Introduction to Aircraft Design
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Lecture – 11
Examples of House of Quality for HALE UAV

Let us have a look at an example of the house of quality for a high altitude long endurance unmanned aerial vehicle or HALE UAV. At this stage, I would like to confirm that you have already watched the video clips where we described the requirements capture and HoQ. So if you have not done that I would recommend that you watch those video clips before you watch this example because here we will not be explaining or describing the working of HoQ, we will just show you how it is applied to an example of a high altitude long endurance unmanned aerial vehicle.

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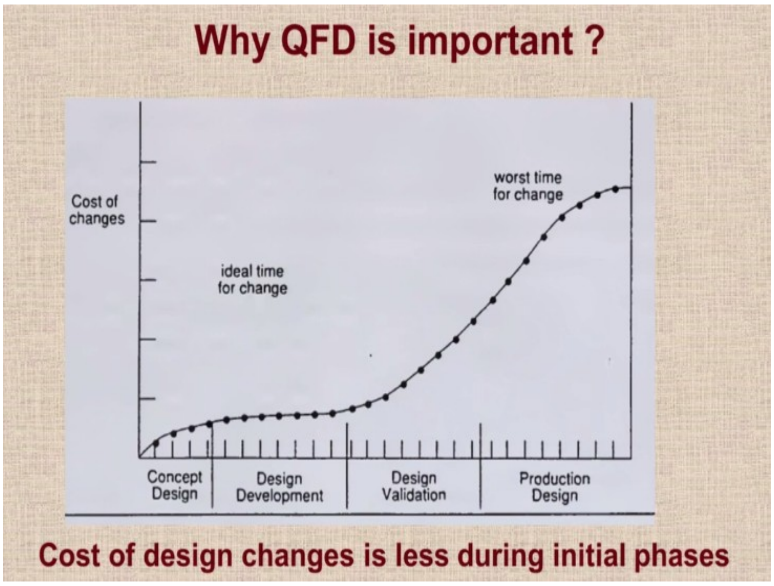

Why QFD is important? This graph shows how the cost of the changes increases as we proceed further and further in the cycle of completing the product. So during the concept design stage, the cost of changes is very low. During design and development, it is slightly higher and that is the ideal time for any changes or any modifications to be done in the design, but as you go into design validation the cost of changes rises.

And when we go to the production design stage and there if you make any major changes that is the worst time for change because the cost of change is very high. So therefore in the initial phases, it is very important to get it right and to make it work so that later on we do not have to really regret and incur heavy expenditure.

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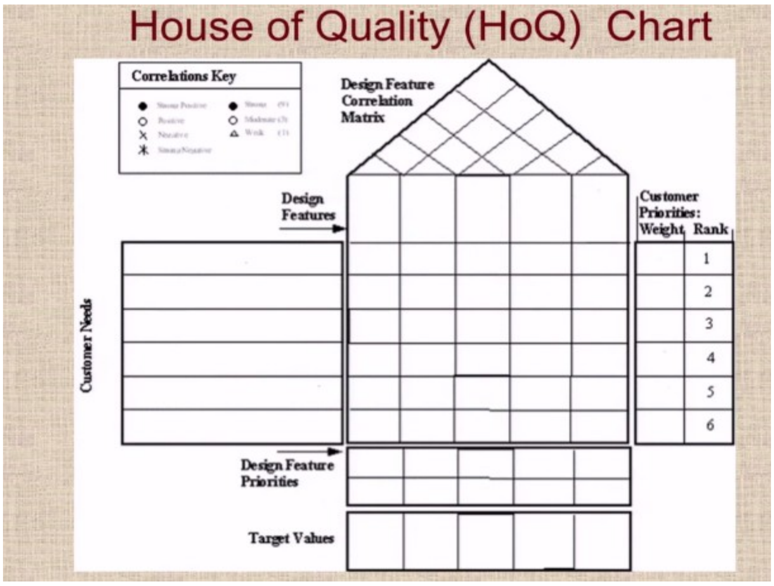

Just a quick revision of the house of quality chart which I am expecting you to have already seen before, but I just want to do a quick revision. So this is the house of quality chart where on the top roof we have the design feature correlation matrix, in the center we have the matrix for design feature priority calculation, on the left we have the input for the customer needs, on the right we have customer priorities with weights and rankings.

And on the bottom we have the horizontal rows for design feature priorities and the target values based on the study of the competition and we are going to fill this central box and the top box with these symbols.

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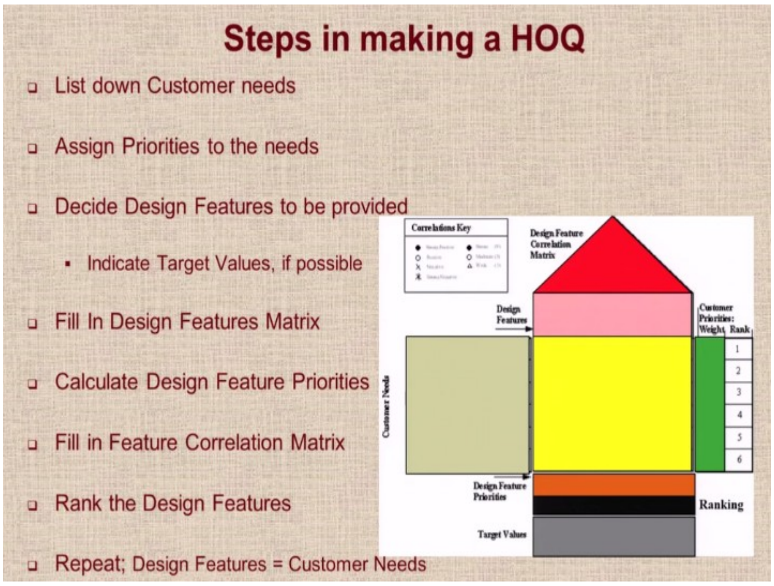

So, just a quick recap that first you list down the customer needs in the box on the left hand side and then you assign the priorities to these needs. So this information comes from a survey of the customer requirements and then you have the design team decides which design features are to be provided in a candidate design. So they fill up this design features box. Then looking at the competition and looking at what aims they would like to follow, some target values for the design features that you are going to investigate have to be given in the bottom box.

There is no point in exceeding these values too much because then something else will be compromised okay and then you fill in the design features matrix. After that you calculate the priorities and then after the priorities are calculated, the rooftop is used to fill in the feature correlation matrix because if there are two design features which strongly support each other that is great.

So there should be a lot of dark dots and open dots in the top and the crosses and you know stars are very bad because that means the features are contrary to each other or contradicting each other. Finally what you do is depending on the design feature priority that you calculate you can rank the design features and then you can drop off the features which have low rank and continue further with the features that have high ranks okay.

So what you do, then you repeat the whole process. Now what you do is use the high-ranking design features as the customer needs and then you go one level down and try to address what features to provide to address these needs. So on and so forth you can do and continue working further till you reach the end of the design.

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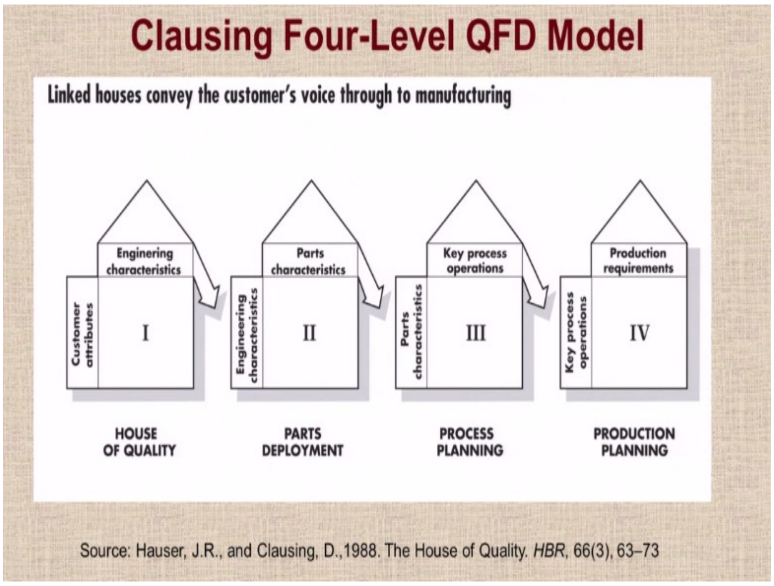

So if you look at the Clausing four-level QFD model which is also explained in the presentation. First the house of quality level one would contain the customer attributes and the engineering characteristics of the product have to be studied. Now with this, the characteristics that score a very high rank then become the requirements and the parts characteristics are to be determined based on which of them are going to address those requirements better.

Once you decide which part characteristics are important, you use them as the design as the customer attributes and now you look at the key process operations. So the process planning comes into play. So you identify the key processes which help you achieve the parts characteristics which help you achieve the engineering characteristics and finally the key processes then go into the production planning requirement.

So this is the four level house of quality where we convey the customers voice through to manufacturing okay. The source of this is a very interesting article in Harvard Business Review by Hauser and Clausing published way back in 1988.

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So, I will take an example from a M.Sc. thesis by a student from the Naval Postgraduate School in Monterey, California. This gentleman was a military officer and he was if I remember correctly a rank of a major working in Singapore and he has done this project at NPS California as part of his master's thesis. So in this particular thesis and from this thesis we will borrow this example. There is a very good way of explaining how you can use this as a conceptual aircraft design tool.

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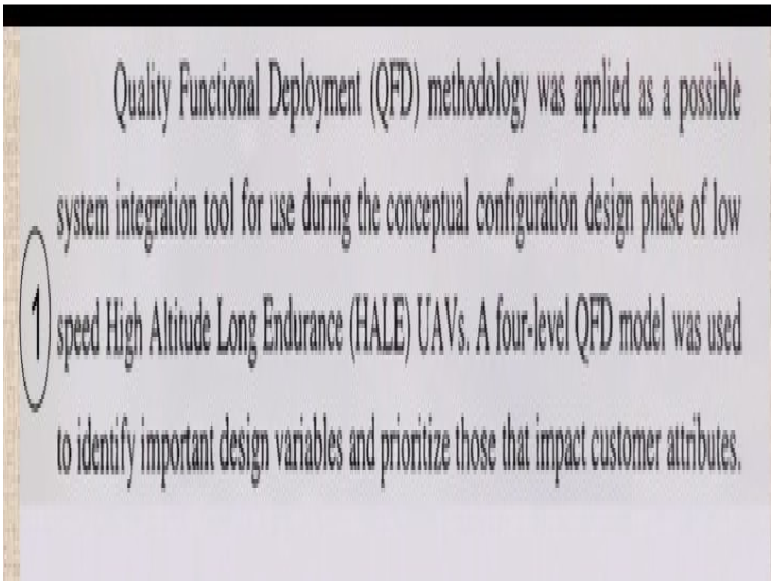

So what I have done here is I have actually taken the abstract of the thesis and I am showing it to you in 4 or 5 small parts so that you are able to appreciate. So in this particular study that we will look at the QFD methodology is applied as a possible system integration tool for use during the conceptual configuration design phase of a low speed high altitude HALE UAV. So he has used a four-level QFD as I have described few minutes ago and the aim of this four-level QFD was to identify the important design variables and to prioritize them such that the customer attributes are impacted. This is the classical job of any QFD.

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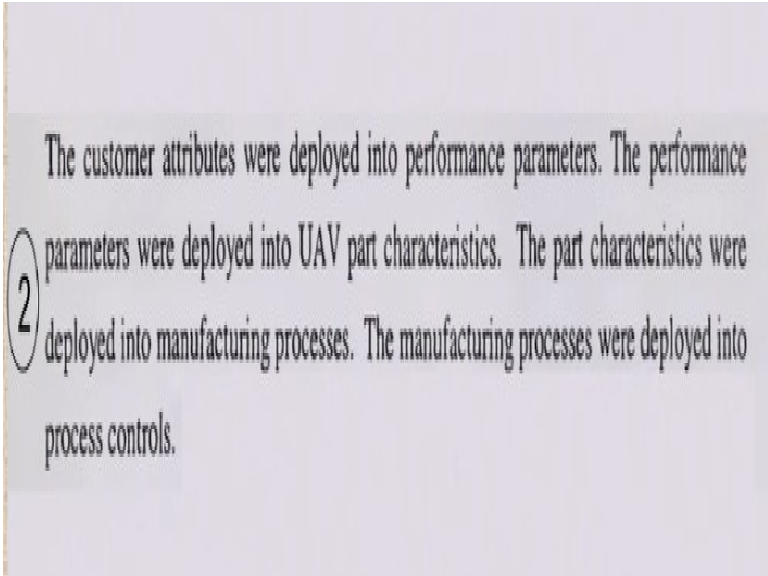

So in this particular study, the customer attributes are deployed into performance parameters that are the link that was achieved. So then these performance parameters were then deployed into UAV part characteristics in the second level. Then the part characteristics were deployed into manufacturing processes in the third level and finally the manufacturing processes were deployed into the process controls.

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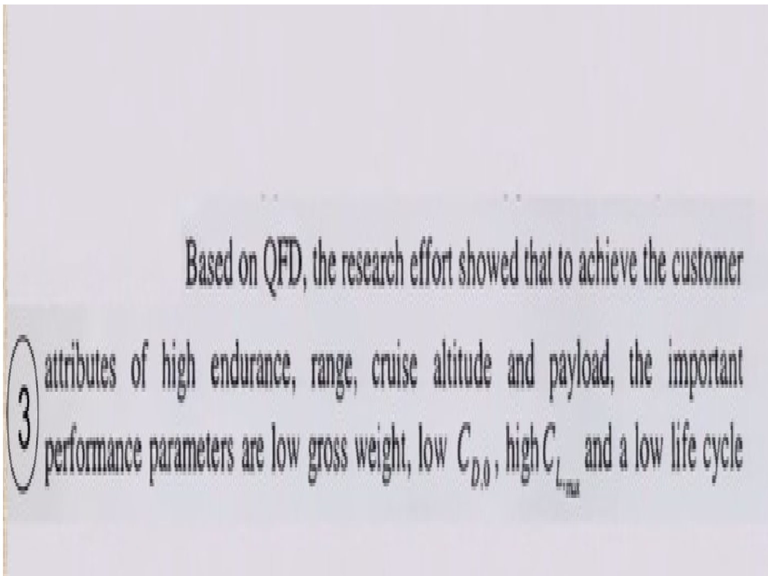

So based on QFD, the research effort showed that to achieve the customer attributes of high endurance, range, cruise, altitude and payload, the important performance parameters are low gross weight, low CDO, high CL max and low life cycle cost. So you can see the customer attributes, there were many attributes, the 4 major ones were identified and there are many suggestions or design features, the main design features have been identified.

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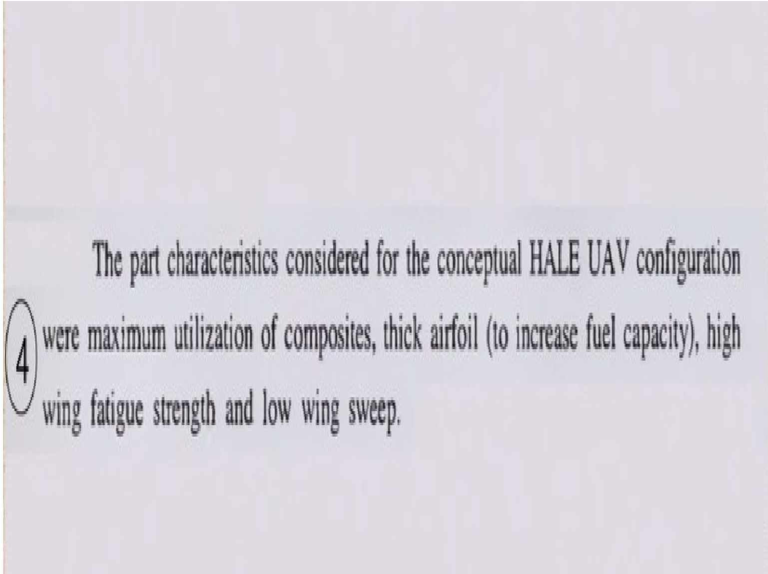

Now once we identify the design features in the next level you arrive at the part characteristics like the utilization of composites, using thick airfoil to increase the fuel capacity, high wing fatigue strength and low wing sweep. These were the part characteristics which were considered conceptually useful and then they were investigated further.

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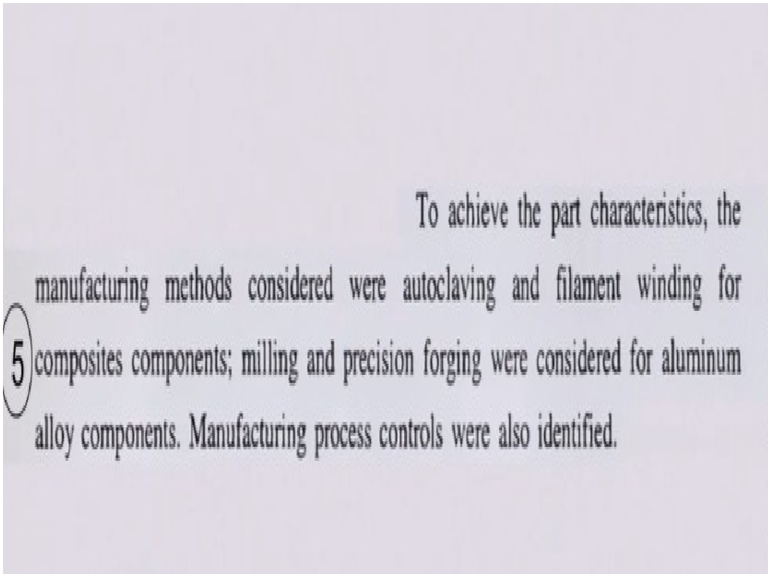

Now to achieve these part characteristics, the manufacturing methods considered were autoclaving. So that means now they have decided that they will go into composites. So therefore autoclaving and filament winding for the composite component, milling and precision forging for aluminum alloy components and also some manufacturing process controls were also identified.

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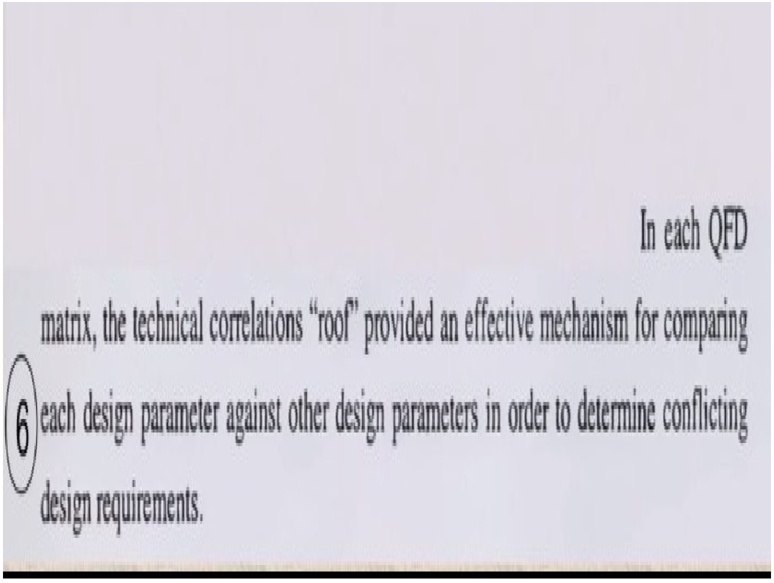

And finally in the last one so in each QFD matrix, the technical correlation roof provided an effective mechanism for comparing each design parameter against the other design parameters to determine the conflicting requirements and also to identify which requirements are supporting each other okay.

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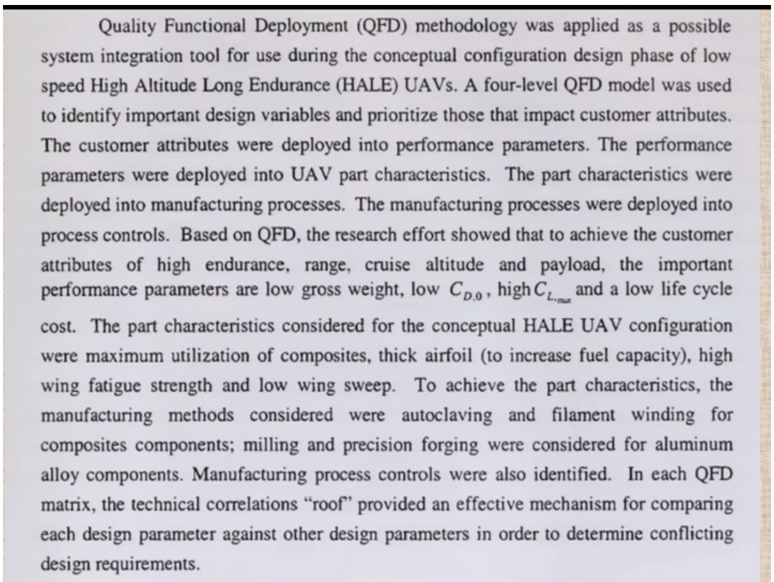

Quality Functional Deployment (QFD) methodology was applied as a possible system integration tool for use during the conceptual configuration design phase of low speed High Altitude Long Endurance (HALE) UAVs. A four-level QFD model was used to identify important design variables and prioritize those that impact customer attributes. The customer attributes were deployed into performance parameters. The performance parameters were deployed into UAV part characteristics. The part characteristics were deployed into manufacturing processes. The manufacturing processes were deployed into process controls. Based on QFD, the research effort showed that to achieve the customer attributes of high endurance, range, cruise altitude and payload, the important performance parameters are low gross weight, low $C_{D,0}$, high $C_{L_{max}}$ and a low life cycle cost. The part characteristics considered for the conceptual HALE UAV configuration were maximum utilization of composites, thick airfoil (to increase fuel capacity), high wing fatigue strength and low wing sweep. To achieve the part characteristics, the manufacturing methods considered were autoclaving and filament winding for composites components; milling and precision forging were considered for aluminum alloy components. Manufacturing process controls were also identified. In each QFD matrix, the technical correlations "roof" provided an effective mechanism for comparing each design parameter against other design parameters in order to determine conflicting design requirements.

So this is the whole of the abstract in one shot. You can pause the video and read it if you would like to go for a more meticulous study.

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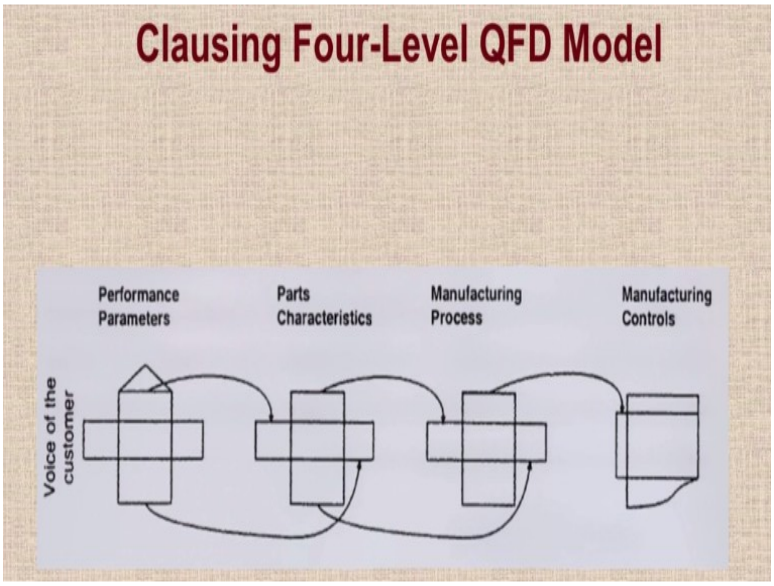

So the first of the four-level models looks at the voice of the customer and converts the principal performance parameters. Then it uses the performance parameters as needs to get the parts characteristics that is used as the need to get the manufacturing processes and that is used as the need to get the manufacturing controls. So we will now see how the house of quality as studied in this particular thesis is used in this four level.

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The example that he has taken is the Global Hawk UAV. Global Hawk is a very well known high altitude long endurance UAV and in this example a critical evaluation of the design of the HALE UAB was carried out.

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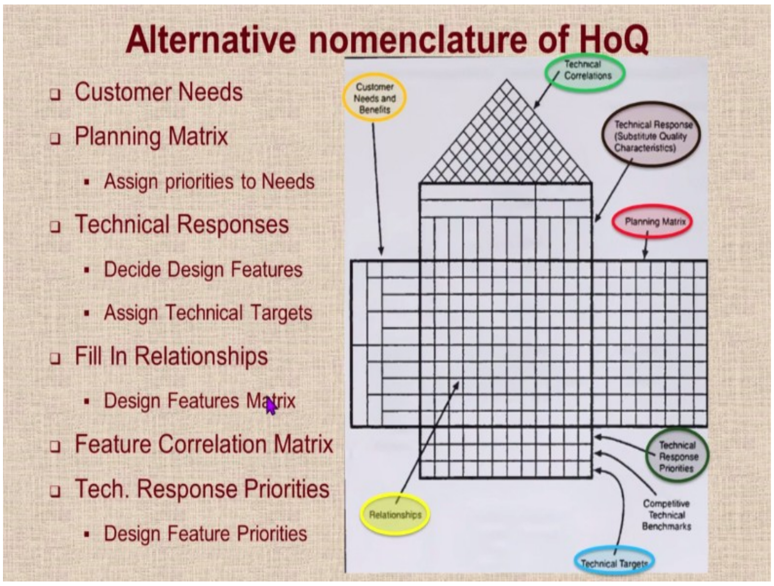

Now there are many many other ways in which the HoQ can be given as a nomenclature. So customer needs are of course the prime and they come in the top always okay. So customer needs are always there which are there in this vertical box. Then you have the planning matrix where you assign varieties of the designs okay. So the customer actually tells us which particular attribute is more important and also assigns the weightage to that.

Then we have the technical responses or essentially the targets which are obtained either from a study of the competition or based on our own assessment of what targets we would like to provide. Then you fill in the relationships in the design feature matrix. Then you do technical correlations on the top that is the feature correlation and finally you have the technical response priorities or the design feature priorities.

So you can notice it is only a difference in the terminology, otherwise you know whether you say that you assign priority to needs or whether you say fill in the planning matrix is the same thing, whether you say decide design prior features or design responses is the same okay.

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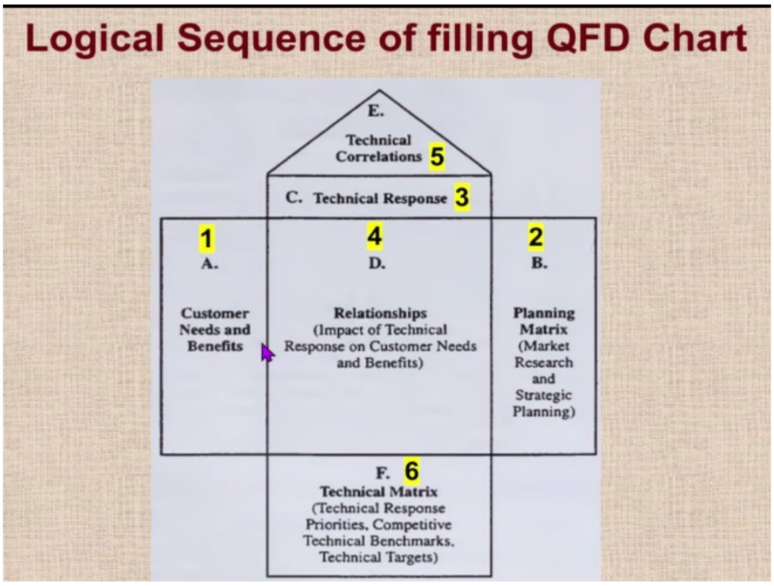

Like that so the logical sequence is very straightforward. First thing you do is to identify the voice of the customer, look at the wants and the needs and for this you have to look at the RFP, the request for proposal from the customer. Then you look at the planning matrix, so you can look at the market data, look at some strategic goals that the company may have and then you do the rank ordering of the needs.

Sometimes this information comes from the customer directly or from some other market survey and then you fill in the design features or you decide which design features you will investigate. Then you do the mapping between design parameters and customer needs. Then you do the interrelationships between the design parameters both positive and negative interrelations. Notice that in the central box where you do the mapping between the design parameters the customer needs.

You normally do not look for any negative correlation, you ignore all negative correlations and focus only on the positive correlations because here our aim is to decide which one is better. So you can do it purely by finding which has got a higher rank. If you start using negative numbers here, then you might actually cause some confusion because you know it is possible that two features which have negative numbers can cancel the one positive feature, so we do not do that.

We just say that we look only at positive relationships here and negative ones are on the top where we look at the interrelationships, but here we look at negative and positive both and finally based on the numbers that you fill in this particular matrix you can prioritize the design parameters.

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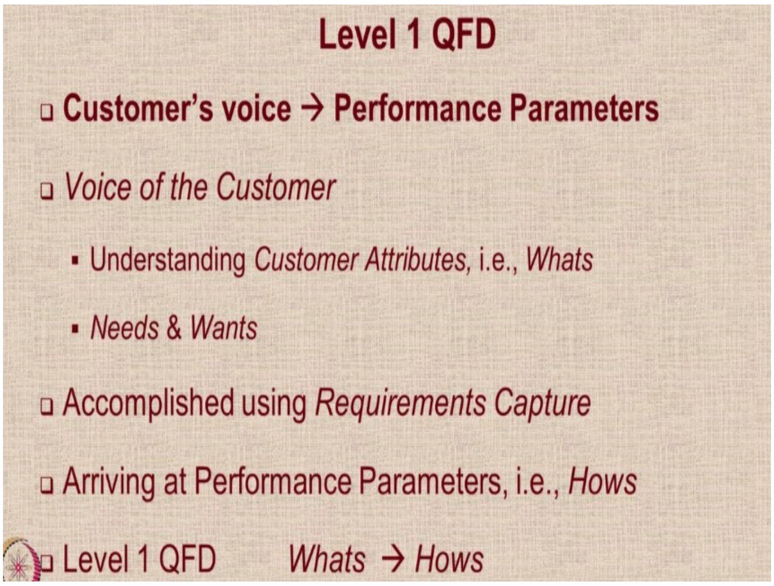

So let us first look at the level 1 QFD which is the customer's voice transformation into the performance parameters. So the voice of the customer essentially means understanding the customer attributes or CAs which is what okay. So needs and wants, actually you have to convert whats into needs and wants and this is accomplished using the process of requirements capture which has already been explained through a separate video clip, so I hope you have seen that.

Using this voice of the customer and whats, you arrive at the performance parameter that is the hows okay. So in level 1 QFD the whats which are the customer attributes are converted into hows which are the design features.

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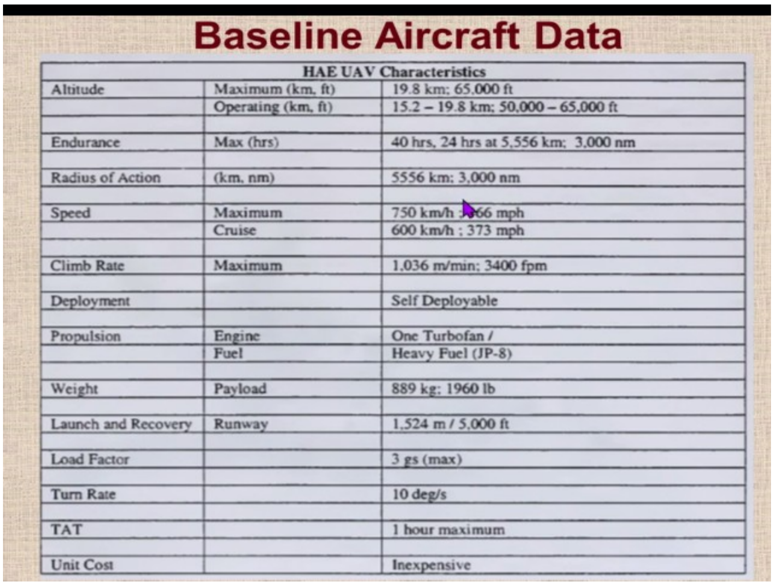

Baseline Aircraft Data

HAE UAV Characteristics		
Altitude	Maximum (km, ft)	19.8 km; 65,000 ft
	Operating (km, ft)	15.2 – 19.8 km; 50,000 – 65,000 ft
Endurance	Max (hrs)	40 hrs, 24 hrs at 5,556 km; 3,000 nm
Radius of Action	(km, nm)	5556 km; 3,000 nm
Speed	Maximum	750 km/h ; 466 mph
	Cruise	600 km/h ; 373 mph
Climb Rate	Maximum	1,036 m/min; 3400 fpm
Deployment		Self Deployable
Propulsion	Engine	One Turbofan /
	Fuel	Heavy Fuel (JP-8)
Weight	Payload	889 kg; 1960 lb
Launch and Recovery	Runway	1,524 m / 5,000 ft
Load Factor		3 gs (max)
Turn Rate		10 deg/s
TAT		1 hour maximum
Unit Cost		Inexpensive

So in this particular study, the customer requirements are all listed here. So there are these various parameters, what altitude it has to fly? How much endurance it should have? What is the radius of action, etc. All of these are given as the requirements of the customer okay.

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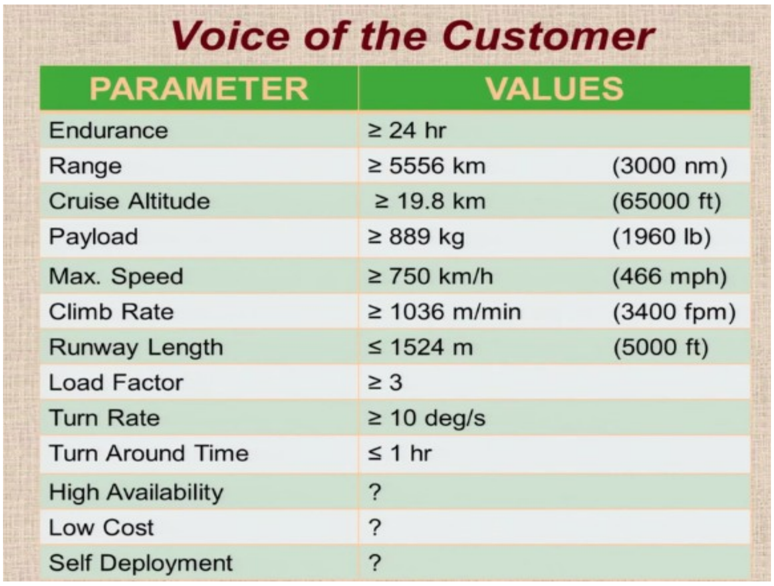

Voice of the Customer

PARAMETER	VALUES	
Endurance	≥ 24 hr	
Range	≥ 5556 km	(3000 nm)
Cruise Altitude	≥ 19.8 km	(65000 ft)
Payload	≥ 889 kg	(1960 lb)
Max. Speed	≥ 750 km/h	(466 mph)
Climb Rate	≥ 1036 m/min	(3400 fpm)
Runway Length	≤ 1524 m	(5000 ft)
Load Factor	≥ 3	
Turn Rate	≥ 10 deg/s	
Turn Around Time	≤ 1 hr	
High Availability	?	
Low Cost	?	
Self Deployment	?	

So by a study of the customer's requirements one can make a table like this where all the customer requirements as expressed explicitly in numerical values have been tabulated okay. So this is what the customer wants. Now when you look at terms like high availability, low cost and self deployment, the customer is not able to give specific numbers in this case and neither are we able to assign specific numbers, so we just have to leave it at that.

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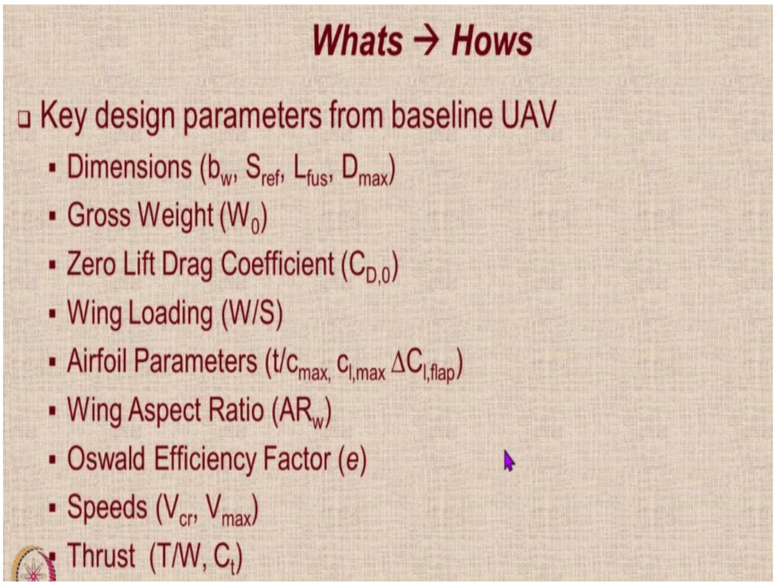

So how do you convert whats into hows okay? So from the baseline UAV you look at some key design parameter. There are some dimensions the wingspan, the wing reference area, the fuselage length and the maximum diameter. There is gross weight of the aircraft. Then you have the zero left drag coefficient, the wing loading, some airfoil parameters like the maximum thickness to chord ratio, the maximum lift coefficient, the maximum increment in the Cl because of the flaps, etc.

Then you having wing aspect ratio, Oswald efficiency factor. There are some speeds, the cruise speed and the maximum speed and then there are thrust to weight ratios and the SFC. So these are the key design parameters from the baseline UAV.

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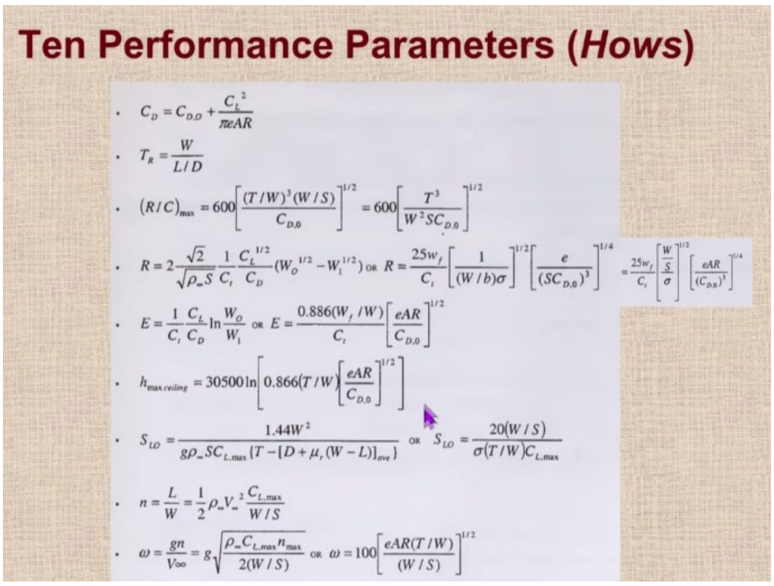

Their numerical values have been taken and then what you do is with respect to each of these requirements, you start correlating them into performance parameters. So CD is one of the important performance parameter, TR is the thrust required in level flight, rate of climb maximum which is available as a ratio of either you can use an expression like this or you can convert this into just T cube by W square okay.

Then the range which could also be simplified, this is for the FPS system that is why these numbers are appearing okay and from here you can simplify it further. This is the endurance, so 24 hour endurance is needed so that is obtained by the Breguet range and endurance equation and because it is a jet UAV you are using this 0.866 times for the L by D max value. For the ceiling you have an expression that correlates parameters like aspect ratio e CD0 and T by W with the maximum ceiling.

This is the formula that correlates the landing, liftoff distance, take off ground roll with the parameters during takeoff. You can simplify it by neglecting some of the terms okay and then you have the load factor n and the turn rate omega okay. So these are the 10 performance parameters.

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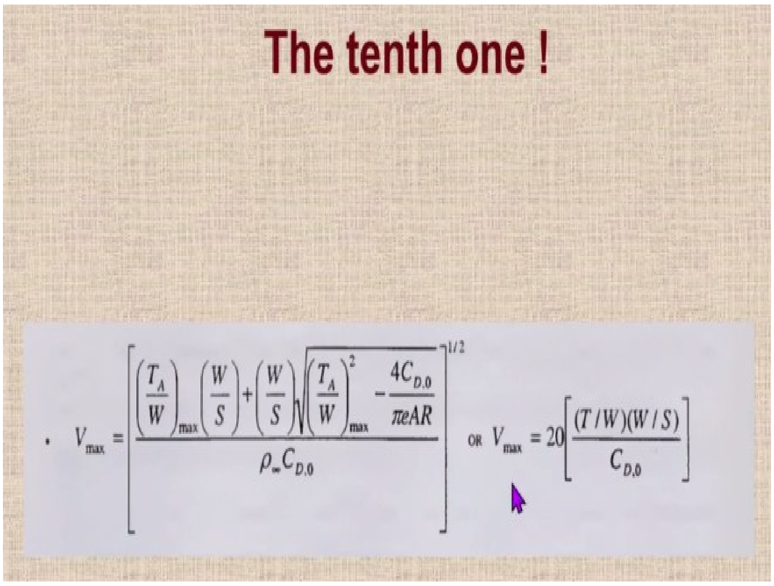

$$V_{max} = \left[\frac{\left(\frac{T_A}{W}\right)_{max}\left(\frac{W}{S}\right) + \left(\frac{W}{S}\right)\sqrt{\left(\frac{T_A}{W}\right)_{max}^2 - \frac{4C_{D,0}}{\pi e AR}}}{\rho_\infty C_{D,0}} \right]^{1/2} \quad \text{OR} \quad V_{max} = 20\left[\frac{(T/W)(W/S)}{C_{D,0}}\right]$$

There is a there is a tenth one. The nine were there but this one was the V max value or the maximum speed that you can obtain okay.

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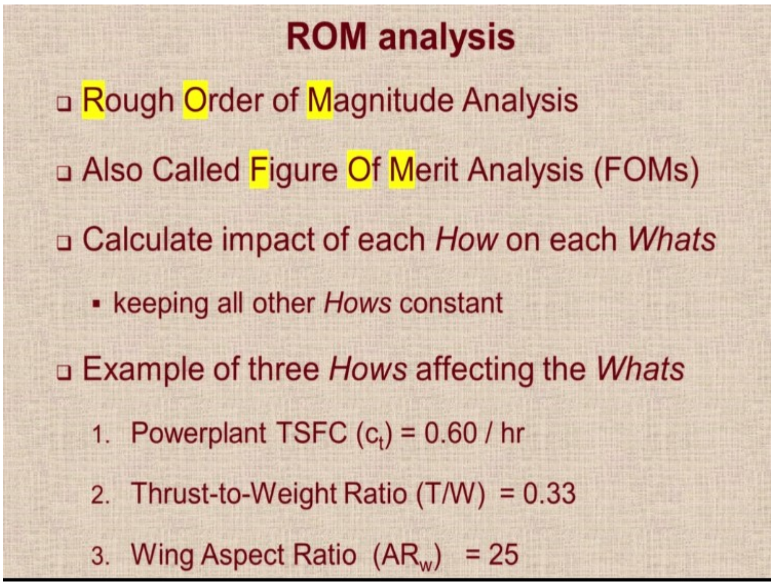

So what you do is you do a rough order of magnitude analysis that means to correlate between changes. For example a small change in Cl how much will it change in the various performance parameters, you can do this by making order of magnitude analysis, also called as figure of merit analysis. So what you do is you keep all other house constant, take every every one how, every one design parameter and see the effect on each of the whats or the requirements.

So let us look at three parameters. So we look at only TSFC, thrust to weight ratio and wing aspect ratio. The baseline value is 0.6 per hour, 0.33 and 25. So what we need to see is okay keeping everything else constant if the powerplant TSFC is changed, both positive and negative, how does it affect the values.

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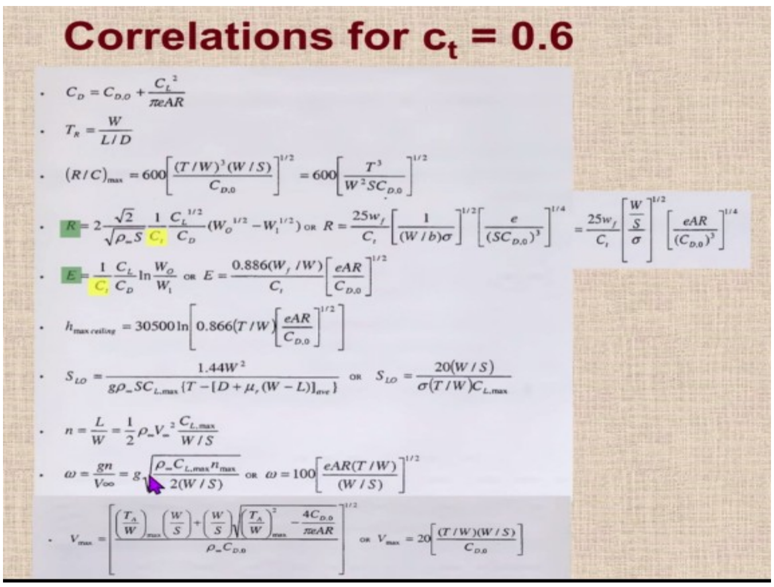

So what you do for that is basically you can notice that if you look at for correlations for Ct = 0.6, so if you look at the first parameter that is the thrust coefficient okay that is the thrust SFC. So Ct = 0.6 you notice that only these two expressions contain the Ct terms that is the endurance and range, everywhere else the SFC does not matter.

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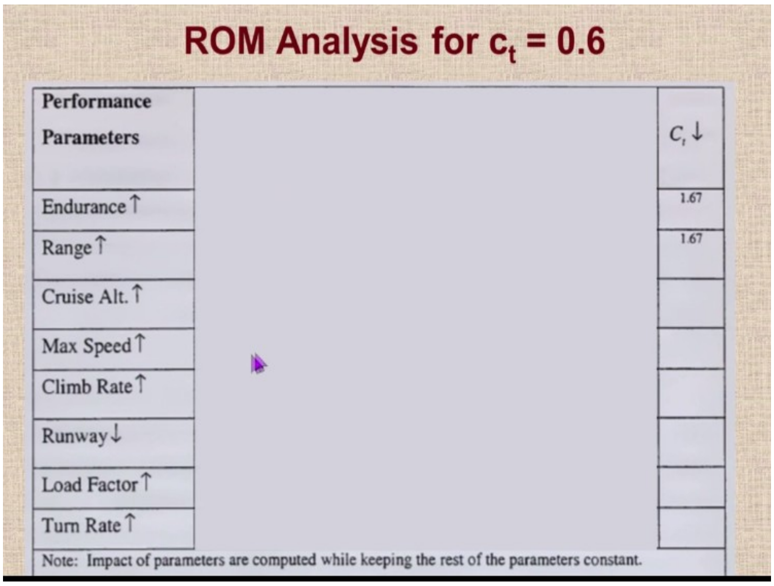

So therefore it is only endurance and range. So what you do is you change the value, you reduce the value by an order of magnitude okay and then you see what happens to the endurance and the range.

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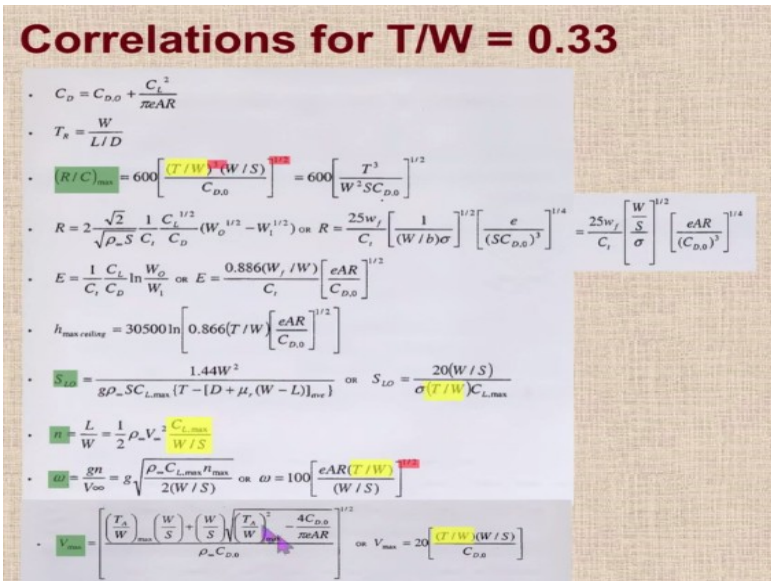

Now if you look at T by W, T by W appears in 1, 2, 3, 4, 5 equations okay. So it appears in 5 equations and the base value is 0.33.

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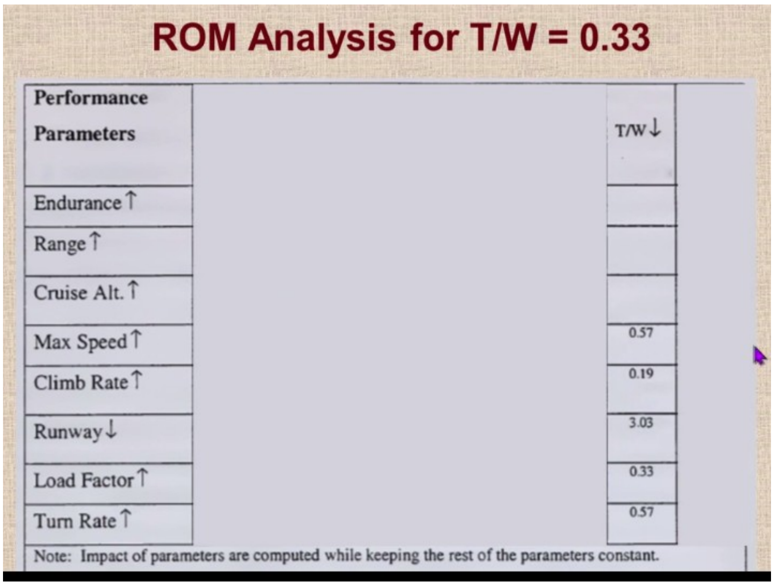

Performance Parameters		T/W↓
Endurance↑		
Range↑		
Cruise Alt.↑		
Max Speed↑		0.57
Climb Rate↑		0.19
Runway↓		3.03
Load Factor↑		0.33
Turn Rate↑		0.57

Note: Impact of parameters are computed while keeping the rest of the parameters constant.

So what you do now is you change this value, first thing you notice whether it is improving or decreasing this particular performance parameters okay. If it is improving then that is good because that is what you are looking for, and in these particular so impact of the parameters is computed while keeping the rest of the parameters constant.

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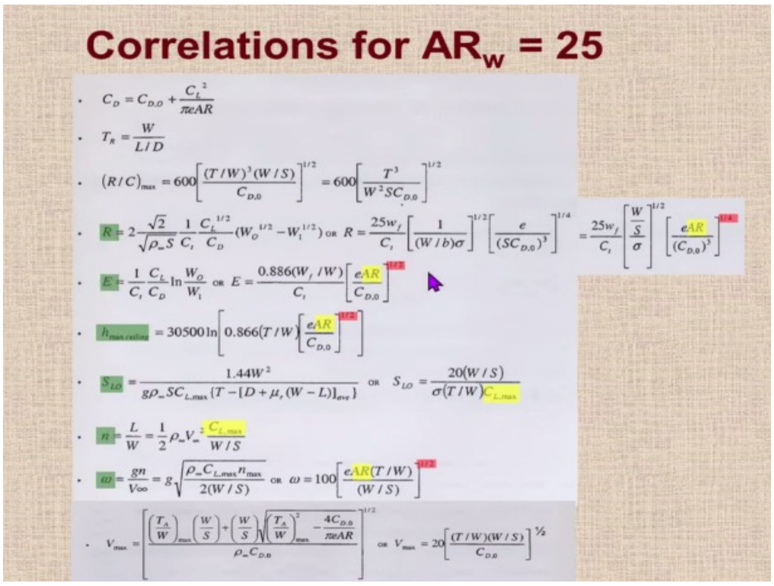

Similarly if you look at aspect ratio it appears in 1, 2, 3, 4, 5, 6 equations and in various ways. So for example here aspect ratio appears as root of some parameter. So you have to put accordingly that it will be root okay.

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ROM Analysis for Ar_w = 25

Performance Parameters		AR ↑
Endurance ↑		5
Range ↑		2.24
Cruise Alt. ↑		5
Max Speed ↑		
Climb Rate ↑		
Runway ↓		5
Load Factor ↑		5
Turn Rate ↑		5

Note: Impact of parameters are computed while keeping the rest of the parameters constant.

So for aspect ratio we notice that it appears in 3+3, 6 equations and therefore you just calculate the effect there.

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ROM Analysis for all 8 *Hows*

Performance Parameters	25600 W_o ↓	47 $\frac{W}{S}$ ↓	33 $\frac{L}{D}$ ↑	1.60 $C_{L_{max}}$ ↑	0.0161 $C_{D.0}$ ↓	25 AR ↑	0.33 T/W ↓	0.60 C_t ↓
Endurance ↑	0.85		33.31	1.60	7.88	5		1.67
Range ↑	6.25 E(-3)	6.32		1.26	22.12	2.24		1.67
Cruise Alt. ↑	3.9 E(-5)				7.88	5		
Max Speed ↑		6.32			7.88		0.57	
Climb Rate ↑	6.25 E (-3)	6.32			7.88		0.19	
Runway ↓	25.6 E (3)	47.4		0.63		5	3.03	
Load Factor ↑		0.02		1.60	7.88	5	0.33	
Turn Rate ↑		0.16				5	0.57	

Note: Impact of parameters are computed while keeping the rest of the parameters constant.

Now let us look at the ROM analysis for all the 8 hows, just like we showed you for 3, you can do it for all 8 of them and you can notice in the top I have written the baseline values and the bottom I have given how much it changes because of a change in the value okay.

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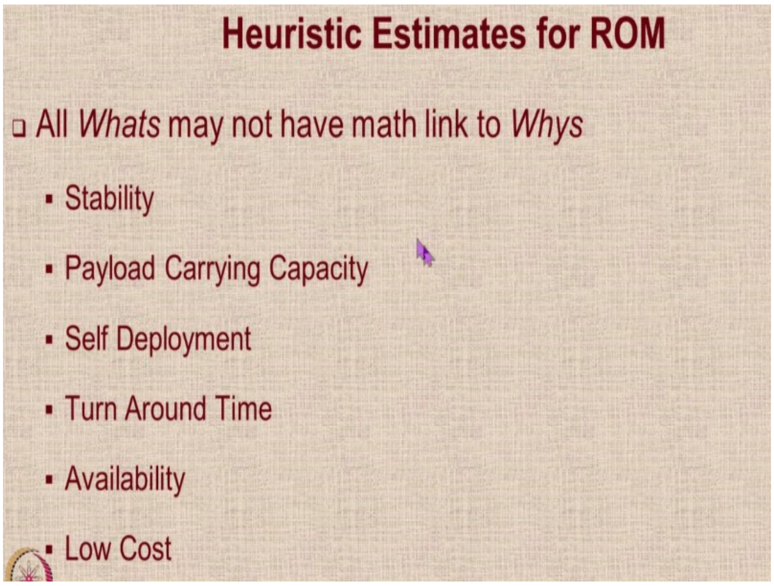

So then now all of the whats are not necessarily linked with whys mathematically. For example stability of the aircraft, it is a very complicated relationship, payload carrying capacity, self deployment time, turnaround time, availability, low cost. These are parameters where there is difficult to assign some numerical value as a target okay. So you would like to have a high payload carrying capacity, but you do not know right now how much payload to be carried.

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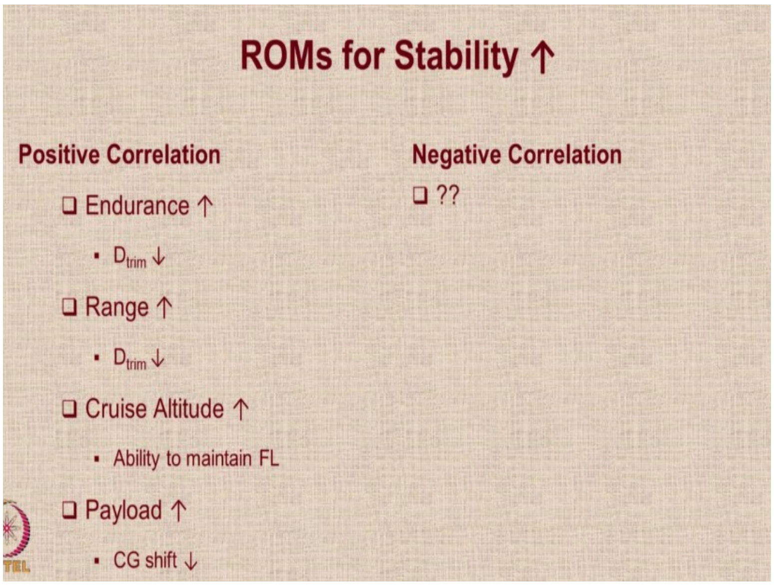

So for stability for example let us see. If the stability increases; then endurance will increase and trim drag will decrease. Because of the lower trim drag, the endurance will increase okay. Then range will increase again because trim drag has gone down. You can maintain flight at a higher flight level at a lower density right, so the payload also will increase but there is a negative correlation which we do not know right now, maybe there is no negative correlation, we need to figure out.

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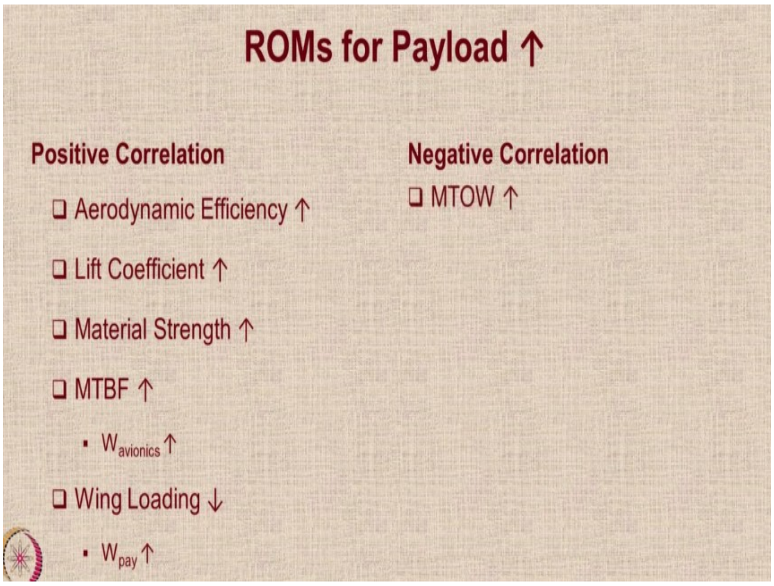

Similarly what happens if you include the payload okay. The dynamic efficiency increases, the lift coefficient increases, material strength has to be increased, MTBF between the failure mean time also is going to increase because the weight of the avionics is increased. As wing loading is decreased, the payload is going to increase. For negative correlation you can see that if you increase the payload obviously the max takeoff weight will also increase.

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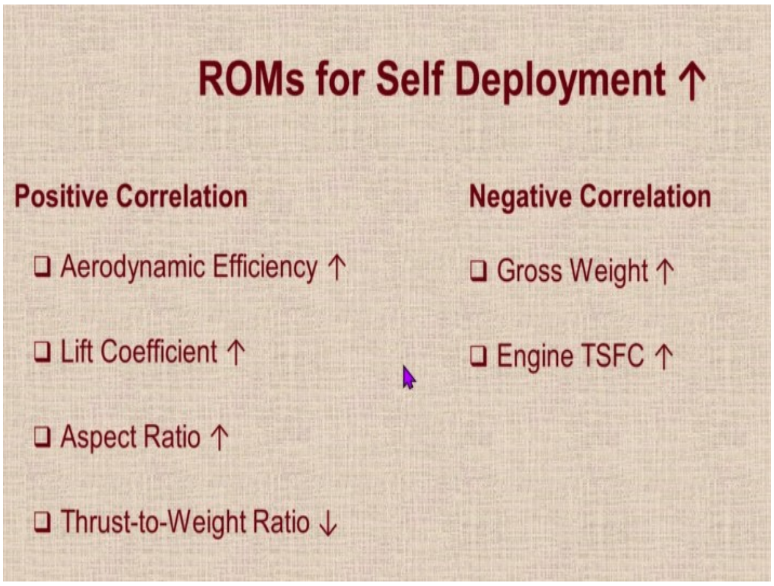

Now let us look at self deployment. In self deployment; if aerodynamic efficiency improves, then self deployment improves. If lift coefficient improves, then you should take off at a shorter distance, so therefore it allows self deployment. If aspect ratio improves increases, you get better value of induced dry coefficient, so you consume less fuel, so again self deployment improves this.

Similarly if thrust to weight ratio reduces, then the self deployment increases because that means you have a smaller engine okay, but gross weight and engine TSFC they correlate negatively with self deployment.

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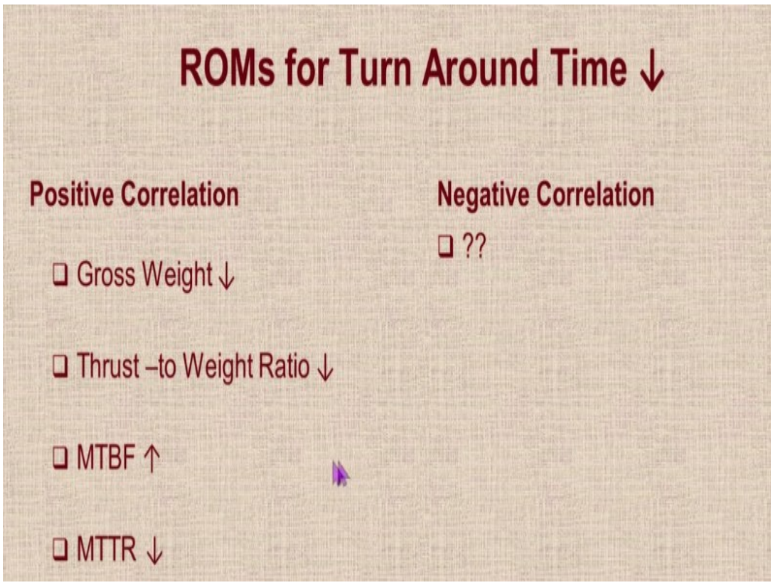

Turn around time. For example I want to reduce turn around time, so I find that gross weight helps, thrust weight ratio helps, but the mean time between failures is going to go up and the MTTR is going to reduce. Now there could be some negative correlations also, but we do not know right now, so we are not able to put it.

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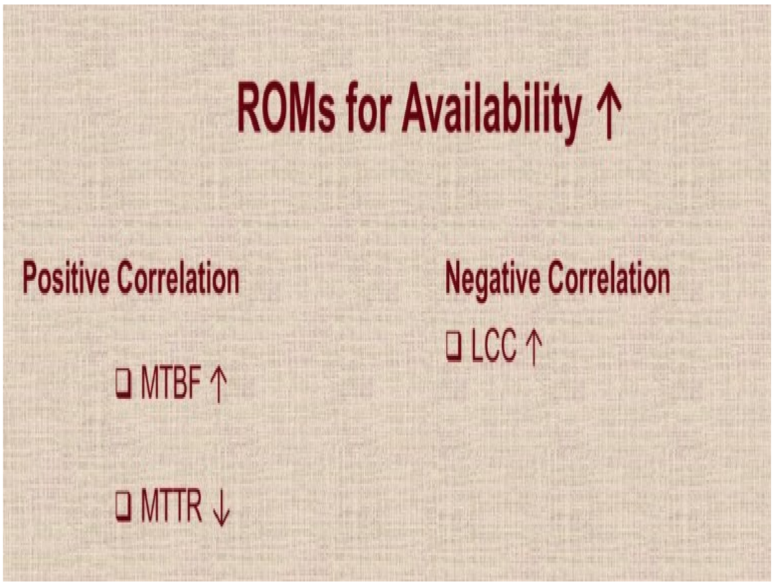

Similarly availability; if MTBF increases, availability will increase. If MTTR reduces, availability will increase. Now the thing is that as life cycle cost increases then there is a problem okay.

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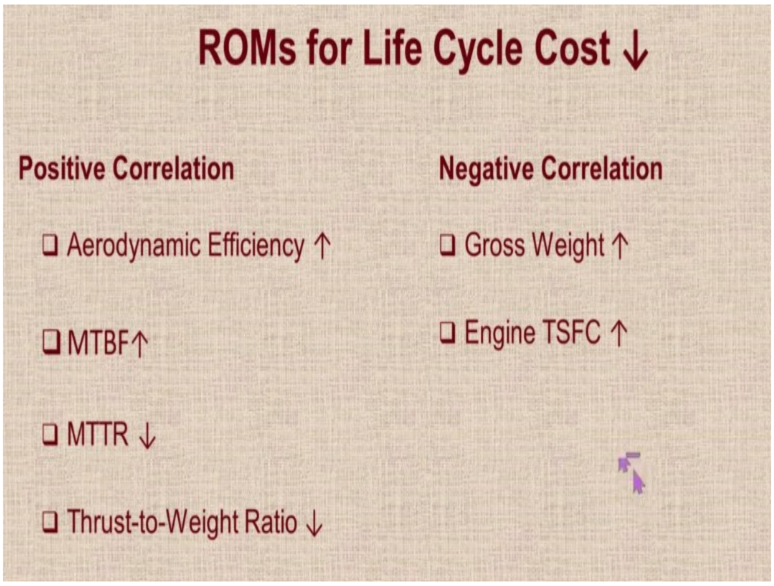

So look at life cycle cost. The positive correlation is with aerodynamic efficiency, mean time between failure okay and the thrust to weight ratio, MTTR. Negative correlation is with gross weight. As the gross weight increases, life cycle weight actually does not decrease, I would like to decrease it, but increasing TSFC is going to make it further.

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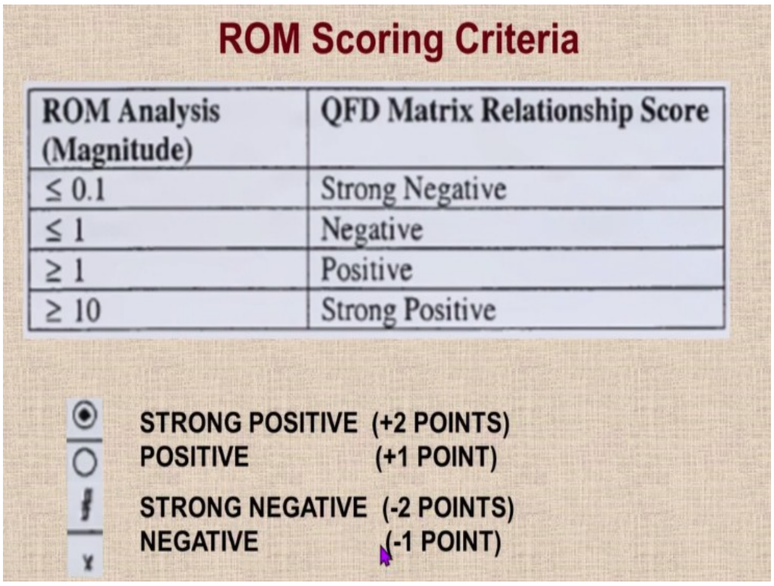

So what we do is we look at the scoring criteria. If we do the ROM analysis and if it is less than 0.1, it is strong negative, etc., etc. Strong positive is only if it is more than 10 that is a very high score okay. So for strong positive you give 2 marks, for a positive you give 1 point, for strong negative you give -2 and for negative you give -1. So you can just get the requirements from the customer.

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Mapping *Hows* to *Whats*

Customer Attributes / Operational Requirements — WHATs	IMPC	Wo	W / S	L / D	CL_max	CDo	AR	Stability	T / W	TSFC, Ct	Spec. Strgth	LCC	MTTR	MTBF
Endurance 24 hrs/3000 nm	13	x		◉	○	◉		○		○		x	○	○
Range 3000 nm	12	ʃ	○			◉	○	○		○		x	○	○
Cruise Alt 65000 ft	11	ʃ			◉	○	○	○				x		
Payload 1960 lbs	10	x	○	○	○			○			○	x	○	○
Max Speed 466 mph	9		○			○			x			x		
Climb Rate 3400 fpm	8	ʃ	○			○			x				○	○
Self Deploy	7	x		◉	◉		◉		○					
Runway 5000 ft	6	ʃ	ʃ		○		x		x			x		
Load Factor 3 gs	5		ʃ		○	○	○		x		○		○	○
Turn Rate 10 deg / s	4		x				○	○	x		○			
TAT max 1 hr	3	○												
High Availability	2											x	◉	◉
Low Cost	1	○							○		x		○	○
WEIGHT IMPORTANCE		13	1	6	11	12	5	7	3	4	2	10	9	8
RELATIVE IMPORTANCE		-100	13	50	70	83	40	50	-24	25	18	-63	53	53

For example endurance 24 hours at takeoff if you go along this thing you will see that there are some parameters like L by D increases. So if if L by D increases definitely the endurance will go up much better. If CDO is reducing, it will go up much better. So like that some parameters have a very strong correlation, some have a weak correlation okay.

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Level 1 HoQ TRADE STUDIES

Performance Parameters		UAV HALE Design Areas To Be Evaluated
$W_o \downarrow$	$L/D \uparrow$	Now, to achieve $\left(\frac{C_L}{C_D}\right)_{max} = \frac{(C_{D,0}\pi e AR)^{1/2}}{2C_{D,0}}$; the design team may select a large Aspect Ratio (holding other variables constant). The larger AR would likely lead to an increase in aircraft gross weight.
$W/S \downarrow$	$L/D \uparrow$	If the W / S is decreased by means of a larger wing area, then the AR is reduced, which may lead to a lower L / D.
$W/S \downarrow$	$C_{D,0} \downarrow$	If the W / S is decreased by increasing wing area, the zero-lift drag will increase due to the dominant factor of friction.
$W/S \downarrow$	$AR \uparrow$	If W/S is reduced by means of increasing wing area, S – then the design team has to note that that AR will be reduced (for b held constant). This is because $AR = b^2/S$.
$C_{L,max} \uparrow$	$C_{D,0} \downarrow$	Increasing $C_{L,max}$, say by having a thicker airfoil or requiring flaps down during cruise, would increase $C_{D,0}$. The design team has to be aware that an airfoil offering a higher $C_{L,max}$ would likely be obtained at the expense of a higher $C_{D,0}$.
$AR \uparrow$	$LCC \downarrow$	A higher aspect ratio will likely incur a higher cost.

So level 1 HoQ trade studies means what you have concluded is that the W0 reduction means L by D has to be increased. To achieve higher L by D, the design team may set a larger aspect ratio holding other variables constant. Like that if you want to reduce the wing loading, then increase L by D, automatically CD0 reduce that will help.

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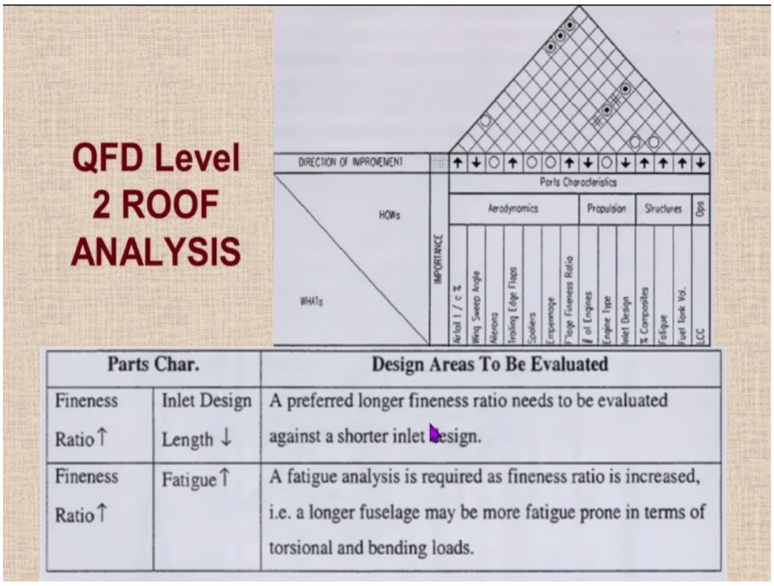

So with the initial requirement we have gone to the second level. In second level, we look at more specific information regarding the aircraft as our possible candidates to be given to improve the design and on the y axis where we have the design feature correlation matrix we are looking at fineness ratio, inlet design and fineness ratio.

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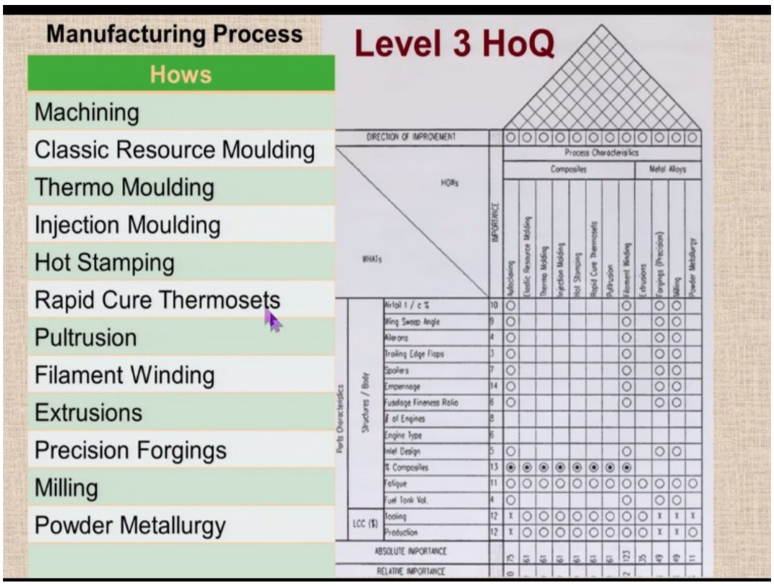

So then what you do is to achieve those good quality components, you then go to a component level where you can take one component and try to arrive at various new fixtures which can be created to address the requirements. So we have looked at the manufacturing processes and it was very clear that use of composites was a big help, so therefore so many processes which are related to composites have come in, but also we have brought in something like powder metallurgy, precision forging, extrusions okay, pultrusion, pultrusion, hot stamping these are also some other methods by which it can be done.

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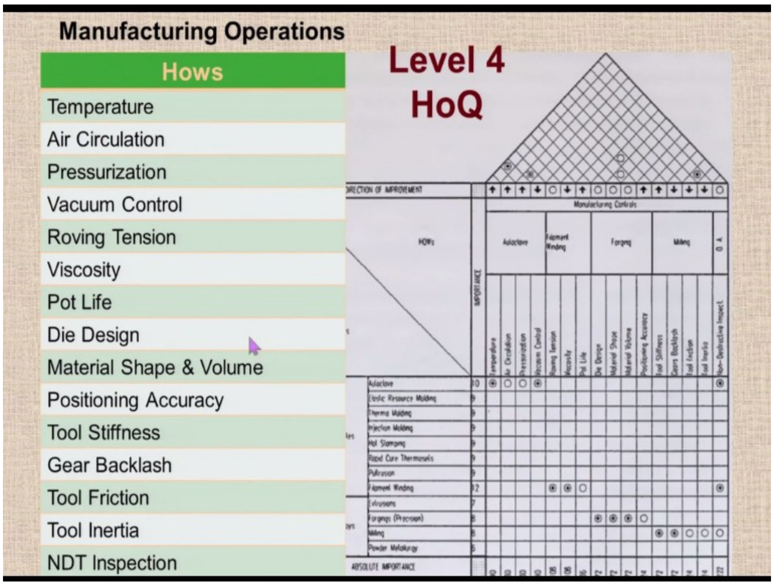

The next level has been drawn is now you have to look at the manufacturing operations okay and finally once you go through this particular thesis carefully you will be able to appreciate much better. The idea of this exercise was just to give you a very brief overview. Thank you so much.