Subjective Scaling Elimination Test for Index-based Inherent Safety Assessment Methods

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Abstract

The index-based inherent safety assessment method is preferable in comparing alternative chemical process routes due to its ability to be used in the early process design stage with limited details availability of the route assessed. However, the current index-based inherent safety assessment methods available have the shortcoming of subjective scaling. The Numerical Descriptive Inherent Safety Technique (NuDIST) is an inherent safety assessment method for the research and development design stage that overcomes the shortcoming of subjective scaling by incorporating logistic functions in its scoring assignment. The aim of this paper is to verify the NuDIST method in comparison with the Prototype Index for Inherent Safety (PIIS) and Inherent Safety Index (ISI) in terms of subjective scaling elimination. The inter-boundary case subjective scaling is considered solved if the scores difference between sub-edge boundaries is small while the intra-boundary case subjective scaling is considered solved if every value in a range has different scores. The results of the subjective scaling elimination test agree that NuDIST eliminates the shortcomings of subjective scaling with positive results for both inter-boundary and intra-boundary.

Keywords: Index-based; Inherent Safety Assessment Method; NuDIST; Subjective Scaling Elimination Test; Inter-boundary Subjective Scaling; Intra-boundary Subjective Scaling.

1.0 INTRODUCTION

Hazards avoidance during the design phase or also known as the concept of inherent safety is important to develop inherently safer processes without impacting efficiency, safety, or productivity of the plant during the occurrence of operational errors [1]. Before any modification can be made to avoid the hazard posed by the process, it is important to identify and assess the presence of potential hazards to identify the suitable mitigation or prevention techniques that need to be applied. There are various types of inherent assessment techniques, for example, the index-based, computer-aided, integration with statistical, and graphical approaches.

Srinivasan and Nhan [2] stated that index-based method is more preferred that the other inherent safety assessment techniques for alternative process routes comparison due to its ability to be used in the early process design stage with limited details of the route assessed are available. Besides, index-based method is also able to simplify numerous aspects associated to the process route into one quantitative factor for decision-making. Examples of index-based methods are Prototype Index for Inherent Safety (PIIS) [3], Inherent Safety Index (ISI) [4], and i-Safe method [5; 6]. There are also inherent safety assessment methods that adopt computer-based simulation modelling, for example, ASPEN PLUS and HYSYS softwares. This technique is developed for the safety assessment of the detailed process design stage which comprises energy and mass flowrate. One example of the inherent safety assessment method with computerized technique is iRET by Mohd Shariff et al. [7]. Statistical analysis provides differentiability between routes assessed and able to identify the most significant factor for risk management

[2]. The integration of assessment methods with statistical analysis enables the process to be assessed as a whole instead of focusing on individual parameters as in the index-based methods. An example of an inherent safety assessment method with statistical analysis integration is the Inherent Benign-ness Index (IBI) [2]. Compared to the index-based method, a graphical approach for the evaluation of inherent safety was introduced by Gupta and Edwards [8]. The graphical approach offers a simple inherent safety evaluation with easy result interpretation. This method has the advantage of huge numbers of parameters that can be considered, for instance, regulatory, economic, health aspects, or pollution control [8].

Implementation of index-based method can be done during the early stage of process design, where limited amount if information is available, making it preferable in comparing alternative process routes [2]. Index-based methods reduced the associated factors evaluated to one quantitative factor which results in the suitability of these methods to be used in decision making [2]. The index-based method is also attractive for industrial usage due to its simplicity [8]. However, there are various shortcomings of index-based method as stated by Srinivasan and Nhan [2] and subjective scaling is one of them. According to Shariff *et al.*, [9], subjective scaling is the most prominent deficiency of the indexing technique.

There are two cases of subjective scaling. The first case is score assignments according to subjective ranges in which one of them is scaling by allocating chemical or physical properties into subjective ranges with every range is given scores based on the authors' judgment, for instance, dividing the range of the value into ten equal sub-ranges as demmonstrated in Lawrence [3]. Nevertheless, this indicates that all physical or chemical values in that specific sub-ranges have similar hazard level, for example, in PIIS score for temperature parameter where 100°C and 190°C possess the same level of hazard which is the score of 2 when in actual truth that is not the case.

Gupta and Edwards [8] highlighted another case of subjective scaling which is discontinuity at the sub-range boundary. For example, in the PIIS method, 199°C is assigned with a score of 2 whereas 200°C is assigned with a score of 3. As the score is given to every sub-range instead of every value, the process assigned with higher score is indicated as having higher hazard than a process with lower score when actually both processes may have similar hazard level. In order to make it easier for further reference, the first case of subjective scaling will be indicated as the intra-boundary while the second case of subjective scaling is indicated as the inter-boundary.

The Numerical Descriptive Inherent Safety Technique (NuDIST) [10] is an inherent safety assessment method for the research and development (R&D) stage of process design. This technique overcomes the limitation of subjective scaling in inherent safety assessment methods by incorporating logistic functions in its scoring assignment. The aim of this paper is to verify the elimination of subjective scaling in NuDIST through the subjective scaling elimination test conducted. The subjective scaling elimination test conducted for the NuDIST method was done in comparison with the Prototype Index for Inherent Safety (PIIS) [3] and Inherent Safety Index (ISI) [4] for verification. These two techniques were selected for comparison due to their similarity, in terms of types of inherent safety parameters assessed and application for the R&D design stage, to the NuDIST method. Besides, these two methods possess both inter-boundary and intra-boundary cases of subjective scaling which make them suitable for comparison with the NuDIST method.

2.0 METHODOLOGY

2.1 Brief Introduction to the NuDIST Technique

The Numerical Descriptive Inherent Safety Technique (NuDIST) assessed alternative process routes in the research and development (R&D) stage according to total scores and ranking through the application of logistic equation. In this work, logistic function produces the scores for the inherent safety assessment which eliminate the problem of subjective scaling encountered in various existing methods for similar purpose. Another advantage of logistic function is its flexibility. This technique allows users to tailor the every parameter equation to their own preferences by manipulating the logistic equation. Currently in this research, the scores produced by the logistic equations are based on chemical and physical properties data. However, user may use other sources of data for example statistical accidents data or the company's own standard data. The general logistic equation is shown in Equation (1) [11]. This equation can be used to construct a logistic curve.

$$y = \frac{C}{1 + Ae^{-Bx}} \tag{1}$$

There are three main constant parameters in the logistic equation, which are C, B and A as shown in Equation (1). C indicates the upper limit of the curve. The upper limit will give a restriction on the output value of y; this means that the y value will only be equal to or less than the C value. This characteristic is suitable for score establishment. For example, if the C value is set as 100, the maximum value for output y cannot exceed 100. In NuDIST, the output value of y is referred to as the NuDIST score while 100 is set as the C value. B affects the slope of the logistic curve represented by Equation (2) through the m value, which represents the slope inclination for the curve to be made, while A affects the mid-point of the logistic curve represented by Equation (3) through the k value, which is the x-axis value at y=C/2.

$$m = \frac{BC}{4} \tag{2}$$

$$A = e^{Bk} \text{, k is the x-point at y =C/2} \tag{3}$$

The x-axis values in NuDIST are known as the input values or values to be evaluated in every parameter. In NuDIST, the k-value refers to the mid-score of the assessment, which is 50 as the NuDIST score is set to be 100 as the highest.

The parameters evaluated in the NuDIST technique are divided into process safety and chemical safety. There are four parameters taken into consideration for chemical safety assessment (flammability, explosiveness, toxicity and reactivity) and four parameters for process safety (temperature, pressure, heat of reaction and process inventory). Table 1 shows the logistic function produced for inherent safety parameters included in NuDIST.

Table 1 Logistic Functions for Inherent Safety Assessment Scoring in NuDIST

Parameter		Parameter Value	Logistic Equation	Equation No.
Chemical Safety	Flammability	Flash Point	$S_{FL} = 100 \times (1 - \left(\frac{1}{1 + 3.03e^{-0.02 x_{FL}}}\right))$	(4)
	Explosiveness	Explosiveness Limits	$S_{EXP} = 100 \times \left(\frac{1}{1 + 1096.63e^{-0.14 x_{EXP}}}\right)$	(5)
	Toxicity	Threshold Limit Values (TLV-STEL)	$S_{TOX} = 100 \times (1 - \left(\frac{1}{1 + 403.4288e^{-0.012 x_{TOX}}}\right))$	(6)
	Reactivity	NFPA Reactivity Rating	$S_R = 100 \times \left(\frac{1}{1 + 270.43e^{-2.8 x_R}}\right)$	(7)
Process Safety	Operating Temperature	• > 25°C • < 25°	$S_{T>25°C} = 100 \times \left(\frac{1}{1 + 403.43e^{-0.012 x_{T>25°C}}}\right)$ $S_{T<25°C} = 100 \times (1 - \left(\frac{1}{1 + 0.0025e^{-0.012 x_{T<25°C}}}\right))$	(8) (9)
	Operating Pressure		$S_P = 100 \times \left(\frac{1}{1 + 148.41e^{-0.2 x_P}}\right)$	(10)
	Heat of Reaction	• > 0 kJ/mol • < 0 kJ/mol	$S_{HR>0kJ/mol}$ $= 100 \times \left(\frac{1}{1 + 601.85e^{-0.016 x_{HR>0kJ/mol}}}\right)$ $S_{HR<0kJ/mol}$ $= 100 \times ((\frac{1}{1 + 403.43e^{0.006 x_{HR<0kJ/mol}}}))$	(11) (12)
	Process Inventory	Percentage Yield	$S_{PI} = 100 \times (1 - \left(\frac{1}{1 + 1339.43e^{-0.12 x_{PI}}}\right))$	(13)

Further explanation on this technique can be found in Ahmad *et al.*, [10] and its extension in Ahmad *et al.* [12].

2.2 Verification of the NuDIST Technique

The subjective scaling elimination test was done by comparing the NuDIST method to two methods which are the Prototype Index for Inherent Safety (PIIS) and the Inherent Safety Index (ISI). Values taken in performing this test was according to the score tables in both PIIS and ISI methods as shown in Table 2. Aside from values, the test can only be done on parameters that exist in both methods which are process inventory, operating pressure and temperature, toxicity, flammability, and explosiveness for PIIS method while for ISI method the parameters taken for subjective scaling elimination test are heat of reaction, operating temperature and pressure, explosiveness, toxicity, and flammability.

Table 2 Values Utilized by Both Methods in Subjective Scaling Elimination Test

Parameters Considered	Values Taken from PIIS Method		Values Taken from ISI Method	
	Range	Score	Range	Score
Flammability (°C)	Non-Flammable	0	Non-Flammable	0
	>60	1	>55	1
	38-59	2	≤55	2

	<37.7	3	<21	3
			<0	4
Explosiveness (%UEL-%LEL)	0-9	1	Non-Explosive	0
	10-19	2		
	20-29	3	0-19	1
	30-39	4		
	40-49	5	20-44	2
	50-59	6		
	60-69	7	45-69	3
	70-79	8		
	80-89	9	70-100	4
	90-99	10		
Toxicity (ppm)	<0.001	8	>10000	0
	0.001-0.009	7	≤10000	1
	0.01-0.09	6	≤1000	2
	0.1-0.9	5	≤100	3
	1-9	4	≤10	4
	10-99	3	≤1	5
	100-999	2	≤0.1	6
	1000-9999	1		
Temperature (°C)	< (-25)	10	<0	1
	(-25) – (-11)	3		
	(-10) – 9	1	0-70	0
	10-29	0		
	30-99	1	70-150	1
	100-199	2		
	200-299	3	150-300	2
	300-399	4		
	400-499	5	300-600	3
	500-599	6		
	600-699	7	>600	4
	700-799	8		
	800-899	9		
	900	10		
Pressure	0-90 (psi)	1	0-0.5 (atm)	1
	91-140 (psi)	2		
	141-250 (psi)	3	0.5-5 (atm)	0
	251-420 (psi)	4		
	421-700 (psi)	5	5-25 (atm)	1
	701-1400 (psi)	6		
	1401-3400 (psi)	7	25-50 (atm)	2
	3401-4800 (psi)	8		
	4801-6000 (psi)	9	50-200 (atm)	3
	6001-8000 (psi)	10	200-1000 (atm)	4
Process Inventory (%Yield)	100	0	-	-
	90-99	1		
	80-89	2	-	-

	70-79	3		
	60-69	4	-	-
	50-59	5		
	40-49	6	-	-
	30-39	7		
	20-29	8		
	10-19	9	-	-
	0-9	10		
Heat of Reaction (J/mol)	-	-	≤200	0
	-	-	<600	1
	-	-	<1200	2
	-	-	<3000	3
	-	-	≥3000	4

In the intra-boundary case, the scores were divided into ten equal sub-ranges with implications that every physical or chemical values in that specific sub-ranges to have the same hazard level for example in PIIS score for temperature parameter where 100°C and 190°C possess the same level of hazard which is the score of 2 when actually that is not true. Therefore, it is assumed that the subjective scaling elimination is proven if the scores differ for every value in the boundary. Meanwhile, in the inter-boundary case of subjective scaling, the scores are allotted to every sub-range instead of every value making the process with a score of one value higher than the score of another process to be assumed to have higher hazard. However, both processes might have similar hazard level in reality. These cases of subjective scaling is considered eliminated if the scores differences between values at sub-range boundaries are small.

There are five steps taken in conducting the subjective scaling elimination test. For the purpose of this discussion, operating temperature parameter is taken as an example.

1. The temperature ranges selected were assigned with their associated score values for temperature parameter taken from the PIIS method and are tabulated here in Table 3. In Table 3, the range limit column refers to the score range boundaries of the range chosen for verification. The PIIS Score is given according to the score stated in Table 2 for every range limit value. The values in a range, for example -25 and -11 in the 1st Range and -10 and 9 in the 2nd Range, are used for the first case of subjective scaling which is the intra-boundary cases. Meanwhile for the second case of subjective scaling, values between two different ranges are taken, for example -11 which is the upper limit of the 1st range and -10 which is the lower limit of the 2nd range.

Table 3 Score Ranges and Its Values

Ranges	Range Limit	Value	PIIS Score
1st Range	Lower	-25	3
	Upper	-11	3
2nd Range	Lower	-10	1
	Upper	9	1
3rd Range	Lower	10	0
	Upper	29	0
4th Range	Lower	30	1
	Upper	99	1

2. The maximum score in the PIIS method is 10 while the maximum score in the NuDIST method is 100. Currently, both scoring methods have a different scoring base. Some alterations were made on the NuDIST method in order for both methods to have the same maximum scores for them to be fairly compared. In order to change the maximum score of the NuDIST method, instead of multiplying the equation with 100 as shown in Equation (8) and (9), the equations were multiplied by 10 as shown in Equation (14) and (15). This will results in the NuDIST scores to have the same maximum score as the PIIS, which is 10. Table 4 shows the new NuDIST scores after alteration.

$$S_{T>25°C} = 10 \times \left(\frac{1}{1 + 403.43e^{-0.012 x_{T>25°C}}}\right) \tag{14}$$

$$S_{T<25°C} = 10 \times \left(1 - \left(\frac{1}{1 + 0.0025e^{-0.012 x_{T<25°C}}}\right)\right) \tag{15}$$

Table 4 Alteration of NuDIST Score

Ranges	Range Limit	Value	PIIS Score	NuDIST Original Score	New NuDIST Score After Alteration
1st Range	Lower	-25	3	0.33	0.033
	Upper	-11	3	0.28	0.028
2nd Range	Lower	-10	1	0.28	0.028
	Upper	9	1	0.22	0.022
3rd Range	Lower	10	0	0.22	0.022
	Upper	29	0	0.25	0.025
4th Range	Lower	30	1	0.25	0.025
	Upper	99	1	0.81	0.081

3. Currently, both methods are comparable in terms of their maximum score value. Table 5 shows the identified intra-boundary and inter-boundary values and their designated scores. A curve each for both cases of inter-boundary and intra-boundary values versus their designated scores is constructed.

Table 5 Identified Values for Intra-boundary and Inter-boundary Cases of Subjective Scaling for Temperature Parameter

Intra-boundary Case of Subjective Scaling				Inter-boundary Case of Subjective Scaling			
Range	Values	PIIS Scores	New NuDIST Score	Range	Values	PIIS Scores	New NuDIST Score
1st Range	-25	3	0.033	Upper Limit of 1st Range and Lower Limit of 2nd Range	-11	3	0.028
	-11	3	0.028		-10	1	0.028
2nd Range	-10	1	0.028	Upper Limit of 2nd Range and Lower Limit of 3rd Range	9	1	0.022
	9	1	0.022		10	0	0.022
3rd Range	10	0	0.022	Upper Limit of 3rd Range and Lower Limit of 4th Range	29	0	0.025
	29	0	0.025		30	1	0.025
4th Range	30	1	0.025				
	99	1	0.081				

4. In this step identification of any differences for the inter-boundary case and any score similarities for the intra-boundary case is conducted. The identified score differences for the inter-boundary case and the score similarities in the intra-boundary case are discussed in the next section.

5. The steps were then repeated for the ISI method.

3.0 RESULTS AND DISCUSSION

3.1 NuDIST Validation through Comparison with PIIS Method

The base values for this test were taken from score ranges in PIIS for comparison purposes. Only parameters that are incorporated in both PIIS and NuDIST are compared which are process inventory, operating temperature and pressure, explosiveness, explosiveness, and flammability. In this work, it is assumed that the inter-boundary case is solved if the scores differences between values at sub-range boundaries are small while the intra-boundary case can be solved if the scores differ for every value in the boundary.

3.1.1 Intra-Boundary Case of Subjective Scaling

In order to inspect the score differences clearly for inter-boundary cases, the slope value between the sub-edge values is identified as shown in Table 6. The slope is using Equation (16) where (x_1, y_1) and (x_2, y_2) refers to coordinate of the first and second point, respectively, in the line found in the curves constructed. Steeper slope refers to small differences between values at the sub-edge boundary. In summary, Table 6 shows that the NuDIST method has lower score differences for all parameters evaluated compared to the PIIS method with NuDIST method slope values is as low as 0.

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

(16)

Table 6 Differences in Scores between NuDIST and PIIS for Inter-Boundary Cases

Parameters Considered	Sub-edge Value	PIIS Method		NuDIST Method	
		Score	Slope	Score	Slope
Flammability (°C)	60	1	-1	1.42	-0.02
	59	2		1.43	
	38	2	-3	1.81	-0.02
	37.7	3		1.81	
Explosiveness (%UEL-%LEL)	9	1	1	0.03	0.005
	10	2		0.04	
	19	2	1	0.13	0.019
	20	3		0.15	
	29	3	1	0.50	0.071
	30	4		0.57	
	39	4	1	1.77	0.213
	40	5		1.98	
	49	5	1	4.65	0.349
	50	6		5.00	
	59	6	1	7.79	0.232
	60	7		8.02	
	69	7	1	9.35	0.081
	70	8		9.43	
	79	8	1	9.83	0.022
	80	9		9.85	
	89	9	1	9.96	0.006
	90	10		9.96	
Toxicity (ppm)	0.0009	8	-10000	7.98	0
	0.001	7		7.98	
	0.009	7	-1000	7.98	0
	0.01	6		7.98	
	0.09	6	-100	7.98	0
	0.1	5		7.98	
	0.9	5	-10	7.98	0
	1	4		7.98	
	9	4	-1	7.98	0
	10	3		7.98	
	99	3	-1	7.94	-0.001
	100	2		7.93	
	999	2	-1	0.02	0
	1000	1		0.02	
Temperature (°C)	-26	10	-7	0.034	0
	-25	3		0.033	
	-11	3	-2	0.028	0
	-10	1		0.028	
	9	1	-1	0.022	0
	10	0		0.022	
	29	0	1	0.025	0
	30	1		0.025	
	99	1	1	0.081	0
	100	2		0.082	
	199	2	1	0.263	0
	200	3		0.266	
	299	3	1	0.823	0.01
	300	4		0.832	
	399	4	1	2.293	0.02
	400	5		2.315	
	499	5	1	4.970	0.03
	500	6		5.000	
	599	6	1	7.664	0.02
	600	7		7.685	
	699	7	1	9.159	0.01
	700	8		9.168	
	799	8	1	9.731	0
	800	9		9.734	
	899	9	1	9.917	0
	900	10		9.918	
Pressure (psi)	90	1	1	0.22	0
	91	2		0.23	
	140	2	1	0.43	0.01
	141	3		0.44	
	250	3	1	1.68	0.02

	251	4		1.70	
	420	4	1	6.72	0.03
	421	5		6.75	
	700	5	1	9.89	0
	701	6		9.89	
	1400	6	1	10	0
	1401	7		10	
	3400	7	1	10	0
	3401	8		10	
	4800	8	1	10	0
	4801	9		10	
	6000	9	1	10	0
	6001	10		10	
Process Inventory (%Yield)	100	0	-1	0.08	-0.01
	99	1		0.09	
	90	1	-1	0.27	-0.03
	89	2		0.30	
	80	2	-1	0.83	-0.10
	79	3		0.93	
	70	3	-1	2.31	-0.22
	69	4		2.54	
	60	4	-1	5.00	-0.30
	59	5		5.30	
	50	5	-1	7.69	-0.21
	49	6		7.89	
	40	6	-1	9.17	-0.09
	39	7		9.26	
	30	7	-1	9.73	-0.03
	29	8		9.76	
	20	8	-1	9.92	-0.01
	19	9		9.93	
	10	9	-1	9.98	0
	9	10		9.98	

Figure 1 compares both NuDIST and PIIS methods in terms of the inter-boundary case of subjective scaling for all parameters. NuDIST scores has lower differences compared to the PIIS method for flammability parameter as shown in Figure 1(a). This shows that NuDIST have lower sub-edge boundary score differences compared to PIIS. This result agrees that NuDIST reduces the inter-boundary subjective scaling issue due to the small score differences at the sub-range boundaries. The differences can be seen in detail by looking at the slope values shown in Table 6 which are lower for the NuDIST methods compared to the PIIS. Other parameters in NuDIST also exhibit similar result in which these parameters have lower sub-edge boundary score differences compared to PIIS as shown in Figure 1(b) for explosiveness parameter, Figure 1(c) for toxicity parameter, Figure 2(a) for operating temperature parameter, Figure 2(b) for operating pressure parameter, and Figure 2(c) for process inventory parameter. Comparison between both methods shows that NuDIST is successful in reducing the issue of subjective scaling in its scoring assignment.
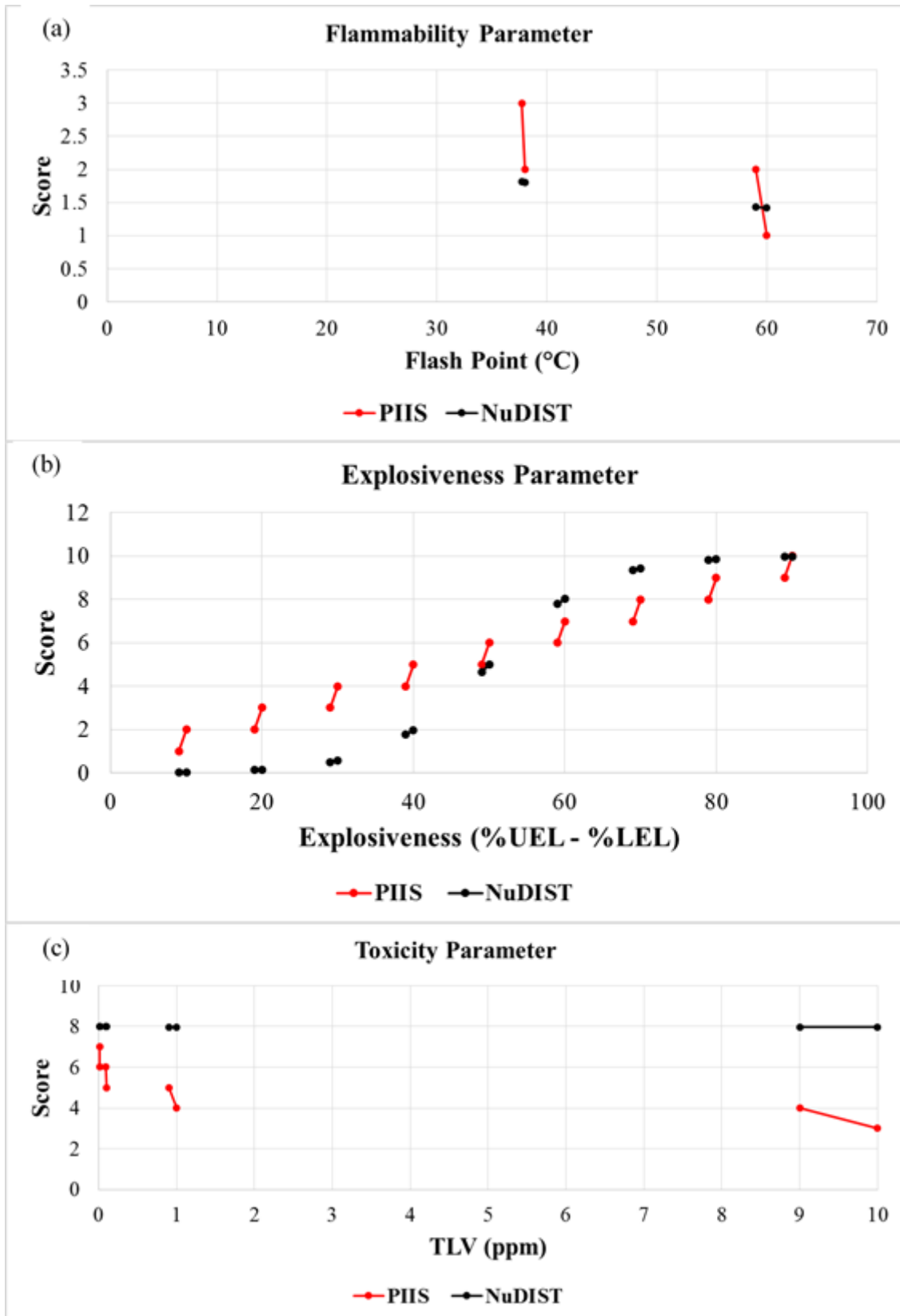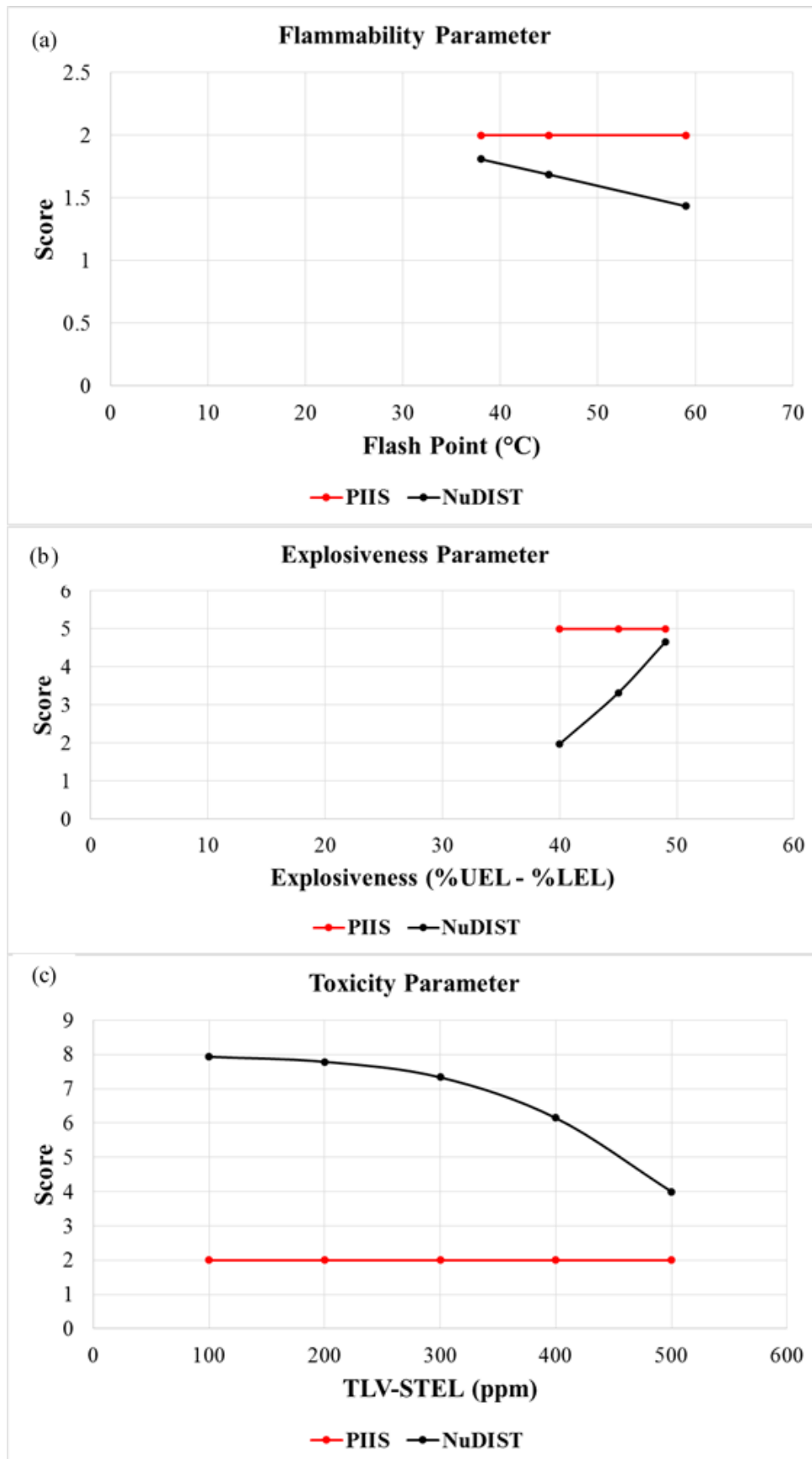
Figure 1 NuDIST and PIIS Comparison for Inter-Boundary Case for (a) Flammability; (b) Explosiveness; (c) Toxicity Parameters
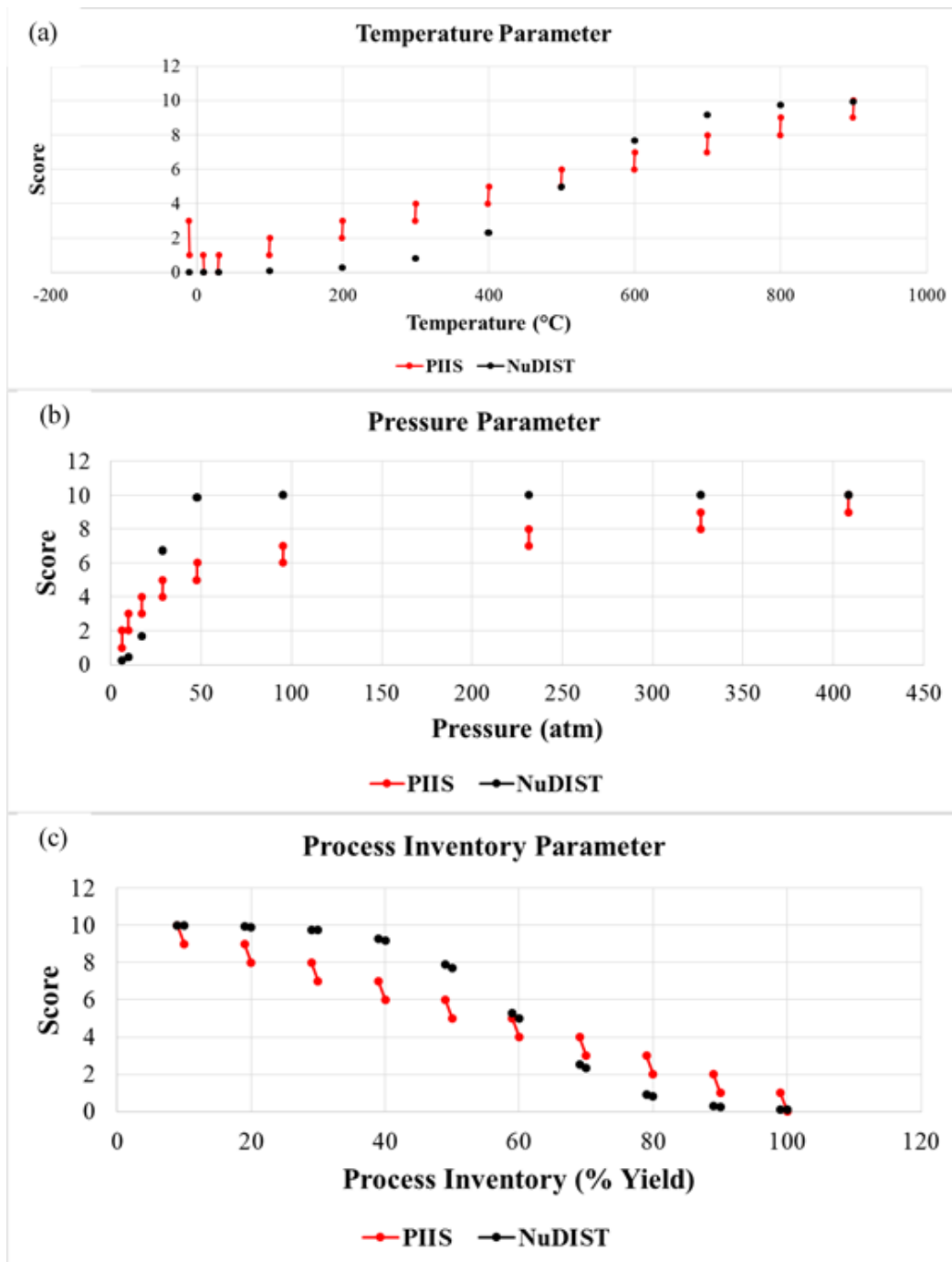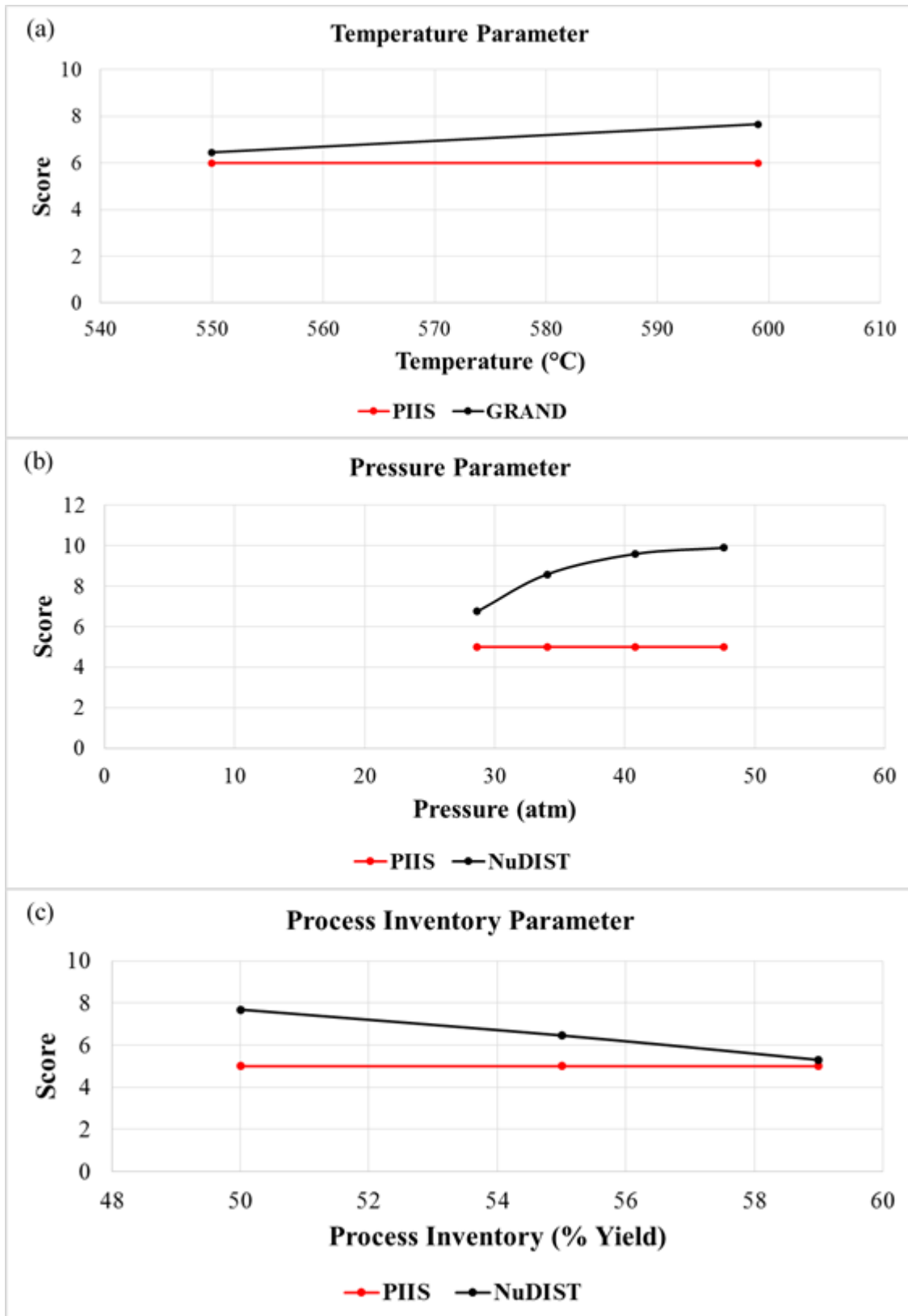
Figure 2 NuDIST and PIIS Comparison for Inter-Boundary Case for (a) Operating Temperature; (b) Operating Pressure; (c) Process Inventory Parameters

3.1.2 Intra-Boundary Case of Subjective Scaling

The intra-boundary case of subjective scaling is considered eliminated if the scores differ for every value in the boundary. Figure 3(a) compares the flammability parameter for NuDIST and PIIS methods for the intra-boundary case. Figure 3(a) shows that in the same range of flash point values of 30°C until 70°C, PIIS evaluation resulted in the same scores while NuDIST evaluation resulted in different scores for every flash point values. This indicates that while PIIS assigns the score of 2 to every value in the range, NuDIST assigns a different score to each flash point value in the range. This proves that the NuDIST method eliminates the intra-boundary case of subjective scaling in its score assignment compared to the PIIS method. Similar results can be observed in other parameters as shown in Figure 3(b) for explosiveness parameter, Figure 3(c) for toxicity parameter, Figure 4(a) for operating temperature parameter, Figure 4(b) for operating pressure parameter, and Figure 4(c) for process inventory parameter.

Figure 3 NuDIST and PIIS Comparison for Intra-Boundary Case for (a) Flammability Parameter; (b) Explosiveness Parameter; (c) Toxicity Parameter

Figure 4 NuDIST and PIIS Comparison for Intra-Boundary Case for (a) Operating Temperature Parameter; (b) Operating Pressure Parameter; (c) Process Inventory Parameter

3.2 NuDIST Validation through Comparison with ISI Method

Score ranges in ISI were taken for subjective scaling elimination verification and only parameters that are incorporated in both ISI and NuDIST will be compared which are operating temperature and pressure, heat of reaction, toxicity, explosiveness, and flammability. As mentioned previously, the inter-boundary case is solved if the scores differences between values at sub-range boundaries are as small as possible while the intra-boundary case can be solved if the scores differ for every value in the boundary. The score differences were inspected according to the slope value between the sub-edges values is identified as shown in Table 7 for the inter-boundary case. In summary, Table 7 shows that the NuDIST method has lower score differences for all parameters evaluated compared to the ISI as proven by its slope values which are as low as 0. This indicates that the NuDIST method eliminates the intra-boundary case of subjective scaling in its score assignment compared to the ISI method.

Table 7 Differences in Scores between NuDIST and ISI for Inter-Boundary Cases

Parameters Considered	Sub-edge Value	ISI Method		NuDIST Method	
		Score	Slope	Score	Slope
Flammability (°C)	56	1	-1	1.98	-0.02
	55	2		2.01	
	22	2	-1	2.76	-0.02
	21	3		2.78	
Explosiveness (%UEL-%LEL)	19	1	1	0.05	0.01
	20	2		0.06	
	44	2	1	1.21	0.12
	45	3		1.33	
	69	3	1	3.74	0.03
	70	4		3.77	
Toxicity (ppm)	1001	1	-1	0.01	0
	1000	2		0.01	
	101	2	-1	5.95	0
	100	3		5.95	
	11	3	-1	5.98	0
	10	4		5.98	
	2	4	-1	5.98	0
	1	5		5.98	
	0.2	5	-10	5.99	0
	0.1	6		5.99	
Temperature (°C)	70	0	1	0.02	0
	71	1		0.02	
	150	1	1	0.06	0
	151	2		0.06	
	300	2	1	0.33	0
	301	3		0.34	
	600	3	1	3.07	0.01
	601	4		3.08	
Pressure (atm)	0.5	1	-10	0.03	0.01
	0.6	0		0.03	
	5	0	1	0.07	0.02
	6	1		0.09	
	25	1	1	2	0.20
	26	2		2.20	
	50	2	1	3.97	0
	51	3		3.98	
	200	3	1	4	0
	201	4		4	
Heat of Reaction (J/g)	200	0	1	0.16	0
	201	1		0.16	
	599	1	1	3.84	0
	600	2		3.84	
	1199	2	1	4	0
	1200	3		4	
	2999	3	1	4	0
	3000	4		4	

Table 8 shows the score variances between the ISI and the NuDIST methods for the cases of intra-boundary subjective scaling. From Table 8 it can be seen that in the same range of parameter values, ISI evaluation resulted in the same scores while NuDIST evaluation resulted in different scores for every value in the range. This proves that the NuDIST method reduced the intra-boundary case of subjective scaling in its score assignment compared to the ISI method.

Table 8 Differences in Scores between NuDIST and ISI for Intra-Boundary Cases

Parameters Considered	Parameters Value	ISI Method	NuDIST Method
Flammability (°C)	55	2	2.01
	44	2	2.27
	33	2	2.52
	22	2	2.76
Explosiveness (%UEL-%LEL)	45	3	1.33
	50	3	2.00
	55	3	2.67
	60	3	3.21
	69	3	3.74
Toxicity (ppm)	600	2	1.39
	500	2	3.00
	400	2	4.61
	300	2	5.50
Temperature (°C)	301	3	0.34
	400	3	0.93
	500	3	2.00
	600	3	3.07
Pressure (atm)	26	2	2.20
	30	2	2.92
	35	2	3.52
	40	2	3.81
	45	2	3.93
Heat of Reaction (J/g)	201	1	0.16
	300	1	0.67
	400	1	2.00
	500	1	3.33
	599	1	3.84

4.0 CONCLUSION

In conclusion, the Numerical Descriptive Inherent Safety Technique (NuDIST) is proven to be successful in reducing both cases of subjective scaling which are inter-boundary and intra-boundary through subjective scaling elimination test conducted. The subjective scaling elimination test was done by comparing the NuDIST with two other methods which are the PIIS and the ISI methods. The inter-boundary case is considered solved if the score differences between sub-edge boundaries is small while the intra-boundary case is considered solved if every value in a range has different score. The results of the subjective scaling elimination test agree that NuDIST has eliminated the shortcomings of inter-boundary and intra-boundary subjective scaling cases compared to the PIIS and the ISI methods. However, this work only focus on general subjective scaling elimination verification. It is recommended for sensitivity analysis be conducted in the extended work related to this topic in the future.

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