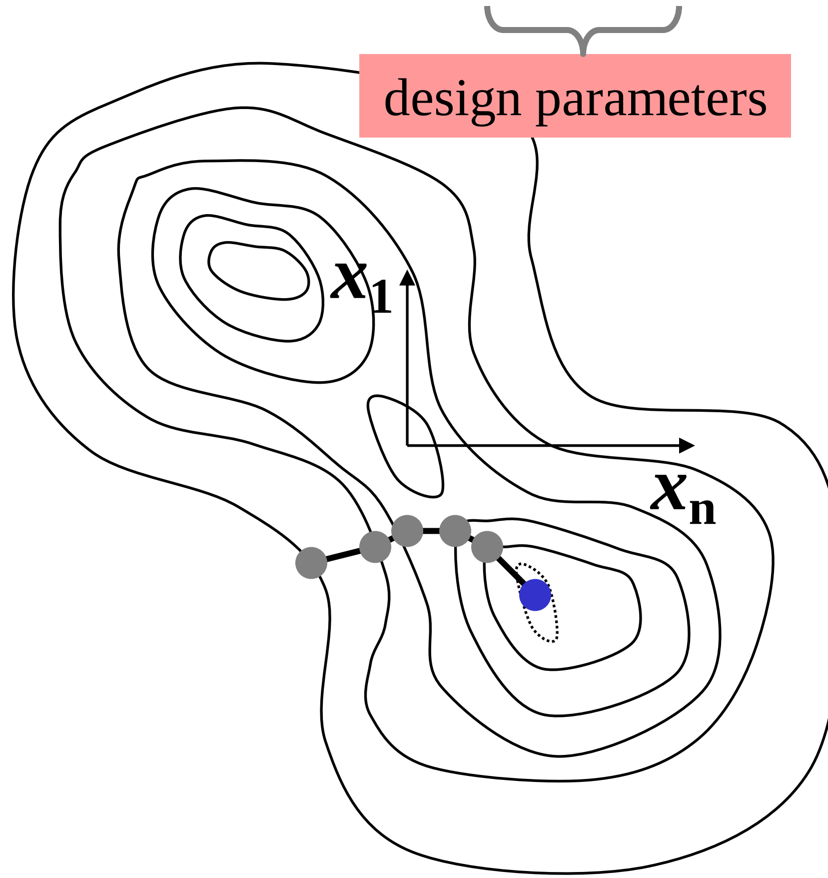
This set is a unique one which minimizes the functional variations regardless of the various and severe customer conditions.

Taguchi's Design of Experiments (DOE) as the optimization method

1. Select the range of design parameters for optimization search.
2. Use an orthogonal array to execute a series of experiments.
3. Calculate the S/N ratio per each experiment and select the optimal values of design parameters.
4. According to the sensitivity of each design parameters, select another range of design parameters for optimization search
5. Repeat the same procedure above from step 2 – 4 until you reach the final optimal values.

unknown:

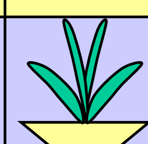
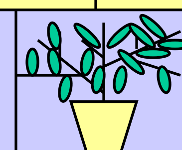
$S/N\ ratio = f\,(x_1, \ldots, x_n)$

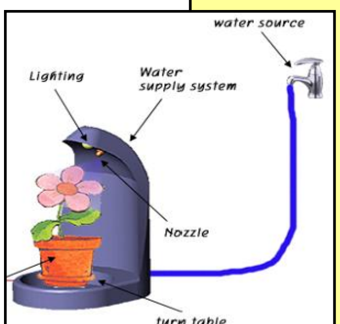


1. Select the range of design parameters for the optimization search.

initial values

- range   + range

class	parameter name	level #1	level #2	level #3
design parameters	A: hose type	rigid	flexible	
	B: nozzle diameter *Dn*	0.7	1.0	1.5
	C: spray angle θn	20	30	40
	D: rotational speed ω	8	12	16
	E: table diameter *Dt*	175	200	250
	F: case total height *h*	475	500	525
	G: slant angle θs	20	30	40
	H: case material	steel	plastic	Al.
customers conditions	N: plant/vessel types + water pressure + temp/humid.	 N1 + 2 -15C/5%		 N2 + 8 40C/95%

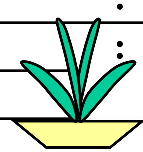


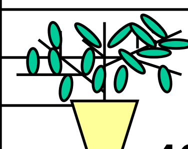
2. Use an orthogonal array to execute a series of experiments.

- Total combinations of design parameter values = 2×3^7 = 4,374.
- We have to select one set among them, which minimizes functional variations.
- If we are testing all the combinations [an exhaustive search],
  - 4,374 x 2 = 8,748 times of experiments have to be done, since two experiments are necessary per each combination,
    - Note that two cases of the customers conditions (N1 and N2) exist per each combination.

If an orthogonal array is used, only 18 x 2 = 36 experiments are required.

test-run number	setting of design parameters								measured amount of water loss								S/N ratio = inverse of the variations of water loss
									N1				N2				
	A	B	C	D	E	F	G	H	#1	#2	#3	#4	#1	#2	#3	#4	
1	1	1	1	1	1	1	1	1	y111	y112	y113	y114	y121	y122	y123	y124	S1
2	1	1	2	2	2	2	2	2	y211	y212	y213	y214	y221	y222	y223	y224	S2
3	1	1	3	3	3	3	3	3	y311	y312	y313	y314	y321	y322	y323	y324	S3
4	1	2	1	1	2	2	3	3	y411	y412	y413	y414	y421	y422	y423	y424	S4
5	1	2	2	2	3	3	1	1	y511	y512	y513	y514	y521	y522	y523	y524	S5
6	1	2	3	3	1	1	2	2	y611	y612	y613	y614	y621	y622	y623	y624	S6
7	1	3	1	2	1	3	2	3		:				:			
8	1	3	2	3	2	1	3	1		:				:			
9	1	3	3	1	3	2	1	2		:							
10	2	1	1	3	3	2	2	1		:							
11	2	1	2	1	1	3	3	2		:							
12	2	1	3	2	2	1	1	3		:				:			
13	2	2	1	2	3	1	3	2		:							
14	2	2	2	3	1	2	1	3									
15	2	2	3	1	2	3	2	1									
16	2	3	1	3	2	3	1	2									
17	2	3	2	1	3	1	2	3		:				:			
18	2	3	3	2	1	2	3	1									





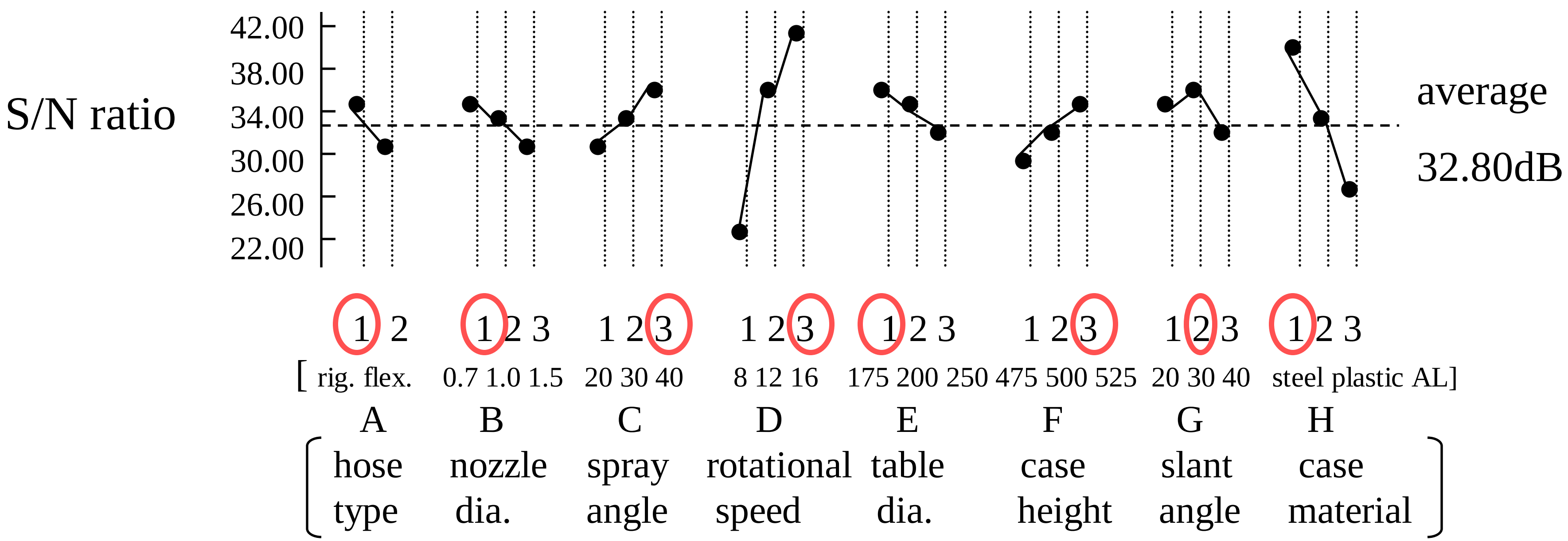
water loss measurement

signal to noise (S/N) ratio

orthogonal array

3. Calculate the S/N ratio and select the optimal values of design parameters.

- **The larger the S/N ratio is, the smaller are the variations of the water loss.**
- **Select a value per each design parameter, which maximizes the S/N ratio.**



Then, we can select the optimal values of design parameters.

- A = 1 (hose type = rigid)
- B = 1 (nozzle diameter = 0.7mm)
- C = 3 (spray angle = 40°)
- D = 3 (table rotational speed = 16 rpm)
- E = 1 (table diameter = 175mm)
- F = 3 (case height = 525mm)
- G = 2 (slant angle = 30°)
- H = 1 (case material = steel)

→ **At this *selected* optimal values, no experiment was done before.**

→ **However, we can estimate the S/N ratio, for example, 57.24dB, which is the maximum we could get.**

A final experiment at the 'selected' optimal values has to be done.

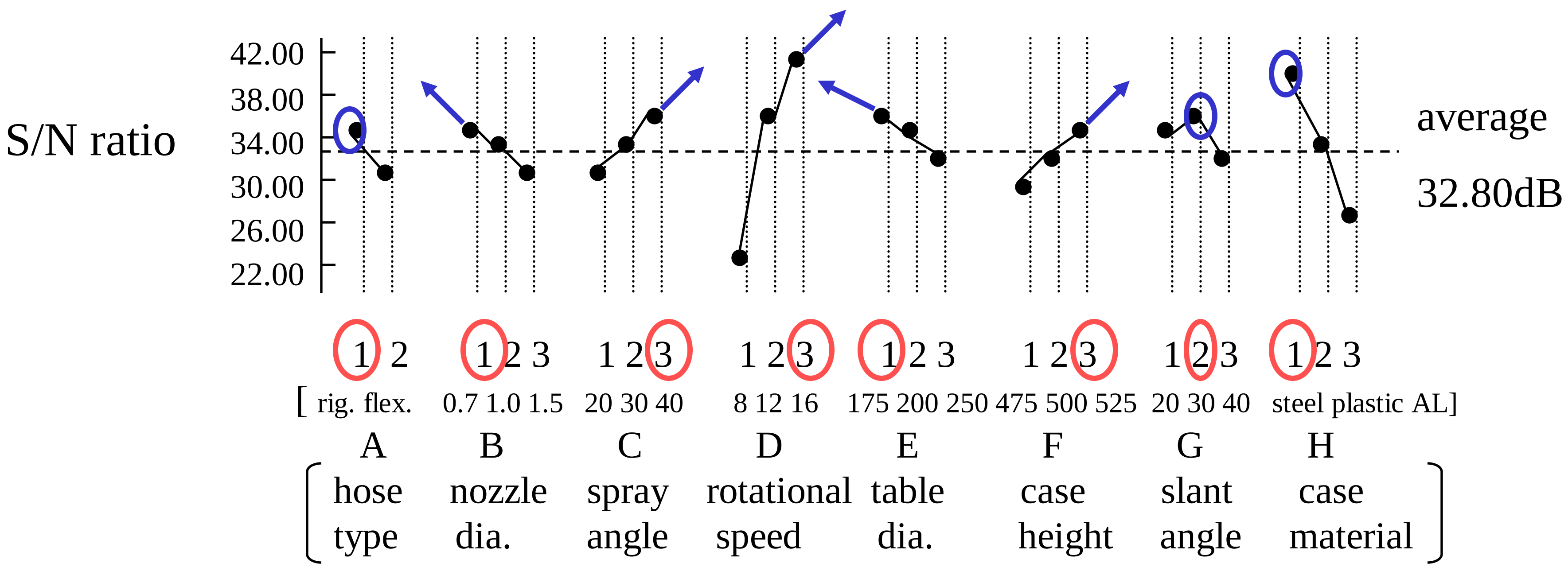
- For example,

	at the initial values	at the optimal values
S/N ratio	34.71dB	54.09dB (57.24dB estimated)

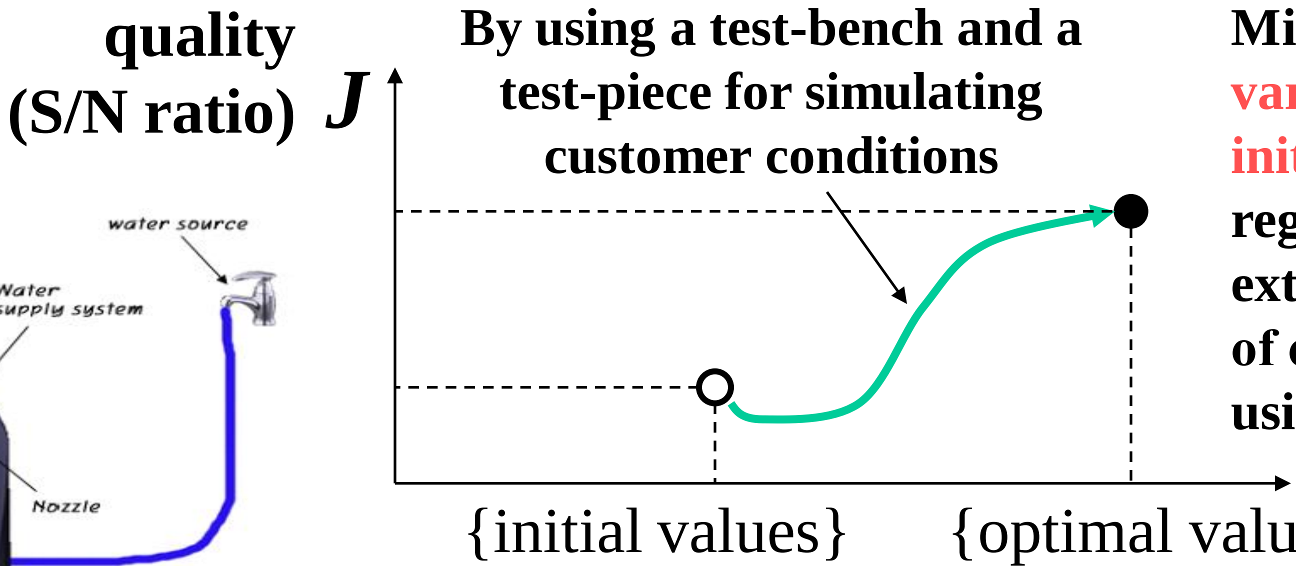
- The S/N ratio is increased by 19.38dB, which means that the functional variation is minimized by $1/10^{19.38/10} = 1/86.7 = 1.15\%$
- At the optimal values of design parameters, the function (water loss) variation of the watering system is minimized even if the customers conditions are varied from N1 to N2. ➔ The best quality system.

4. Select another range of design parameters for the 2nd optimization.

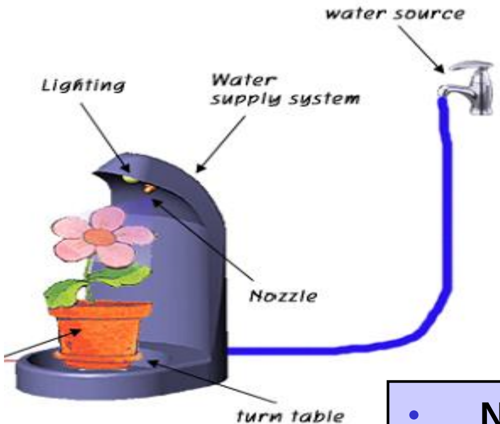
- According to the sensitivity of each design parameters,
  - Fix the hose [A] to be a rigid one, the case material [H] to be steel.
  - Fix the slant angle [G] to be 30 degree.
  - Increase the rotational speed [D] ➔ most sensitive parameter.
  - Reduce the nozzle diameter [B] and the table diameter [E]
  - Increase case height [F] and spray angle [C]



Dr. Taguchi's methodology for designing the best quality product = robust design



Minimize the variation of initial functions regardless of extreme change of customers' using conditions



Initial values:

- Nozzle
  - diameter size *Dn = 1.0mm*
  - spray angle *θn = 30°*
- Turn table
  - rotational speed *ω = 12rpm*
  - diameter size *Dt = 200mm*
- Case
  - total height *h = 500mm*
  - slant angle *θs = 30°*
- Hose
  - type = *flexible*

Optimal values:

- Nozzle
  - diameter size *Dn = 0.7 mm*
  - spray angle *θn = 40 °*
- Turn table
  - rotational speed *ω = 16 rpm*
  - diameter size *Dt = 175 mm*
- Case
  - total height *h = 525 mm*
  - slant angle *θs = 30 °*
- Hose
  - type = *rigid*