The Potential in Simulations and Meta-Modelling for Understanding and Development of NDE

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Abstract. By combining detailed mathematical modelling of the physics in NDE with a broader robust engineering approach based on the sequential steps: screening, modelling and optimization, it would be possible to generate meta-models that can support the NDE Engineering efforts to evaluate NDE applicability in a wider context, as a complement before the repeatability, reproducibility and capability studies normally performed. The aim with the initial screening phase is to effectively evaluate and priorities NDE control parameters from a wider perspective relative the demand in the specific application and to fix parameters of less impact on the output response to their most economical and practical level. The aim with the second and third steps is to study how the important parameters influence and to perform sensitivity analysis of reproducibility and repeatability, for example, followed by procedure development, respectively. The methodology is straightforward when it comes to smooth response surfaces of lower order (up to second or third). The recommendation for the screening phase generally is 'to be bold' when it comes to the definition of the experimental range for each parameter – meaning make them as wide as possible relevant for the specific application. For NDE applications not following the Berens assumption for POD studies: large cracks yield large response signal. Such as, the varying signal amplitude from surface breaking notches in ultrasonic testing, for example. The be-bold-screening recommendation may lead to incorrect prioritization of parameters. In this paper this is illustrated by how the width of the experimental range for the control parameters tested during screening actually influence the screening result. Two basic ultrasonic testing set-ups have been compared using the SimSUNDT simulation software package: Surface Breaking Notch (SBN) and Side Drilled Hole (SDH). Even though the result was expected. It points out the need of development of the screening methodology supporting the NDE engineering, when it comes to addressing the applicability issue: does the data collected tell us what we actually want to know about the tested application (or does it only tell us something of the NDE method).

1 Introduction

There are many roles and functions that need to take decisions about processes and products in operation. Here this is illustrated by the quality assurance of welding process of the load carrying structure for heavy vehicles manufacturing (Pic. 1a) [1]. The applicability of the quality data depends on how the information drawn from the data support the decisions need to be taken. The problem and challenge for each organisation is to bridge the gap between the general data generated by the NDE procedure and the range of decision makers in a structured and effective manor. Designing a lean information flow starts by the identification of the decision makers and their information needs and ends with the data collecting procedure, not the other way around (Pic. 1b) [2]. Today a lot of organisational inefficiency is related to out-dated or non-existing ad hoc information flows where huge amount of data is collected but never processed [1-4] and supporting the decision-maker on a regular basis.

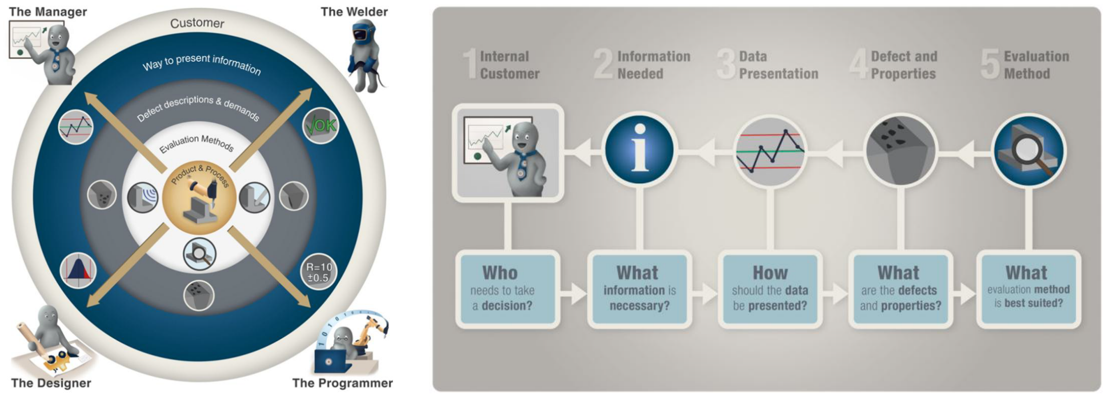
To be able to met an increasing demand of tailored process and product information a higher order of flexibility and NDE Engineering is needed [18]. This implies not only capable NDE methods and procedure but also effective information design methodologies, such as robust engineering, Six Sigma or similar applied on the inter-disciplinary information flow. However since the nature of NDE is as it is with complex physics, advanced mathematics, human influence and expensive testing all possible aids for application dependent parameter studies are welcome. Simulation in combination robust engineering to create meta-models is one way to take a step from the NDE procedures towards the multi-disciplinary web of decision-makers.

Previously some investigations with Meta modelling and simulations on ultrasonic testing contributed to an increased understanding of specific characteristics of the testing system behaviour. In [5] it was discovered that there are a strong correlation between crack tilt distribution used for generation of the synthetic probability-of-detection curves (meta-POD) and how it corresponds to experimentally determined PODs for ultrasonic procedures of detection of mechanical fatigue cracks and detection of stress corrosion cracks, respectively. It was found that the stress-corrosion crack POD is linked to a uniform distribution of crack tilt whereas the mechanical-fatigue crack POD is linked to a normal distribution of crack tilt. This was determined, without detailed physical modelling of parameters at the systems level. In [6] it was discovered that one important component of the POD slope is related to the change of shape of the signal response distribution – influencing detection of probability in other dimensions than crack size. It indicates that the basic assumption in POD modelling of a normally distributed output responses with a standard deviation independent of crack size is not valid for all testing scenarios. In [7] the drop in experimental POD for large cracks was explored using simulations and Meta modelling. And it was illustrated that when large crack destructive interference with ultrasonic wavelength there is an increased risk to miss large cracks. It also illustrated that parameterized POD-models do not capture all NDE application characteristics correctly.

All these studies are examples of the dilemma with applicability studies of NDE; how to prioritize among the huge sets of parameters that are generally influencing each NDE method. The prioritization has to select the relevant parameters from the general list made by experts in handbooks [9] and specific applications [20] on one side; complex technical systems with occasionally non-smooth response surfaces on the second side; and multi-disciplinary web of decision–makers on the third side. It is today not possible to model all parameters involved and the linking between the sides may already occur in some rare cases but are generally very difficult since it is an inter-disciplinary task on organisational semi-level. In the work with [5-7] it has been revealed that there is a need to more generally focus the methodology to choose relevant parameters before experimentation and modelling, that is, the screening procedure. How should it be determined in the application at hand and information needed what parameters to include or not when the responses may or may not be smooth and continuous?

2 Objective

Parameter studies from experimentation generally follow the sequential steps: screening, modelling and optimization. It is standard operation procedure for process development and there are several textbooks on the topic, for example [10]. The aim with the three phases from a NDE perspective, respectively are: first sort out parameters of less influence for the application studied and to fix them to their most practical and economical level (quantitative and qualitative screening); model and study the influence of the important remaining parameters (sensitivity analysis for reproducibility and repeatability studies); and last to improve performance of the total system of products, processes and inspection. To promote that quality and inspection data is used for process and product development.



Pic. 1 (a) There are several users in an operation that utilizes quality data for a large range of decisions [1]. **(b)** The design of a lean information flow process starts with the decision maker and ends with the data collecting procedure, not the other way around [2].

The methodology is straightforward when it comes to smooth response surfaces, where the recommendation for deciding the experimental range for all factors during screening determination is ‘to be bold’ – meaning make them as wide as possible. The screening assumption behind is a first order model to simply sort out the relative impact between high and low factor settings.

For methods not following the Berens assumption for PODs; that large cracks yield large response, like surface breaking notches in ultrasonic testing (Pic. 2); the be-bold-screening methodology may lead to incorrect prioritization of influential parameters – before modelling beguines. The aim with this paper is to illustrate the limitation of the screening assumption above and to raise awareness of the need of development of general methodology, guidelines and recommendation for applicability studies at the interdisciplinary semi-level. The argument is supported with a meta-modelling experiment of the screening phase from sequential modelling. The purpose is to visualise the difference in screening result with a 2^2 full factorial experiment with the factors:

A. Ultrasonic testing application: Surface Breaking Notch (SBN) and Side Drilled Hole (SDH)
B. Width of control parameter experimental range: Wide and Narrow

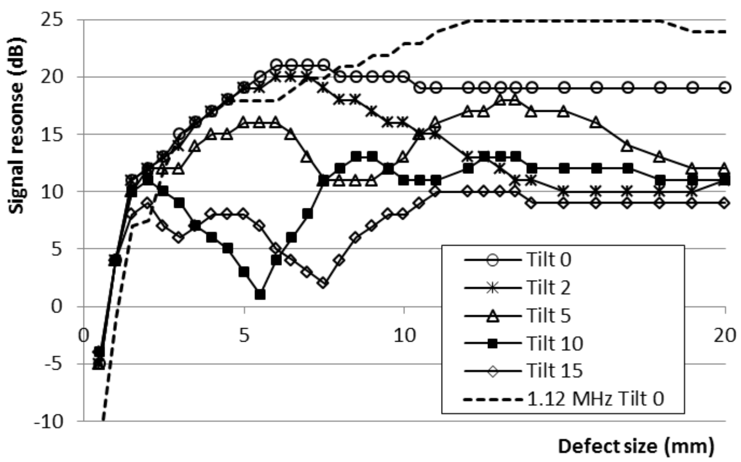
Even though the result is expected from a technical point of view, it points out the need of a screening methodology development supporting NDE engineering aiming to sort out which parameters to vary and which not when it comes to addressing the applicability issue: does the NDE data collected tell us what we actually want to know of the application (or does it only tell us something of the NDE method)?

3 Experimental set-up

3.1 NDE Simulation Engine (SimSUNDT)

The simulation engine used for the ultrasonic application modelling is simSUNDT. It is a Windows®-based pre and post-processor together with a mathematical kernel (UTDefect) dealing with the actual mathematical modelling. The UTDefect computer code was developed at the Dept. of Mechanics at Chalmers University of Technology and has been experimentally validated and verified for both SDH and SBN testing. simSUNDT was delivered to the Swedish nuclear power industry 2004. It is freeware made available for all parties involved in testing activities at Swedish nuclear plants.

The Windows-based software is made to resemble corresponding testing environment and commercial analysis tools available on the market. The output data is in a standard format. A noise model has been implemented in order to render realistic data with noise due to grain scatter. This, since one of the purposes of the software is to complement the use of test blocks. The software simulates the whole testing procedure with the contact probes (of arbitrary type, angle and size) acting in pulse-echo or tandem inspection situations [5, 6, 7, 11-16].



Pic. 2 Ultrasonic signal amplitude is not always increasing with crack size, which violates the Berens assumption [8] for POD modelling. This illustrated above with the normalized signal response vs. crack width(a) at different tilt angles (α) and central frequency 2.25/1.12 MHz

3.2 Simulated UT applications

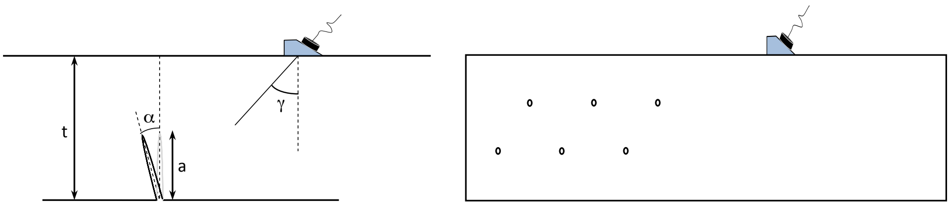
3.2.1 Response parameter

Signal amplitude [dB] has been used in case as the response variable in the simulations. The reason for using this response is that it normally is used in experimental SDH testing to estimate Side Drilled Hole diameter and it is as crack indicator and trigger in the SBN, even though the signal amplitude do not necessarily correspond to crack length (Pic. 2).

3.2.2 Screening Control Factors

The factors illustrating the problematization of screening used in this investigation are:

- Factor A: UT application - Surface Breaking Notch (SBN) and Side Drilled HOLE (SDH), Pic. 3.
- Factor B: Screening parameter range – Narrow and Wider range. Numbers of control parameters used for screening are 13 and 10 for SBN and SDH modelling, respectively. The 13 control factors for SBN modelling are varied at high or low levels according to Table 1 and the SBN Wider range is shown in Table 2. Table 3 and Table 4 show the corresponding control factor levels for the SDH modelling, respectively.



Pic. 3 The two modelled ultrasonic testing applications: SBN to the left and SDH to the right.

Table 1 SBN - Narrow range (except Back Wall Tilt)

Back Wall Tilt [°]	Band width [Mhz]	Centre frequency [MHz]	Couplant	Crack Tilt [°]	Crack Depth [mm]	Damping [%]	Defect depth [mm]	P Speed [km/s]	Probe Angle [°]	S Speed [km/s]	Crack Skew [°]	X Lenght [mm]
-3	0,5	2	0,05	-5	1	1	34	5,74	44	3,144	0	6,5
3	0,7	2,5	0,4	5	7	3	36	5,92	46	3,475	5	7

Table 2 SBN - Wider range (except Back Wall Tilt)

Back Wall Tilt [°]	Band width [Mhz]	Centre frequency [MHz]	Couplant	Crack Tilt [°]	Crack Depth [mm]	Damping [%]	Defect depth [mm]	P Speed [km/s]	Probe Angle [°]	S Speed [km/s]	Crack Skew [°]	X Lenght [mm]
-0,01	0,4	1,5	0,05	-15	2	0	34	5,404	42,5	2,979	0	5,525
0,01	0,8	3	0,4	15	20	4	36	6,604	47,5	3,641	20	7,475

3.2.3 The Screening Procedure

The screening and graphing was done with the in-built Custom Design Platform in JMP®10 software package from SAS [17] generating an experimental design for each UT application and range (four in total) with centre points in order to estimate main effects and two-factor interactions. The design consisted of 117 runs for the SBN and 76 run for the SDH application. The first ten runs of the SDH Narrow range case is shown in Table 5, as an example of the simulation (experimental) designs.

Table 3 SDH - Narrow range

Band Width [mm]	Central frequency [MHz]	Couplant	Damping [%]	Defect Depth	P Speed [km/h]	Probe Angle [°]	SDH Diameter [mm]	S speed [km/h]	Probe Diameter [mm]
0,5	2	0,05	1	34	5,74	44	1	3,144	6,5
0,7	2,5	0,4	3	36	5,92	46	4	3,475	7

Table 4 SDH - Wider range

Band width [mm]	Central frequency [MHz]	Couplant	Damping [%]	Defect Depth [mm]	P Speed [km/h]	Probe Angle [°]	SDH diameter [mm]	S Speed [km/h]	Probe Diameter [mm]
0,5	1,5	0,05	0	34	5,404	42,5	0,5	2,979	5,525
0,8	3	0,4	4	36	6,604	47,5	8	3,641	7,475

Table 5 First ten runs of the SDH narrow screening case.

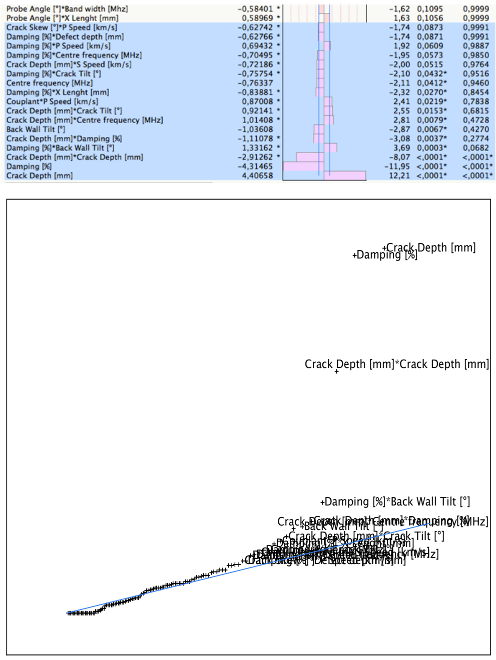
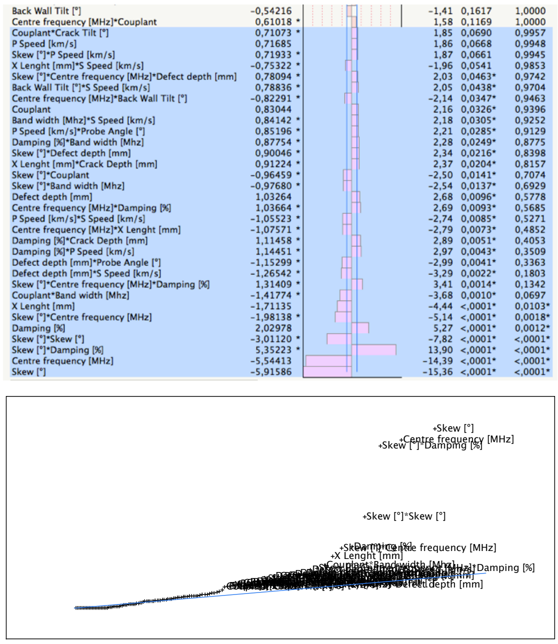
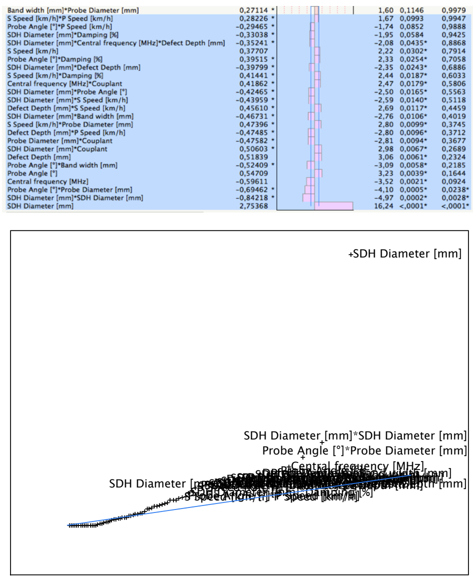
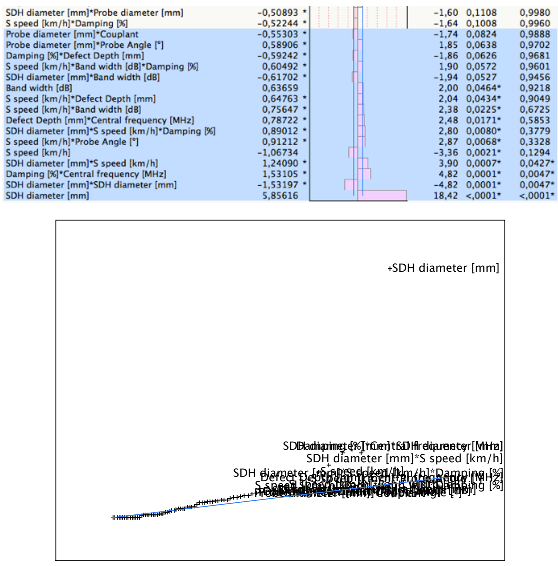
	Band width [mm]	Central frequency [MHz]	Couplant	Damping [%]	Defect Depth	P Speed [km/h]	Probe Angle [°]	SDH Diameter	S Speed [km/h]	Probe Diameter	SDH amplitude [dB]
1	0,5	2,5	0,05	1	36	5,74	44	1	3,144	6,5	-7
2	0,7	2	0,4	1	34	5,92	44	1	3,144	6,5	-4
3	0,7	2,5	0,05	3	34	5,92	44	1	3,144	6,5	-10
4	0,5	2	0,4	3	36	5,92	44	1	3,144	6,5	-10
5	0,5	2	0,05	1	34	5,74	46	1	3,144	6,5	-3
6	0,7	2,5	0,4	3	34	5,74	46	1	3,144	6,5	0
7	0,7	2	0,4	1	36	5,74	46	1	3,144	6,5	-3
8	0,5	2	0,05	3	34	5,92	46	1	3,144	6,5	0
9	0,7	2	0,4	3	34	5,74	44	4	3,144	6,5	2
10	0,5	2,5	0,4	3	34	5,92	44	4	3,144	6,5	0

4 Results

In Table 6, the results of the screening are shown. It is the list of significant parameters sorted in falling individual p-value, with the most significant control parameter at the bottom right above the half-normal effect plot for each of the fours testing cases.
The Wider case of SBN (Table 6: row 1, column 2) is insensitive to the crack depth and the screening has resulted in a totally different prioritisation of factors than the Narrow screening (Table 6: row 1, column 2) would. Table 7visualises the Signal Amplitude [dB] as a function of the dominating parameters. In the screening of the SBN Wider range case (Table 7: row 1, column 2) the upper and lower graph show the same Signal Amplitude

[dB] response as a function of Skew [°] and Damping [%], which is more or less independent of crack depth [mm].

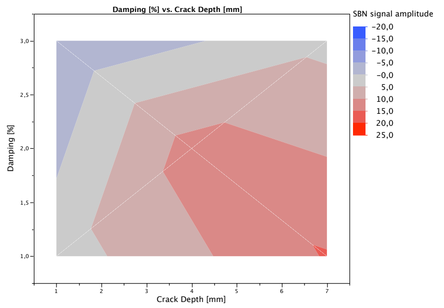
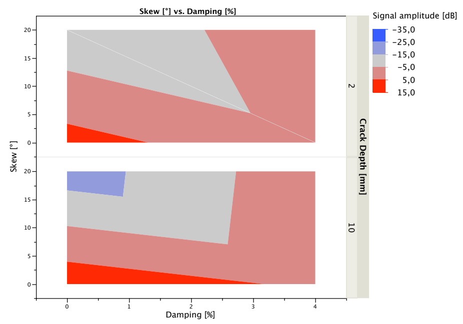
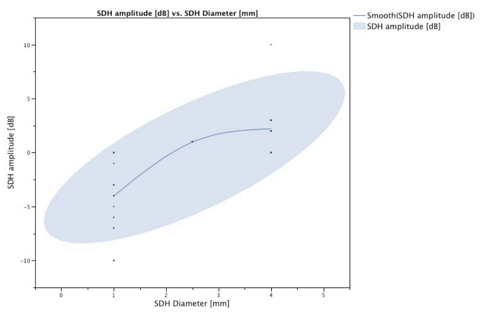
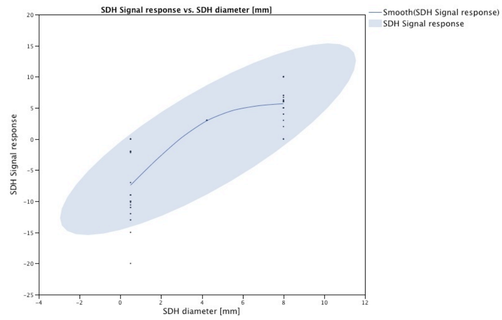
Table 6 The screening results show a list of dominating effects. In the SBN case the width of the factor ranges influence prioritisation of important factors. In the SDH case the ranges are of less importance and the effect prioritisation do not change.

	Narrow	Wider
SBN	 Crack Depth and Damping are dominating factors	 Skew, Central frequency and Damping dominates *but not* Crack Depth
SDH	 SDH (defect) diameter dominates	 SDH (defect) diameter dominates

5 Discussion

There is no surprise that the Signal Amplitude [dB] seam to be independent of Crack Depth [mm] in the wider SBN screening case; Signal amplitude is not used for defect size characterisation in SBN testing, it is only the trigger for other more analysis methods. Since Skew [°] is dominating it is crucial that the testing is done in the right angle to the crack. The manual operators rotate the probe intuitively, which of course, introduce a variation source in the procedure that may be positive since the skew angle is adjusted dynamically, even though the Human Factor may kill this advantage anyway in the holistic perspective [19]. In automatic testing this need to be address specially otherwise the procedure may miss large cracks with a somewhat other skew angle than the expected.

Table 7 Visualisation of most influential parameters on signal amplitude [dB] for each case

	Narrow	Wider
SBN	 Crack Depth and Damping are dominating factors	 Skew, Central frequency and Damping dominates *but not* Crack Depth
SDH	 Defect diameter dominates	 Defect diameter dominates

However, when the screening range is narrower (Table 6 & Table 7, row 1, column 1) the Signal Amplitude [dB] reacts to defect size, which illustrates the screening issue. The technical explanation is of course that the screening assumption: first order model followed by estimations of signal amplitude at the rim of the range do not capture curvature and discontinuities within the range. And there is always a risk that the be-bold recommendation leads to measures of signal amplitude from two different sub-systems. The question is how to bracket the right application relevant sub-space to model?

According to Cox et al [10] there is no firm procedure or methodology how to do screening. The problem is that it needs to be done in the wider perspective for applicability studies, that is, both qualitatively and quantitatively analyses in semi-close co-operation testing, product and process experts and historical data. To close with any of them however, will cause the risk of sub-optimisation and subsequent extrapolation issues to rises quickly. Methods and procedures become locally evaluated with weak connection to the application to be monitored, and since POD=f(defect size, known system parameters, unknown application parameters, interaction and noise) the screening needs to be done from the holistic wider perspective and not expanded from the core to be effective and efficient. Question is How to support NDE Engineering?

6 Conclusion

It has been shown that the range itself of the same set of parameters influence screening result in one of two seemingly similar testing application, but not in the other, leading to an increased risk of incorrect prioritisation of parameters to bring to modelling and deeper studies of NDE reliability.

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