The Systems Engineering Tool Box

Dr Stuart Burge

"Give us the tools and we will do the job"

Winston Churchill

Function Means Analysis (FMA) alias Morphological Analysis

What is it and what does it do?

Function Means Analysis is a highly structured approach to generating, selecting and documenting system design concepts. The resulting table is used to show all potential design options simultaneously, making it easier to apply selection/de-selection criteria to help generate whole system concept solutions. The basic idea is to consider the functions that the system performs and identify all the means of achieving that function. The approach typically uses a Function Means Table as shown in figure 1.

FUNCTION – MEANS ANALYSIS CHART										
System: Intelligent Dish Washer		Sub-System		Date: 1 April	Author: S Clean		Issue: 1.0	Reviewed: D. Dirt		
FUNCTION	**MEANS**									
Detect Load Make Up	Bar coded Items	Vision recognition	Infra red camera and recognition	Ultrasound	Electronic Tags	User defined	Mass Spectroscopy	Position indicators in baskets		
Measure Water Hardness	Hardness sensor	Installation defined	User defined							
Load Dirty Items	Bottom Hinge Door	Slide door Hinge	Top Door	2 Sliding Baskets	Conveyor					
Unload Cleaned Items	Bottom Hinge Door	Slide door Hinge	Top Door	2 Sliding Baskets	Conveyor					
Load Cleaning Agents	Pull out tray	In-door compartment	In-door Hopper	In machine body Hopper	No cleaning agents					
Fill Water	Gravity feed	Main Water pressure	Reciprocating Pump	Rotary Pump	Centrifugal Pump					
Drain Water	Gravity feed	Vaporisation	Reciprocating Pump	Rotary Pump	Centrifugal Pump	Clean and recycle water				
Heat Water	Electric Element	Gas Burner	House hot supply and mix with cold	Solar						
Wash	Rotating Spray arm – one off	Rotating Spray arm – two off	Wall mounted jets	Emersion	Water bath					
Rinse	Rotating Spray arm – one off	Rotating Spray arm – two off	Wall Mounted jets	Emersion	Water bath					
Dry Contents	Electric Element	Gas burner	Blow dry	Left wet	Left wet and hand dry	Spin dry				
Select Cycle	Clockwork dial - user defined	Fuzzy Logic	Neural Network	Rule Based System	Deterministic equation	Look up table	Fixed one cycle			
Control Cycle	Clockwork Controller	Microprocessor and software	Signal Processor	PLC	ASIC	Analogue hardwired	Digital hardwired	Cams and gears		
Receive User Input	Dial	Switches/buttons	LCD touch screen	Plasma touch screen	Soft key pad	Hard key pad	Voice recognition	Mobile phone as remote	TV style remot	
Display User Messages	Dial	Switches/buttons	LCD touch screen	Plasma touch screen	Audible - loudspeaker	Mobile phone	LCD in TV style remote			
Support	Metal Sub-frame	Monocoque	Back-plane Chassis	Force field						
Protect	Steel Casing	Injection/ vacuum moulded plastic	Carbon Fibre casing	Steel side/back casing with plastic facia						
Interface to services	Standard EU/BS Fittings	Snap-fit connectors	Fully plumbed in							

Figure 1: An Example of a Function Means Table

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In this example the left hand side of figure 1 lists the system functionality: the functionality that is deemed necessary to deliver the operational requirements of the system. The remainder of the table contains the potential functional solutions that have been identified by the design team. The table is a representation the solution space for this particular system.

The Function Means Table can be used to identify complete system solutions as shown in figure 2. In this instance three potential whole system concept solutions have been identified. The identification of whole system concept solutions is usually preceded by some de-selection of individual functional solutions as well as promotion of those clusters of functional solutions that benefit the system through their integration.

FUNCTION – MEANS ANALYSIS CHART										
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Receive User Input	Dial	Switches/buttons	LCD touch screen	Plasma touch screen	Soft key pad	Hard key pad	Voice recognition	Mobile phone as remote	TV style remote	
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Protect	Steel Casing	Injection vacuum moulded plastic	Carbon Fibre casing	Steel side/back casing with plastic facia						
Interface to services	Standard EU/BS fittings	Snap-fit connectors	Fully plumbed in							

Figure 2: Function Means Table with potential candidate whole system solutions identified.

Why do it?

As systems become more complex it is no longer possible to create the complete system design in "one go". Moreover, fixing part of the system design before giving due consideration to the un-designed aspects is leaving the door open for undesirable emergent behaviour to appear. Function Means Analysis allows a team (or individual) to generate and represent the "complete" solution space before any solution down-selection. This permits the design process to be systematic, transparent and traceable. If done with some discipline it allows design decisions to be recorded, which in turn will greatly help those people who will have to support the system.

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Where and when to use it?

Function Means Analysis can be applied throughout the design process. It can be used to help establish the overall concept through to the detailed design of individual components. Function Means Analysis lends itself to top-down design through the decomposition of system functionality. This starts with the identification of the system functions at the highest level. The various means of achieving them are identified. It is important that the functions identified are at the same level of generality. The means themselves at this level are likely to also be general in nature. Once agreed solutions have been selected, Function Means Analysis can be applied again at a lower level of detail. Here the general higher level means will themselves demand or require functionality that will form the basis of the lower-level analysis. A simple example will illustrate this point. Consider the function of controlling the access to a building: the part Function Means Table is shown in Figure 3

FUNCTION – MEANS ANALYSIS CHART											
System: Building	Sub-System		Date		Author		Issue		Reviewed		
FUNCTION	MEANS										
Control Access to building	Open Hole	Side Hinged Door	Top Hinged Door	Side Sliding Door	Upward Sliding Door	Roller Door	Strip Curtain	Curtain	IR/ light curtain	Rotating Door	Iris

Figure 3: Part Function Means Table

Let's suppose that the Side Hinged Door is selected as part of the overall concept. This can now be decomposed in terms of its functionality as shown in figure 4. This figure highlights that one of the functions is to hinge the door for which there are many options as shown.

FUNCTION – MEANS ANALYSIS CHART										
System: Building	Sub-System: Control Access			Date		Author		Issue	Reviewed	
FUNCTION	MEANS									
Provide Door Seating (Frame)										
Hinging	Parliament	Strap	Pivot	Piano	Butt	Riding Butt	Plastic	Tee		
Barrier(door)										
Control Opening (lock)										

Figure 4: Part Function Means Table for the Side Hinged Door Solution to the Control Access to Building Function.

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Figure 4 also shows something else that is quite profound about system design in general. As we decompose the system or look in more detail, it becomes more difficult to identify functionality but easier to talk in terms of solutions. Having decided that the method for Controlling Access (function) is to be a Side Hinged Door (solution) it is easier to decompose the door "sub-system" as objects rather than functions. That is the door, the hinges, the door frame, the lock etc. All these things have a job to do (they have a function) but is becomes easier to talk about the problem in the *object domain* rather than the *functional domain*. Good designers know when to change from one domain to the other. This profundity has a corollary:

> *When conducting a Function Means Analysis the functions should be at the same level of generality*

This can be difficult to achieve in practice since it often is not clear until the table is, or tables are, constructed. It is often necessary having completed the first draft of the Function Means table to review it and adjust it to be at the same level of generality. This often involves collecting or aggregating low-level solutions together into groups for which, at the level of generality being addressed, it is possible to sensibly decide between.

The examples given so far all represent product based systems, however, the tool can also apply to process based systems. Here the functions are the process steps or activities. The means are the way we choose to carry out those activities. The tool can also be applied to software based systems[1]

Who does it?

Undertaking a Function Means Analysis is best performed by a team to draw upon the experience and expertise in that team. The first step in the process is to generate potential functional solutions and it is at this point a team will always outperform an individual. Since we are effectively identifying the technologies that the system will use, team members need to have knowledge of the possible technologies that could be used.

As with most team based tools, time size is important and the recommendation is for 5 to 8 members. Below 5 and there is perhaps not enough knowledge in the group and above 8 creates management issues..

There is great benefit in terms of quality of output and time efficiency if the analysis sessions are facilitated by a Function Mean Analysis craftsman.

1
Function Means Analysis can be applied to software based systems; however this is unlikely to happen until the debates about object-oriented design and structured design are sorted out.

How to do it?

Function Means Analysis has two distinct stage or phases. The first employs divergent thinking to generate the potential functional solutions. The aim here is quantity rather than quality and "freewheeling" or "out of the box" thinking should be encouraged. The second stage or phase employs convergent thinking to make sense out of the first stage by eliminating the obvious "non-runners" and organising the remaining ideas into complete or whole system concept solutions. While this second stage is concerned with bringing order to the creative first stage the aim is generate as many as possible whole system concept solutions. This overall design philosophy is portrayed in figure 5 as two funnels.

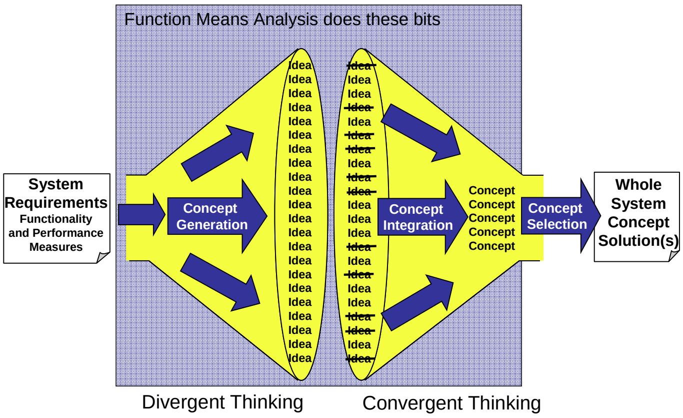

Figure 5: The design philosophy of Function Means Analysis

Figure 6 present a more precise process for undertaking a Function Means Analysis

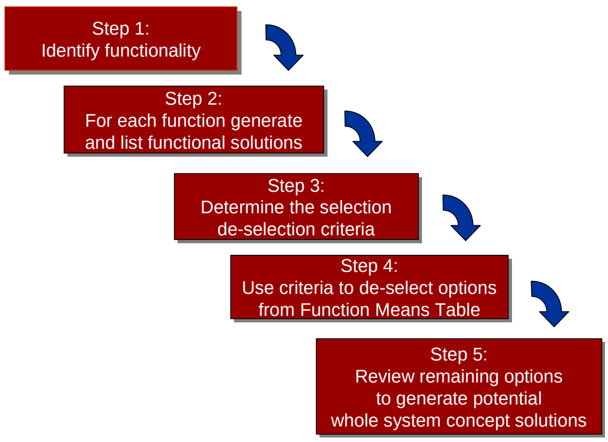

Figure 6: The process for conducting a Function Means Analysis

STEP 1: Identify Functionality

To undertake a Function Means Analysis requires the functionality of the system. Although it is possible to undertake the analysis based on system attributes (see later under FMA derivatives). How

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this functionality is arrived at does not affect the tool, but the functionality must be:

- Complete i.e. encompass the whole of the system
- At the same level of generality

These rules are not rigid. Indeed, Function Means Analysis can help to check whether the system functionality is complete. Very few systems are unprecedented and therefore a check can be made to ensure that current system sit within the means identified. Once identified the functions should be entered in the Function column of the Function Means Table.

While brainstorming can be used to identify the system functionality it is worthwhile using more rigorous and systematic tools such as:

- Viewpoint Analysis
- Functional Modelling
- Use Cases
- Quality Function Deployment
- Functional Failure Modes and Effects Analysis

All of these tools are described individually.

STEP 2: For each function generate and list functional solutions

Taking each function in turn, the team should identify and record in the table all the possible means of achieving the respective function. As noted earlier the aim here is quantity rather than quality and a good rule of thumb is to aim for 9 ideas per function. This assumes 3 conventional, 3 extreme and 3 with high potential.

To help generate the functional solution ideas, tools to overcome the barriers to creative thinking should be used. These tools include:

- Brainstorming and its derivatives (Negative Brainstorming, Affinity Diagram, Brainwriting)
- Similarities and differences
- SCAMPER

All of these tools are described individually. The results are recorded in the Function Means Table. The functional solutions can be recorded as verbal descriptions or diagrams. In general, I tend to find verbal descriptions easier when using the tool at the system level and diagrams and pictures better at the components level. Consider for example the Function Means Table for the door hinge problem shown in figure 4. This would be better if a sketch of each hinge type was used to make clear the differences between the choices.

At this point we have completed the first divergent phase and have a table that shows all the possible system function solutions. The next steps will use this table to extract whole system concept solutions. Our aim is to "plot paths" through the table that define whole system concept solutions. While we do want to find the best complete system solution it is highly likely that several possibilities emerge to be taken forward to more detailed design. There are three strategies that could be used:

- For each function determine the "best" means. The sum of all these is the system solution.
- Consider every possible combination of means
- Eliminate objectively the weaker functional solutions. This reduces the number of possibilities allowing complete system solutions to be identified.

The first strategy does not guarantee to find the optimal complete system solution. The second is just too time-consuming leaving the third as the only viable way forward. However, it is important that this step is approached objectively by defining criteria for selection/de-selection, applying these rigorously and recording the outcomes. This is described in more detail in the following steps.

STEP 3: Determine the selection and de-selection criteria

What is required at this step are some key criteria that can be used to quickly eliminate or promote the solutions documented in the Function Means Table. The aim is to remove the obvious "sore-thumbs". Too many criteria and the exercise can get bogged down and tedious (leading to a loss of enthusiasm and concentration). The general recommendation here is between 3 and 6 criteria. There is of course a drawback with a few criteria in that those that are selected have a significant impact on the selected system solution. The wrong criteria will leave the wrong system solution. A good approach here is to use the primary customer requirements from the Quality Function Deployment phase 1 chart – these should represent the "order winners" (see appendix A). However, care must be exercised to ensure that any key "order losers" (see Appendix A) are also included. It is also recommended that the criteria are organized in order of importance.

STEP 4: Use criteria to de-select options from the Function Means Table

The criteria determined in the previous step are now systematically applied to the removal of many candidate functional solutions. The aim here is to remove approximately 50% quickly, i.e. the obvious "sore thumbs". As functional solutions are removed a note should be made of the criteria and reasoning that led to their removal. This documentation will provide a record of these key design decisions. This is an important activity since most systems will be modified during their life and knowledge of design decisions such as these can be critical to the modification activity. To illustrate this step consider the Function Means Table for a Fork-Lift Truck

FUNCTION	MEANS				
Supply Power	Electric	Petrol	Diesel	Bottled Gas	Steam
Transmit Power	Gears and shafts	Belts	Chains	Hydraulic	Flexible cable
Move	Wheels	Track	Air Cushion	Slides	Pedipulators
Manoeuvre	Rear wheel Steering	Front Wheel Steering	All Wheel Steering	Air thrust	Rails/ Guide wire
Stop	Disk Brakes	Drum Brakes	Electric Braking	Reverse Thrust	Ratchet
Lift Load	Hydraulic ram	Motor & Rack and Pinion	Motor & Screw	Motor & Chain	
Locate Operator	Seated at front	Seated at rear	Standing	Walking	Remote control

Figure 7: Function Means Chart for Fork-Lift Truck

Suppose here the customer's key requirements include

- 8 hour continuous operation
- turning circle of 3m
- operation in a fire risk area

In this case these few requirements allow the removal of many candidate function solutions. The 8-hour continuous operation effectively negates steam and bottled gas. The turning circle of 3 m negates the use of air thrust and tracks and rails, while the operation in a fire risk area removes the Hydraulic options. This immediately decreases the number of options as shown in Figure 8.

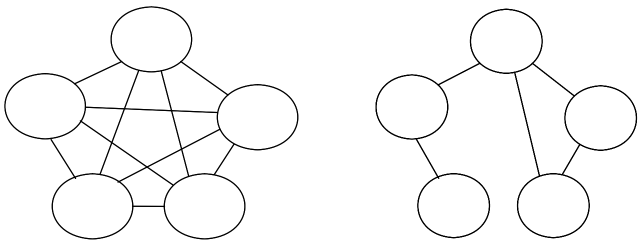
FUNCTION	MEANS				
Supply Power	Electric	Petrol	Diesel	Bottled Gas	Steam
Transmit Power	Gears and shafts	Belts	Chains	Hydraulic	Flexible cable
Move	Wheels	Track	Air Cushion	Slides	Pedipulators
Manoeuvre	Rear wheel Steering	Front Wheel Steering	All Wheel Steering	Air thrust	Rails/ Guide wire
Stop	Disk Brakes	Drum Brakes	Electric Braking	Reverse Thrust	Ratchet
Lift Load	Hydraulic ram	Motor & Rack and Pinion	Motor & Screw	Motor & Chain	
Locate Operator	Seated at front	Seated at rear	Standing	Walking	Remote control

Figure 8: Function Means Chart for Fork-Lift Truck

STEP 5: Review remaining options to generate potential whole system concept solutions

This step aims to integrate the various functional solutions together to form whole system concept solutions. Here we are attempting to bring together part-solutions to give the best possible system. It is where system integration begins. It is at this stage where engineering science often plays an important role and can dictate which functional solutions will work better together. For example an electric powered truck would require a belt drive, whereas a petrol or diesel solution would require gears and a shaft. Equally, there are combinations of functional solutions that just don't work. For example the fork lift truck would not have air cushioned movement and steering by wheels! There are some basic systems principles that can used here:

- Cohesion[2]: Wherever possible functionality should be combined in the design solution. Functions that are physically connected or correlated should be investigated for potential synergies. The correlation matrix of Qualify Function Deployment phase 1 chart can be useful here.

- Binding and Coupling
    - Binding: Functions bind together when they share common interfaces. Groups of functions that are tightly bound should be considered candidates for physical grouping or potential aggregation as sub systems. Hutchins gives the following examples:
    - 

Functions tightly bound
Potential Sub System?

Functions loosely bound
Not a potential Sub System

    - Coupling: the degree of connectivity between sub-systems and we should always attempt to reduce the degree of coupling since it will reduce the number of interfaces. Again Hutchins gives the example:

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[2] The definition of cohesion here comes from classic mechanical engineering good practice (for example the texts of M J French on Engineering Design). The term has a different meaning in software. In software engineering it refers to the "single mindedness" of a module, i.e. each module should do one thing, one thing only, and do it well, without needing any other modules to achieve this..

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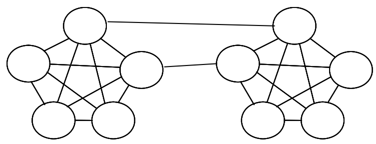
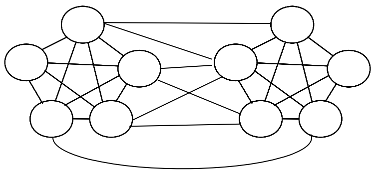


Two sub systems with low coupling. Minimal interfaces therefore “good”



Two sub systems with high coupling. Increased interfaces therefore “bad”

Binding and coupling can be investigated using Functional Models and N^2 analysis.

These principles should not be applied blindly but used with thought.

Common sense is also a good tool here and the aim is to identify as many realistic whole system concept solutions as possible. It is also important to note that for any particular function we can have more that one solution at a time. A useful approach here is to use the reduced Function Means table to “trace out “potential whole system concept solutions as shown in figure 9.

FUNCTION	MEANS				
Supply Power	Electric	Petrol	Diesel	Bottled Gas	Steam
Transmit Power	Gears and shafts	Belts	Chains	Hydraulic	Flexible cable
Move	Wheels	Track	Air Cushion	Slides	Pedipulators
Manoeuvre	Rear wheel Steering	Front Wheel Steering	All Wheel Steering	Air thrust	Rails/ Guide wire
Stop	Disk Brakes	Drum Brakes	Electric Braking	Reverse Thrust	Ratchet
Lift Load	Hydraulic ram	Motor & Rack and Pinion	Motor & Screw	Motor & Chain	
Locate Operator	Seated at front	Seated at rear	Standing	Walking	Remote control

Figure 9: Potential whole system concept solutions for the Fork-Lift Truck

Alternative Forms of Function Means Analysis

There are alternative forms of Function Means Analysis which force the design team to consider combinations of functional solutions that would normally not be considered. In theory any number of functional solutions can be considered, but we can only really visualize up to three. Often called *morphological analysis* the example by Alger and Hays illustrates the approach. This example is for a clothes dryer and is shown in figure 10.

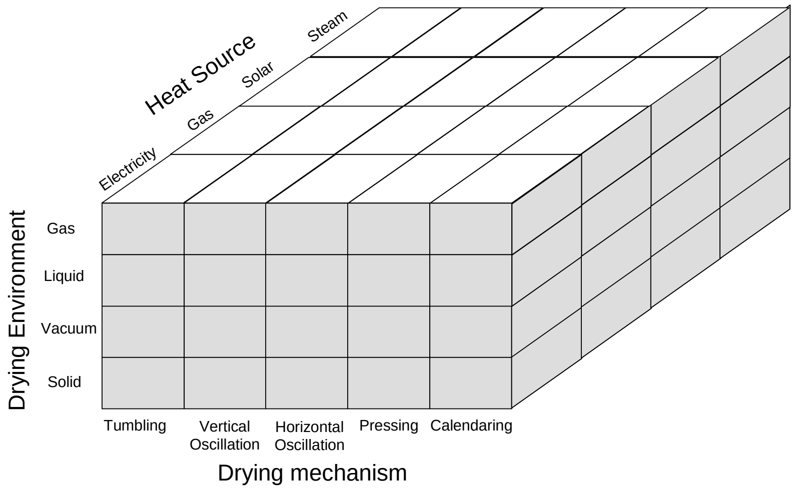


Figure 10: Morphological Box for a Clothes dryer

Figure 10 often called a morphological box, has potential design solutions on all its axes. These could relate to functions or implied functions as in figure 10. The “box” then represents the solution space of 80 sub-cubes , with each sub-cube giving a possible system solution (to the level of granularity used). Obviously some potential solutions can be eliminated, but others could give new and novel possibilities.

What Goes Wrong: The limitations of Function Means Analysis

Missing functionality. Obviously solutions can only be generated for those functions that are included in the analysis. It is important to check the list of functions for completeness. There is of course no guarantee that we will not still miss a function.

Deselecting at the wrong level of generality. Functional solutions are often at a much lower level of generality than their function. This can result in the premature elimination of such solutions. In such cases it is important to ask the question “can we really decide between these solutions at this point?” If the answer is no, then the solutions are too lower level and should be aggregated into groups for which the selection/de-selection decision can be sensibly be made.

Team membership: The quality of a Function Means Analysis depends on the idea generating capability of the team. A common mistake is to have a team comprising only the designers of the previous system who will have the baggage of that experience. It is important to bring in people who are not constrained by the past or by bitter experience.

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Thoughtlessly defined or chosen selection/de-selection criteria: This needs time and thought about the criteria to use. If possible use criteria that have been validated in some way – such as the primary customer requirements for a Quality Function Deployment phase 1 (assuming that this has been done correctly).

Success Criteria

The following represents a set of criteria that have been found to be useful when undertaking a Function Means Analysis.

- Team size between 5 and 8
- Team constitution has expertise and experience in a wide range of solution technologies
- Have developed the system functionality using an appropriate tool (Viewpoint Analysis, Functional Modelling, Quality Function Deployment)
- Use an experienced independent facilitator
- Use several creative thinking tools
- Do review the first draft of the Function Means table to ensure that the functional solutions are at the same level of generality as the functions
- Take time to chose the selection/de-selection criteria
- Apply the criteria systematically and record the reasons for eliminating solutions
- Plan for one-day's effort.

Appendix A

A useful concept when determining selection/de-selection criteria is that of *order winning* and *order qualifying* criteria. First proposed by Terry Hill.

Order Winning Criteria: What aspects of a product that WIN it orders in the market place**.** If we are better than our competition we will win on these aspects. These are sometimes called Unique Selling Points (USP)

Order Qualifying Criteria: What aspects of a product that KEEP it in the market place. We only need to as good as the competition in these aspects. Bettering the competition dose not win any futher orders. However, these can be *order-losing* sensitive. That is we must be as good as the competition, if we are worse we will not win ANY orders.

Selection/de-selection criteria should not be based on just order winners. We also need to keep in mind if there are any order-losing sensitive qualifiers.