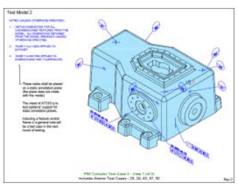
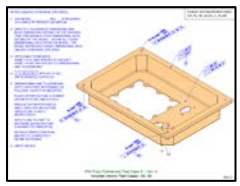
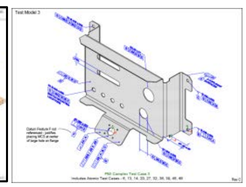
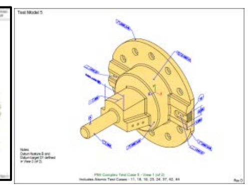
NIST Advanced Manufacturing Series 100-10

Guide to the NIST PMI CAD Models and CAD System PMI Modeling Capability Verification Testing Results



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National Institute of
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U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Kent Rochford, Acting NIST Director and Under Secretary of Commerce for Standards and Technology

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1 Introduction

This guide contains supplemental information for the NIST MBE PMI Validation and Conformance Testing Project [1]. It is assumed that the reader has some familiarity with the project including the test cases and test results. The project created a test system to measure conformance of Computer-Aided Design (CAD) software to American Society of Mechanical Engineers (ASME) standards for product and manufacturing information (PMI), specifically geometric dimensioning and tolerancing (GD&T) information [2, 3]. The test system has three main components: test cases, test CAD models, and verification and validation test results. The verification and validation results measure PMI implementation capabilities in CAD software and derivative STEP, JT, and 3D PDF files.

The project generated three reports:

- Measuring the PMI Modeling Capability in CAD Systems: Report 1 – Combined Test Case Verification [4]
- Measuring the PMI Modeling Capability in CAD Systems: Report 2 – Combined Test Case Validation [5]
- Measuring the PMI Modeling Capability in CAD Systems: Report 3 – Fully-Toleranced Test Case Verification [6]

The test case descriptions and test CAD models generated from those descriptions are available from the project website[1] along with the reports listed above.

This guide contains supplemental information relating to the test case descriptions and verification results that can be used to: (1) provide insights into the test cases, PMI annotations, and verification testing results, and (2) inform future testing projects in the development of test cases and testing procedures and criteria.

1.1 Disclaimers

The specific test of PMI capabilities in CAD systems documented in the reports are a snapshot in time. Specific test cases were developed using particular versions of the ASME Y14 tolerancing standards and PMI constructs. The test cases were modeled in particular versions of four CAD systems with a specific modeling methodology to give precedence to PMI representation (semantic PMI) over PMI presentation (graphical PMI). The CAD models were compared to each other with a particular version of CAD validation software to generate the verification results. The test cases are not intended to represent best practice in how to apply GD&T to a part. Simpler GD&T strategies could have been used. The test cases are intended to exercise valid presentations of GD&T defined in the ASME Y14 standards.

The verification and validation testing results related to the PMI in the test cases were generated based on the 2012 and 2015 versions of the CAD systems. Issues identified for the semantic and graphic representation of PMI in each CAD system may have been resolved since the original testing took place.

Any mention of commercial products is for information purposes only; it does not imply recommendation or endorsement by NIST.

[1] https://www.nist.gov/el/systems-integration-division-73400/mbe-pmi-validation-and-conformance-testing

2 Test Case Descriptions

Two types of test cases were developed for the testing project. Each test case contains PMI annotations for geometric tolerances, dimensional tolerances, datum targets, and datum features that are applied to discrete-part geometry models. A fully-toleranced test case (FTC) has all geometric features fully-toleranced, i.e. controlled and constrained, and accounts for all hierarchical interrelationships. The PMI annotations for a combined test case (CTC) are not complete specifications of PMI for the part and not intended to be fully-toleranced.

2.1 CAD Systems

For the verification testing, the CAD models for the CTC were generated in:

- Dassault Systemes CATIA V5 R21
- Dassault Systemes SolidWorks 2012
- PTC Creo 2
- Siemens NX 8

The FTC were modeled in:

- Dassault Systemes CATIA V5-6R2014
- Dassault Systemes SolidWorks 2015
- PTC Creo 3
- Siemens NX 9

CAD models for FTC 7, 10, and 11 were not generated for the project.

The verification testing results refer to the CAD systems as CAD A, B, C, and D. No assumption should be made as to which CAD system is A, B, C, or D.

2.2 Test Case Drawings

Figures 1-11 show one view of each of the five CTC and six FTC. Drawings of other views for each test case are provided in Appendix B of the verification reports [4, 6] except for FTC 7, 10, and 11. Those test cases were not included in the verification testing.

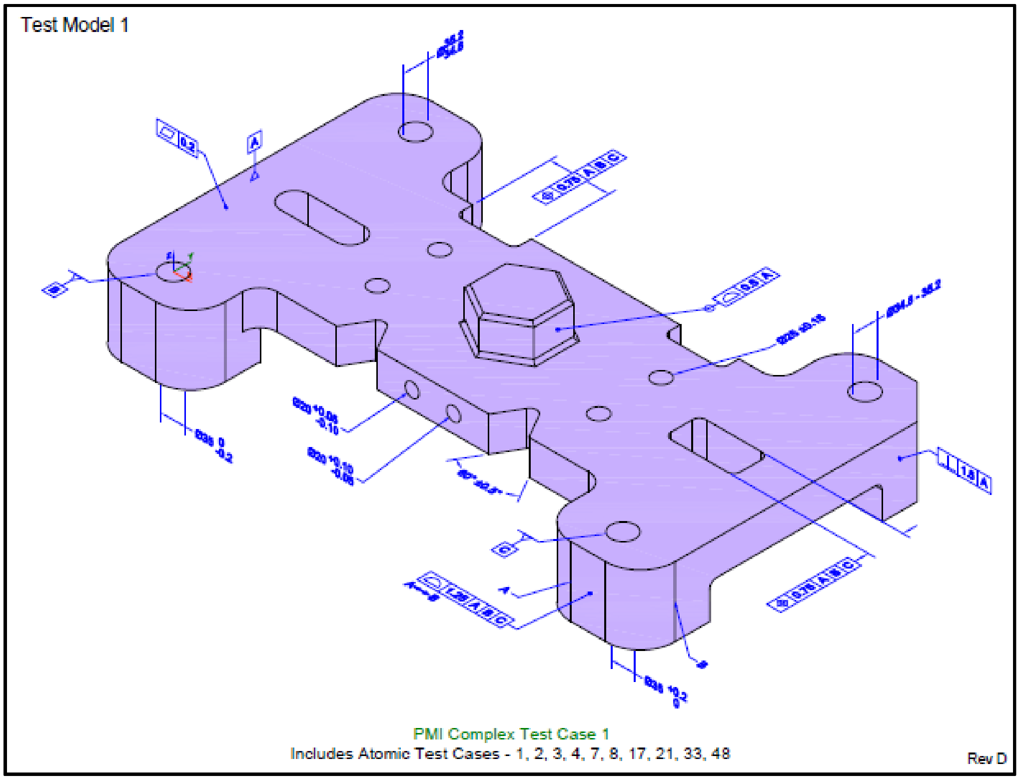

Figure 1: Combined test case 1 (CTC 1) drawing

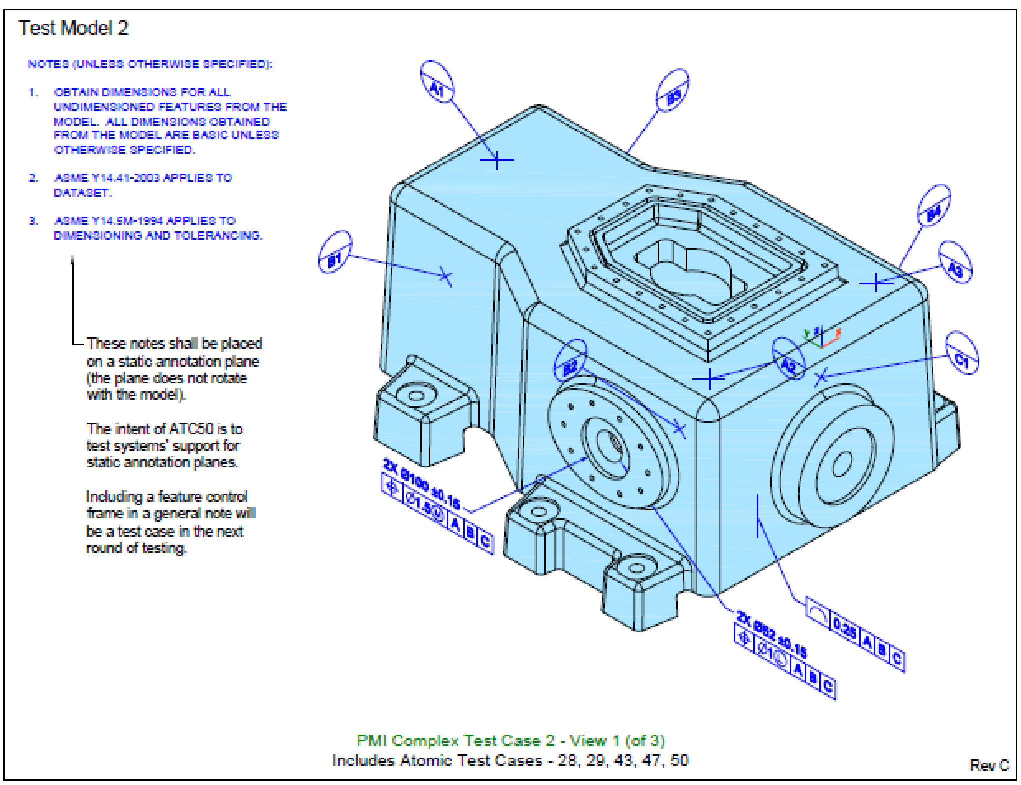

Figure 2: Combined test case 2 (CTC 2) drawing, view 1 of 3

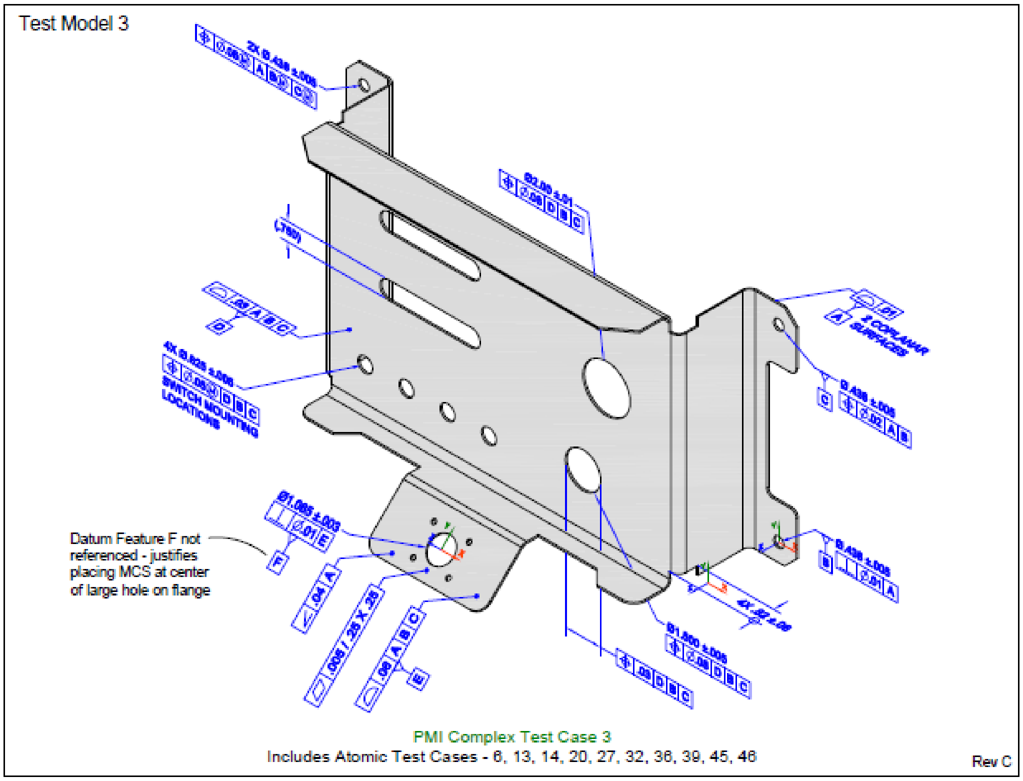

Figure 3: Combined test case 3 (CTC 3) drawing

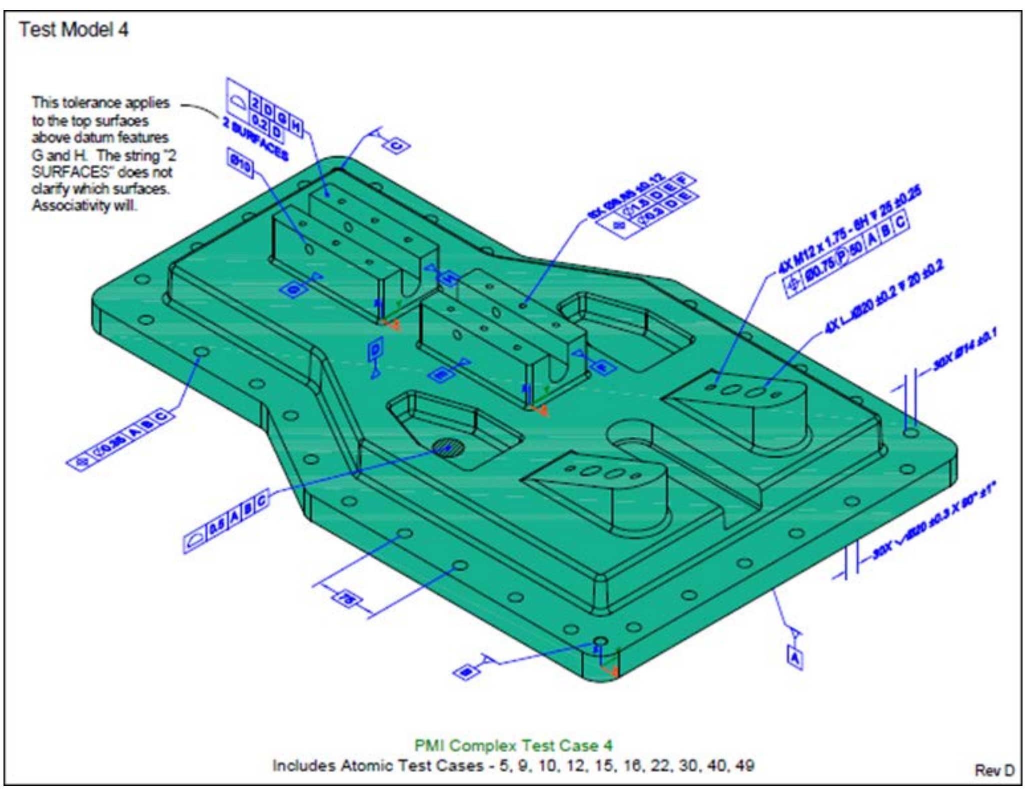

Figure 4: Combined test case 4 (CTC 4) drawing

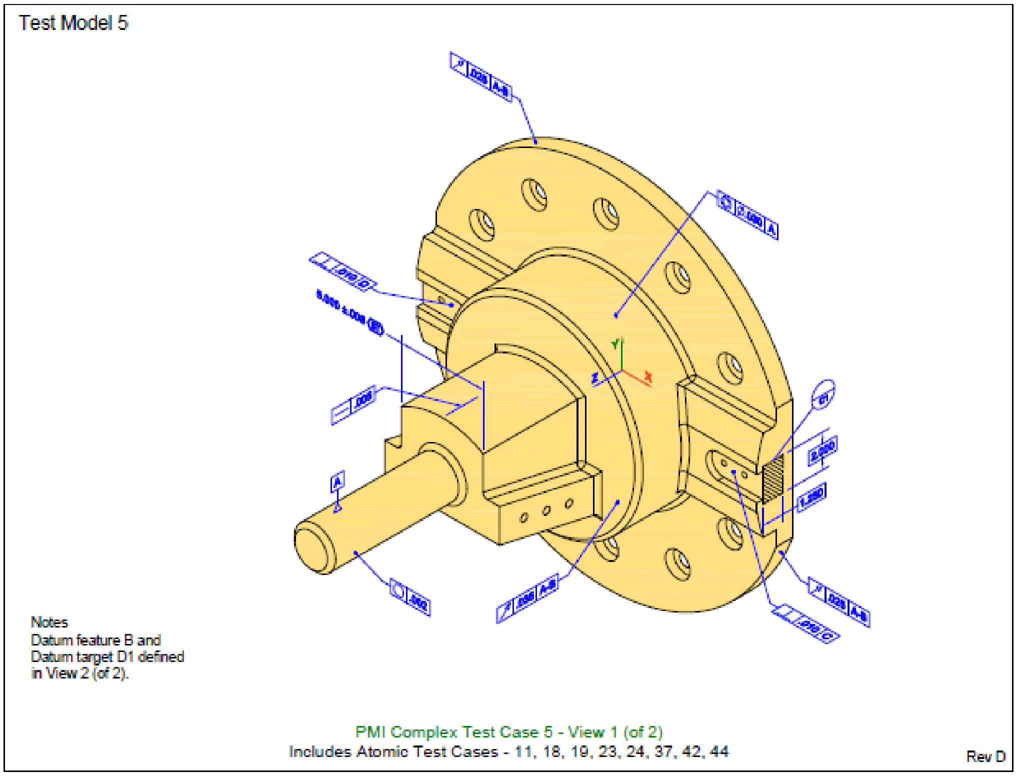

Figure 5: Combined test case 5 (CTC 5) drawing, view 1 of 2

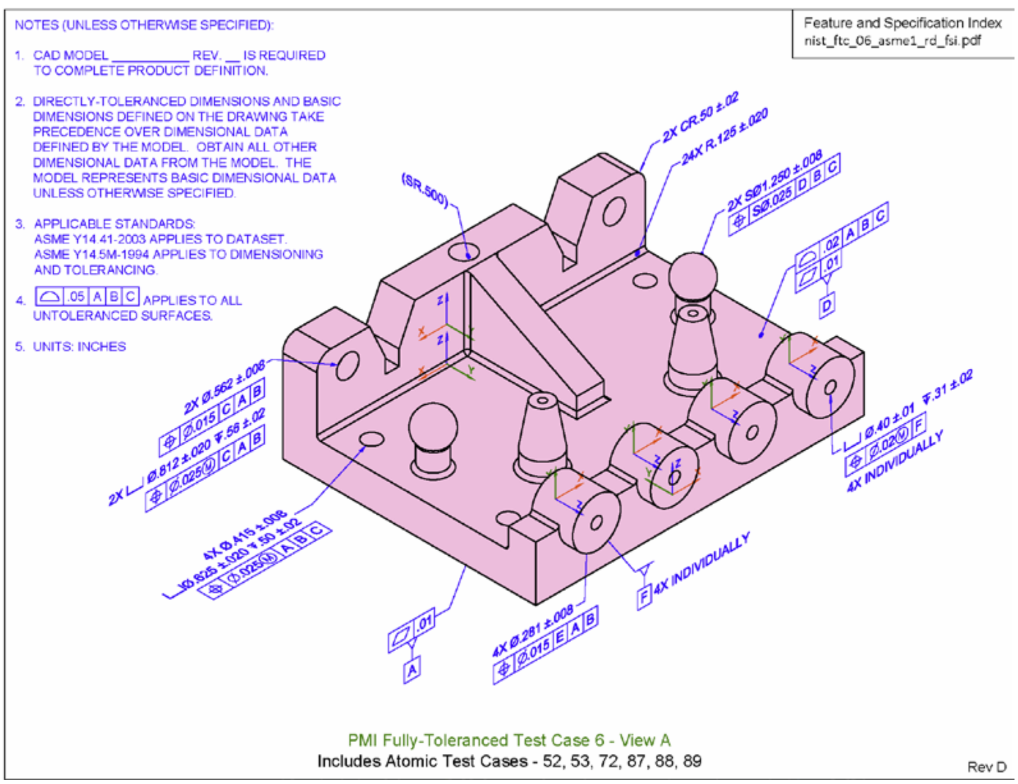

Figure 6: Fully-toleranced test case 6 (FTC 6) drawing, view 1 of 3

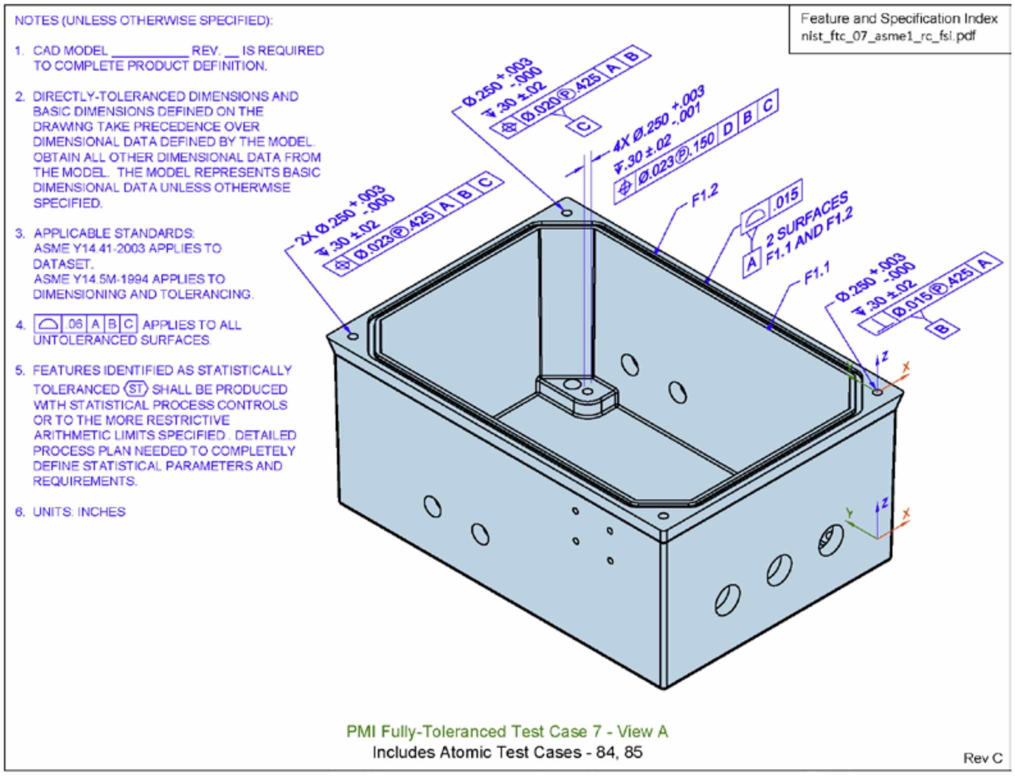

Figure 7: Fully-toleranced test case 7 (FTC 7) drawing, view 1 of 4

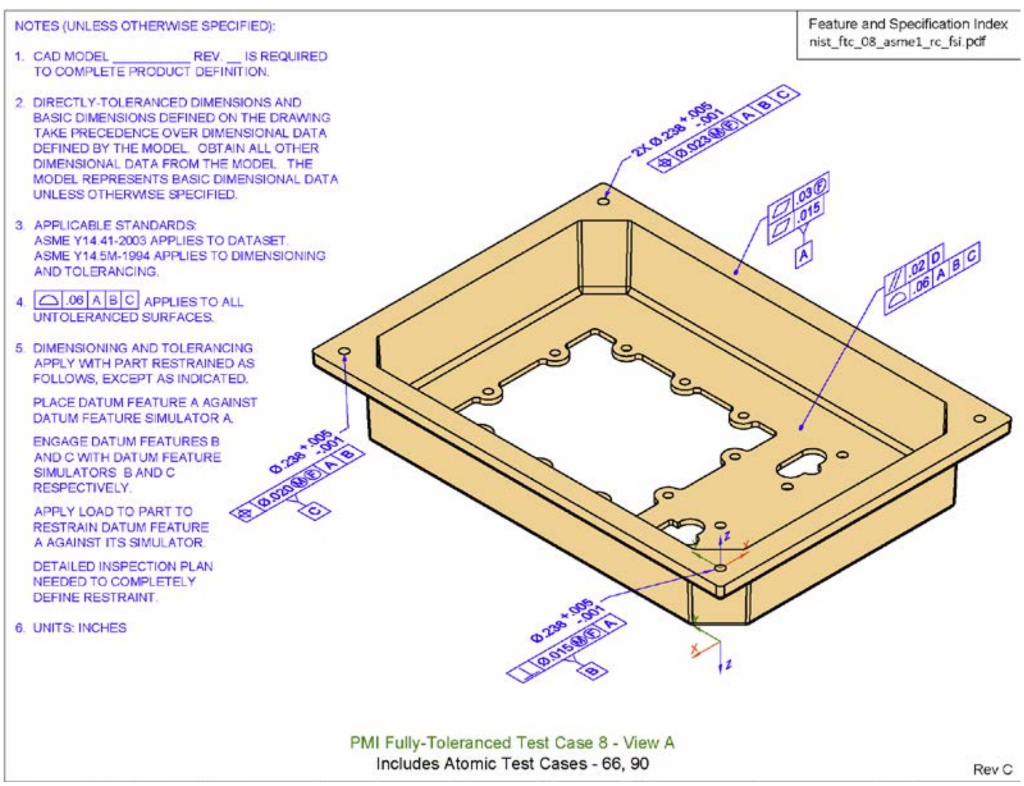

Figure 8: Fully-toleranced test case 8 (FTC 8) drawing, view 1 of 4

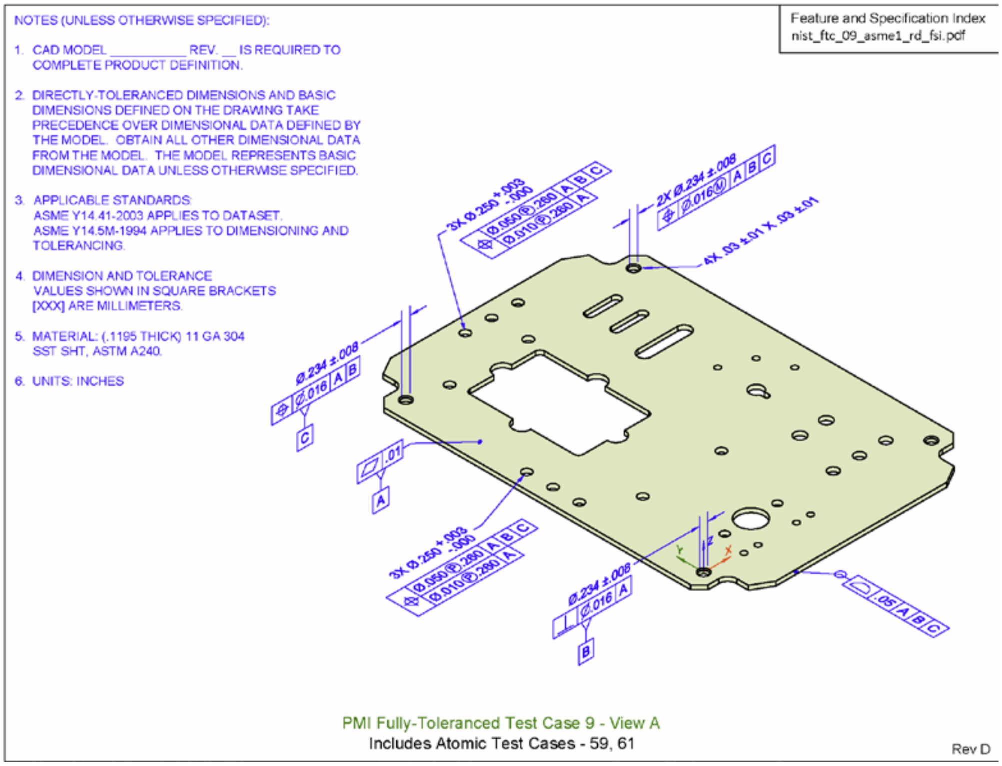

Figure 9: Fully-toleranced test case 9 (FTC 9) drawing, view 1 of 4

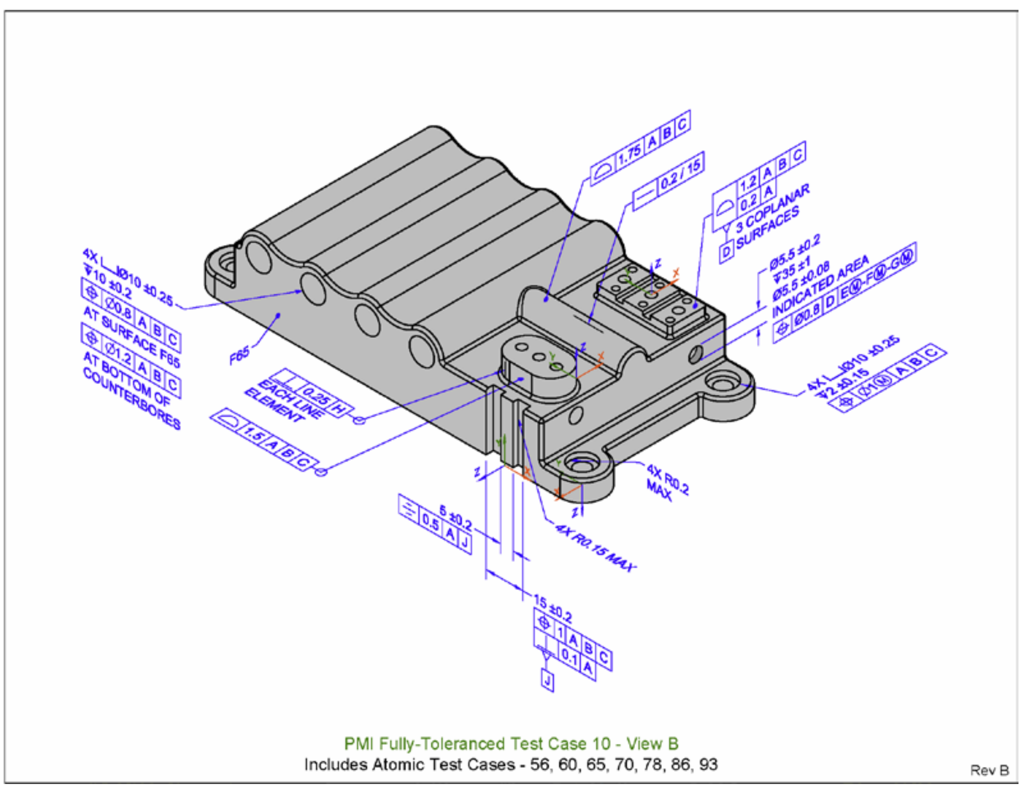

Figure 10: Fully-toleranced test case 10 (FTC 10) drawing, view 2 of 5

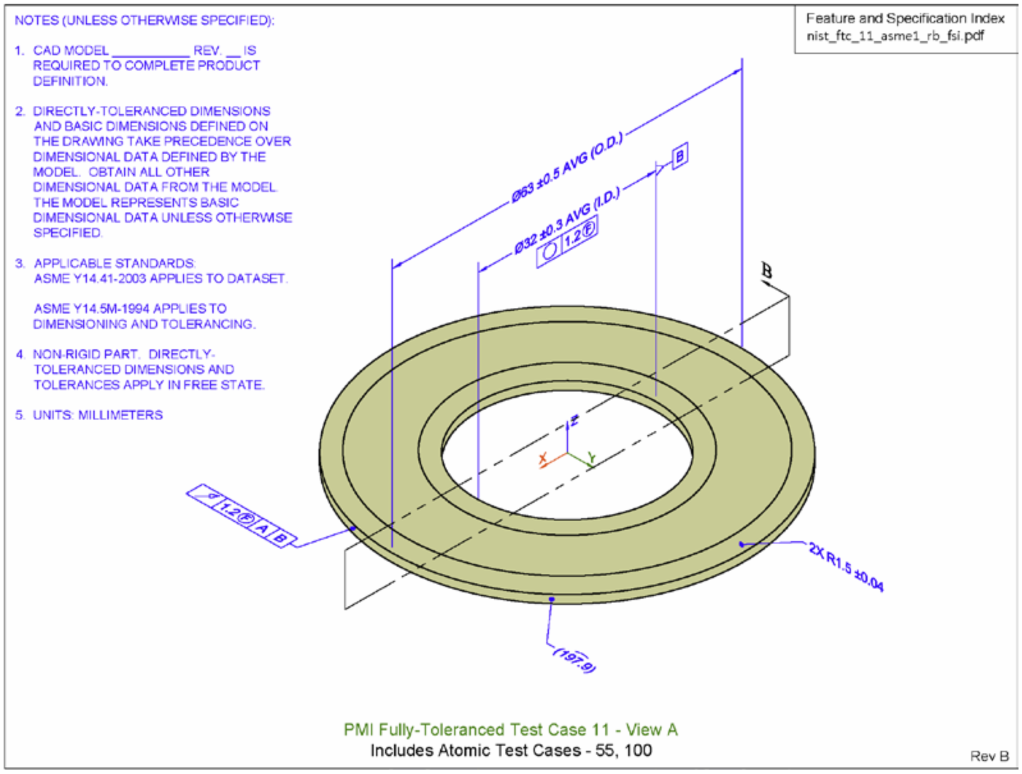

Figure 11: Fully-toleranced test case 11 (FTC 11) drawing, view 1 of 2

2.3 PMI Annotation Characteristics

It is difficult to find a particular type of PMI annotation or annotation characteristic with only the test case drawings shown in the previous section and related CAD models. For example, in all of the test cases CTC 3 contains the only angularity tolerance and CTC 5 and FTC 11 are the only test cases without a position tolerance. The following tables contain the number of PMI annotation characteristics for each test case. The annotation characteristics are enumerated in the output of the STEP File Analyzer [7].

Table 1 shows the number of geometric tolerances in each test case including the use of all-around and composite tolerances.

Table 1: Tolerance Types and Characteristics

Tolerance Characteristic	CTC 1	CTC 2	CTC 3	CTC 4	CTC 5	FTC 6	FTC 7	FTC 8	FTC 9	FTC 10	FTC 11
angularity			1								
circular runout					3						1
coaxiality					1						
concentricity											
cylindricity										2	
flatness	1	1	1			3	1	3	1	1	1
line profile		1									
parallelism							1	5			
perpendicularity	1	3	2		2	2	1	1	4	5	
position	2	4	6	4		11	10	13	23	19	
roundness					1						1
straightness					1					1	
surface profile	2	13	3	3		11	11	11	3	9	1
symmetry										1	
total runout					2						
all around	1							6	3	2	
composite				2		4	6	6	2	3	

Table 2 shows the number of dimensions, dimensional tolerances, and other characteristics of dimensions for each test case.

Table 2: Dimension Characteristics

Dimension Characteristic	CTC 1	CTC 2	CTC 3	CTC 4	CTC 5	FTC 6	FTC 7	FTC 8	FTC 9	FTC 10	FTC 11
location			2	2	5	10	5	1	8	2	1
angular location	1			1							
size	7	7	7	6	1	14	11	9	14	16	5
diameter	7	7	7	5	1	10	11	9	14	16	2
radius						1	1			2	2
spherical diameter						1					
spherical radius						1					
controlled radius						1					
square								1			
arc length											1
basic dimension				2	4						
reference dimension			1			5		1			1
bilateral tolerance	2	7	8	7	2	19	7		19	18	4
unilateral tolerance	2						3		2		
unequal bilateral tolerance	2						5	9			
value range	2						1				
type qualifier										2	3
tolerance class										3	
oriented dimension			1						6		
countersink				1							
counterbore				1		3	1			3	
depth				2		5	5			5	
dimension origin			1								
statistical					1		1				

Table 3 shows the number of datums, datum targets, and datum characteristics for each test case.

Table 3: Datums and Datum Targets

Datums and Datum Targets	CTC 1	CTC 2	CTC 3	CTC 4	CTC 5	FTC 6	FTC 7	FTC 8	FTC 9	FTC 10	FTC 11
datum	3	10	6	8	4	10	5	11	8	11	2
multiple datum features					3			2		1	
point target		8									
line target						4					
circular curve target						2					
circle area target		1									
rectangle area target					2						
general area target										4	
movable datum target										2	

Table 4 shows the number of tolerance zone types and modifiers.

Table 4: Tolerance Zone Characteristics

Tolerance Zone Characteristic	CTC 1	CTC 2	CTC 3	CTC 4	CTC 5	FTC 6	FTC 7	FTC 8	FTC 9	FTC 10	FTC 11
diameter		7	7	4	1	8	11	14	17	22	
spherical diameter						1					
projected				1			4		4	3	
unequally disposed		3									
maximum value							2				
unit-basis			1				1				
statistical tolerance							1				

Table 5 shows other modifiers and notes used in feature control frames.

Table 5: Modifiers, Notes, Other

Modifiers, Notes, Other	CTC 1	CTC 2	CTC 3	CTC 4	CTC 5	FTC 6	FTC 7	FTC 8	FTC 9	FTC 10	FTC 11
between	1							1			
conical taper						1					
free state								5			4
hole thread				1						3	
least material requirement		7								1	
maximum material requirement		5	4			4	4	18	11	14	
separate requirement									2		
simultaneous requirement							2				
slope						1					
tangent plane								3			

2.4 Distribution of PMI Annotations

The figures in this section show the distribution of PMI annotations in all of the test cases. The figures are screenshots from the Keshif[2] web-based data exploration environment [8]. The input for Keshif is a spreadsheet of values where each column maps to a different value type in the Keshif display. In this case, there are three value types: Test Case, Annotation Type, and PMI Annotation.

All of the following figures that were generated from Keshif can be reproduced with the online version of the Keshif display for the distribution of PMI annotations: https://pages.nist.gov/CAD-PMI-Testing/models.html The online version contains the PMI annotation for all five CTC and six FTC. However, FTC 7, 10, and 11 were not modeled in any CAD system and are not represented in the following figures.

Figure 12 shows the distribution of the 297 PMI annotations in the five CTC and three FTC (6, 8, 9) drawings. In the upper left of the Keshif display are the number of annotations per test case for the five CTC and three FTC. There are more annotations per FTC because those test cases are fully-toleranced.

On the right of Figure 12 are the individual PMI annotations and the number of their occurrences in all of the CTC and FTC. The PMI annotations are shown as best as possible given the limitations of character set available in the original spreadsheet data [9]. PMI annotations with multi-line feature control frames (FCF) are shown on one line. A ‘|’ delimits the sections of a FCF. A ‘/’ delimits multiple lines of a FCF. Tolerance zone and datum reference frame modifiers such as a maximum material modifier (letter M in a circle) appear as the letter bracketed by parentheses, e.g., (M).

The first eight PMI annotations are datum features A-H. Datum features A and B have seven occurrences each in all of the test cases. The next annotation after the datum features is a flatness tolerance with a tolerance zone magnitude of 0.1. The next annotation after the flatness tolerance is a surface profile tolerance with a tolerance zone magnitude of 0.6 and a FCF of ABC. In a similar manner, all of the PMI annotations are shown. Tolerances or dimensions with “(Oriented)” after the FCF means that the tolerance or dimension has a specific orientation in a test case drawing. Other modifiers similar modifiers are: Origin, All Around, and UOS. UOS means “Unless Otherwise Specified” and is usually associated with an overall surface profile in the notes. The “179 More” highlighted at the bottom of the PMI annotations indicates that there are 179 more annotations that are not shown but can be seen in the online version.

In the bottom left of Figure 12 is a classification and count of the PMI annotations by geometric tolerance type, datums, datum features, and dimensions. Dimensions split into three categories: dimensions, dimensions related to holes (depth, counterbore, countersink, hole thread), and other dimensions (slope, conical taper, radius). It is clear from the classification of annotation types and Table 1 that some types of tolerances are used infrequently in the test cases such as angularity, circular runout, coaxiality, line profile, parallelism, roundness, straightness, and total runout.

[2] https://keshif.me/

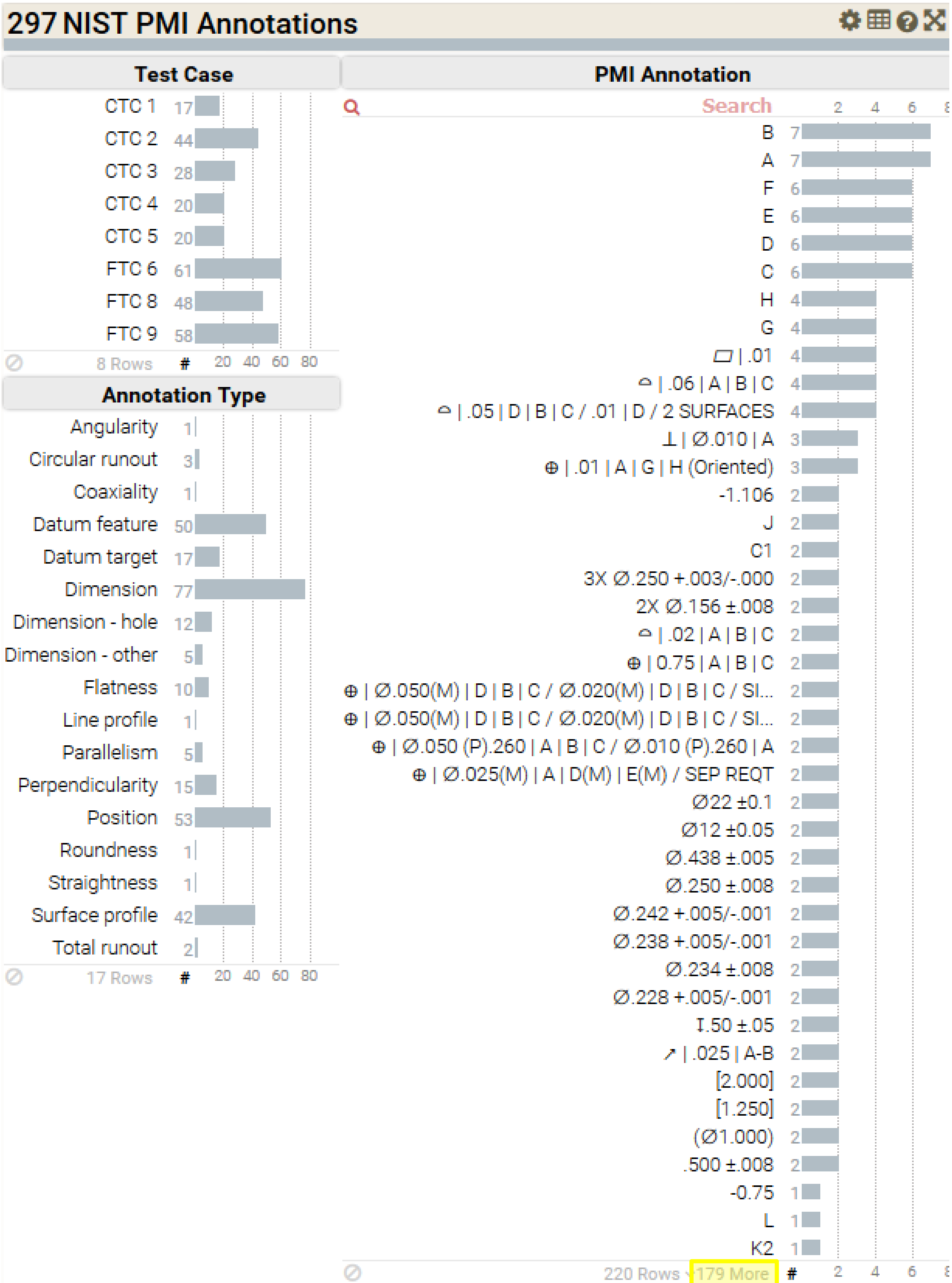

Figure 12: PMI Annotations for all test cases

2.4.1 Distribution of PMI Annotations in the CTC

There are many ways to interactively visualize data in Keshif. The following figures explore a few of those methods. Figure 13 shows that by hovering the mouse over CTC 1 in the display, the corresponding annotation types and PMI annotations associated with CTC 1 are highlighted in orange. The characteristic by which the results are being highlighted is shown at the top of the display.

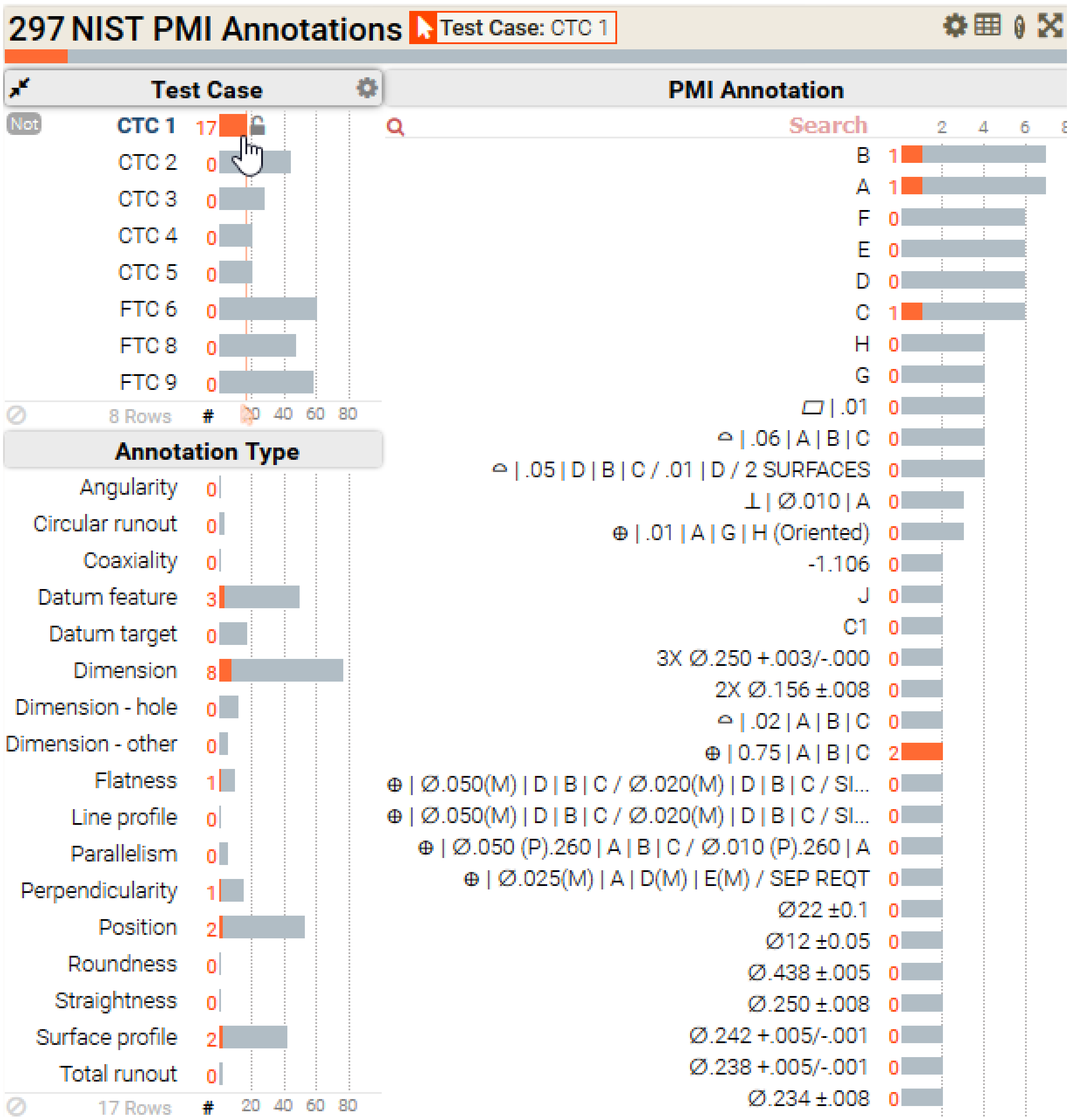

Figure 13: PMI annotations highlighted for CTC 1

Figure 14 shows that by selecting CTC 1, PMI annotations for all other test cases are filtered out and only the PMI annotations for CTC 1 are shown. The distribution of the annotations types is updated to show only the count for the annotation types in CTC 1. Figure 15 through Figure 18 shows the distribution of PMI annotations and types for CTC 2-5. The total number of PMI annotations and characteristic by which the results are being filtered is shown at the top of the display.

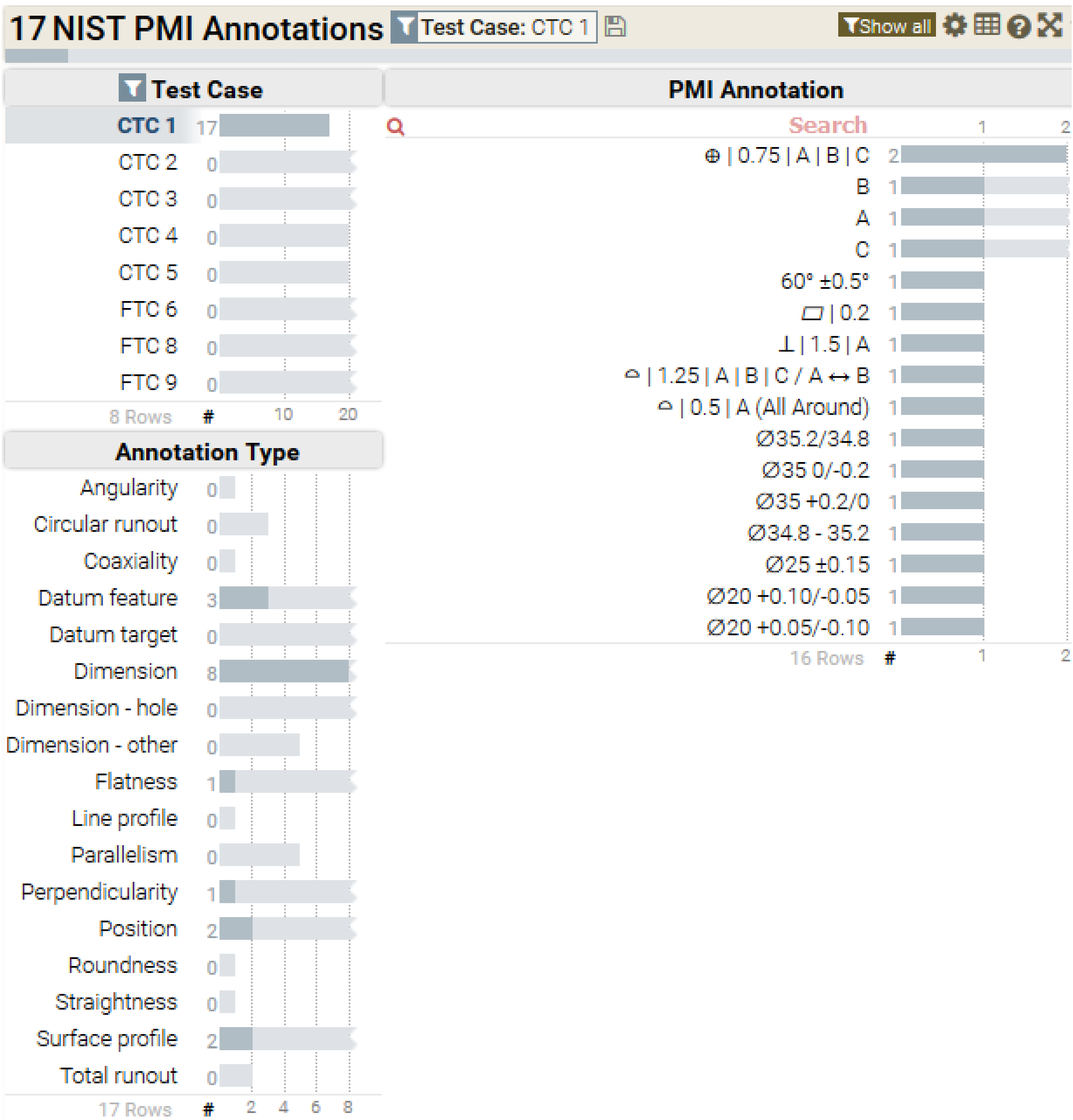

Figure 14: PMI annotations for CTC 1

Figure 15 shows the distribution of PMI annotations and types for CTC 2.

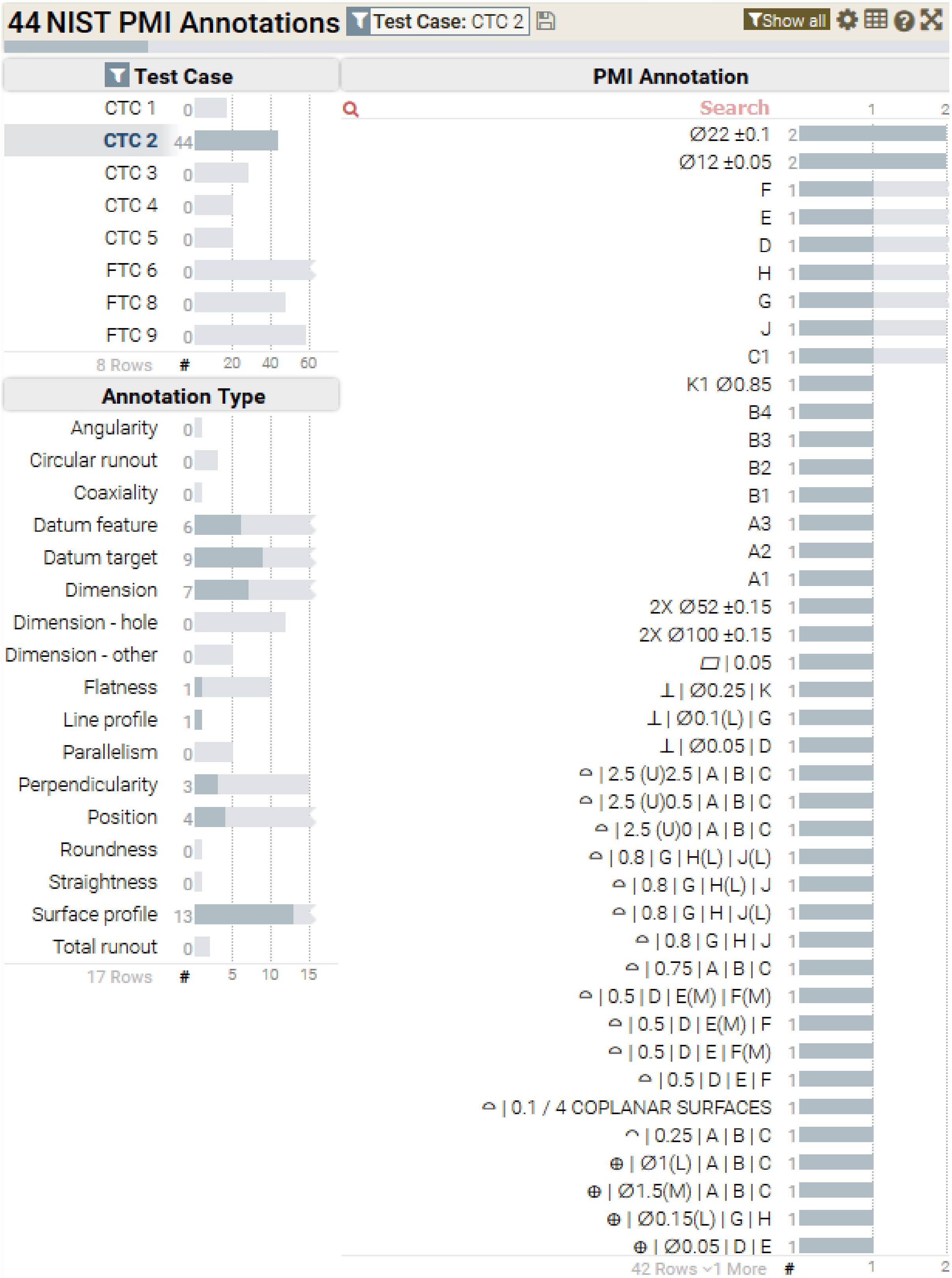

Figure 15: PMI annotations for CTC 2

Figure 16 shows the distribution of PMI annotations and types for CTC 3.

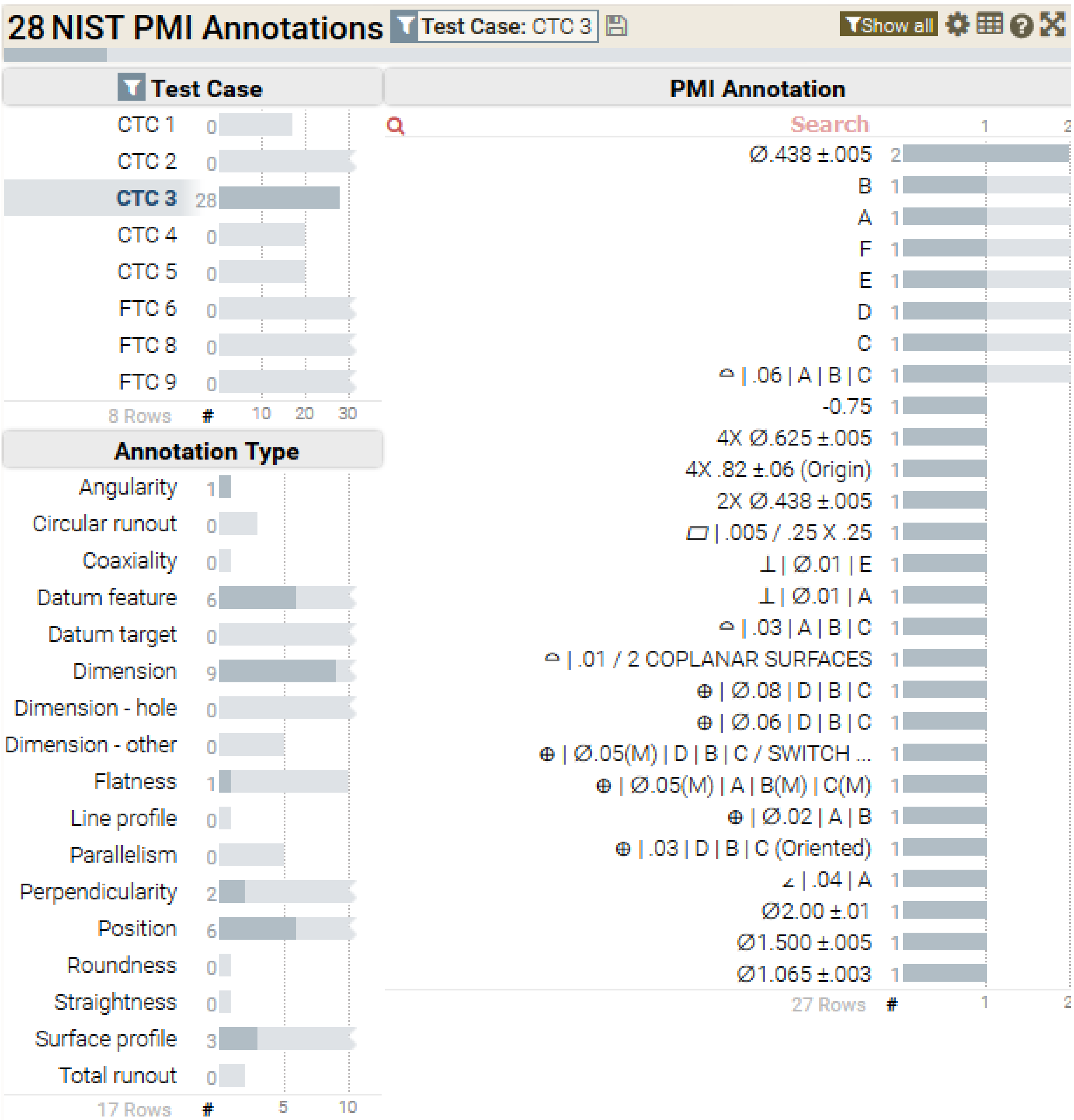

Figure 16: PMI annotations for CTC 3

Figure 17 shows the distribution of PMI annotations and types for CTC 4.

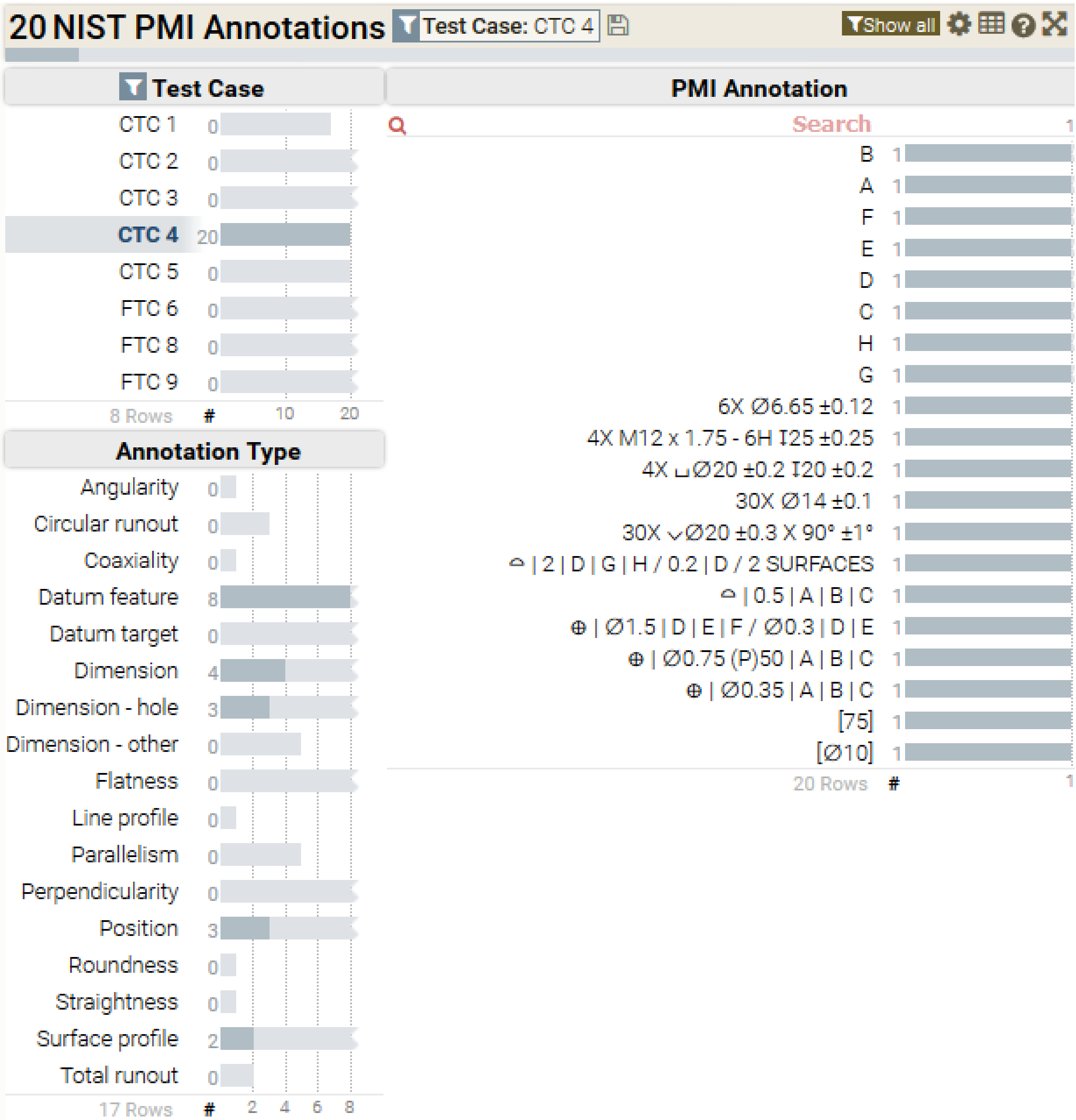

Figure 17: PMI annotations for CTC 4

Figure 18 shows the distribution of PMI annotations and types for CTC 5.

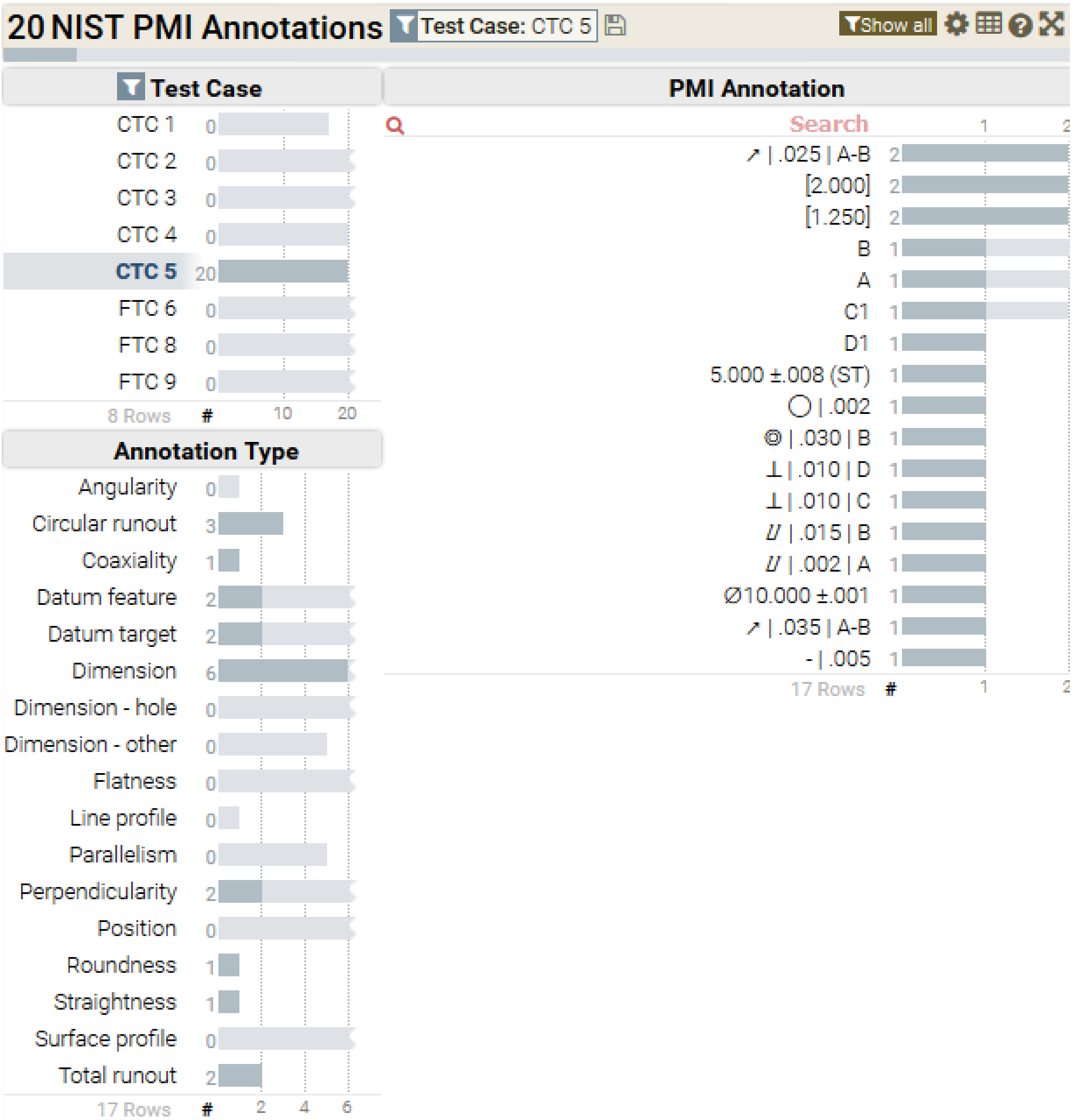

Figure 18: PMI annotations for CTC 5

2.4.2 Distribution of PMI Annotations in the FTC

Figure 19 through Figure 21 shows the distribution of PMI annotations and types for FTC 6, 8, and 9 where the PMI annotations for datum targets and datum features have been excluded in Annotation Type. This allows for more of the other PMI annotations to be shown on the right.

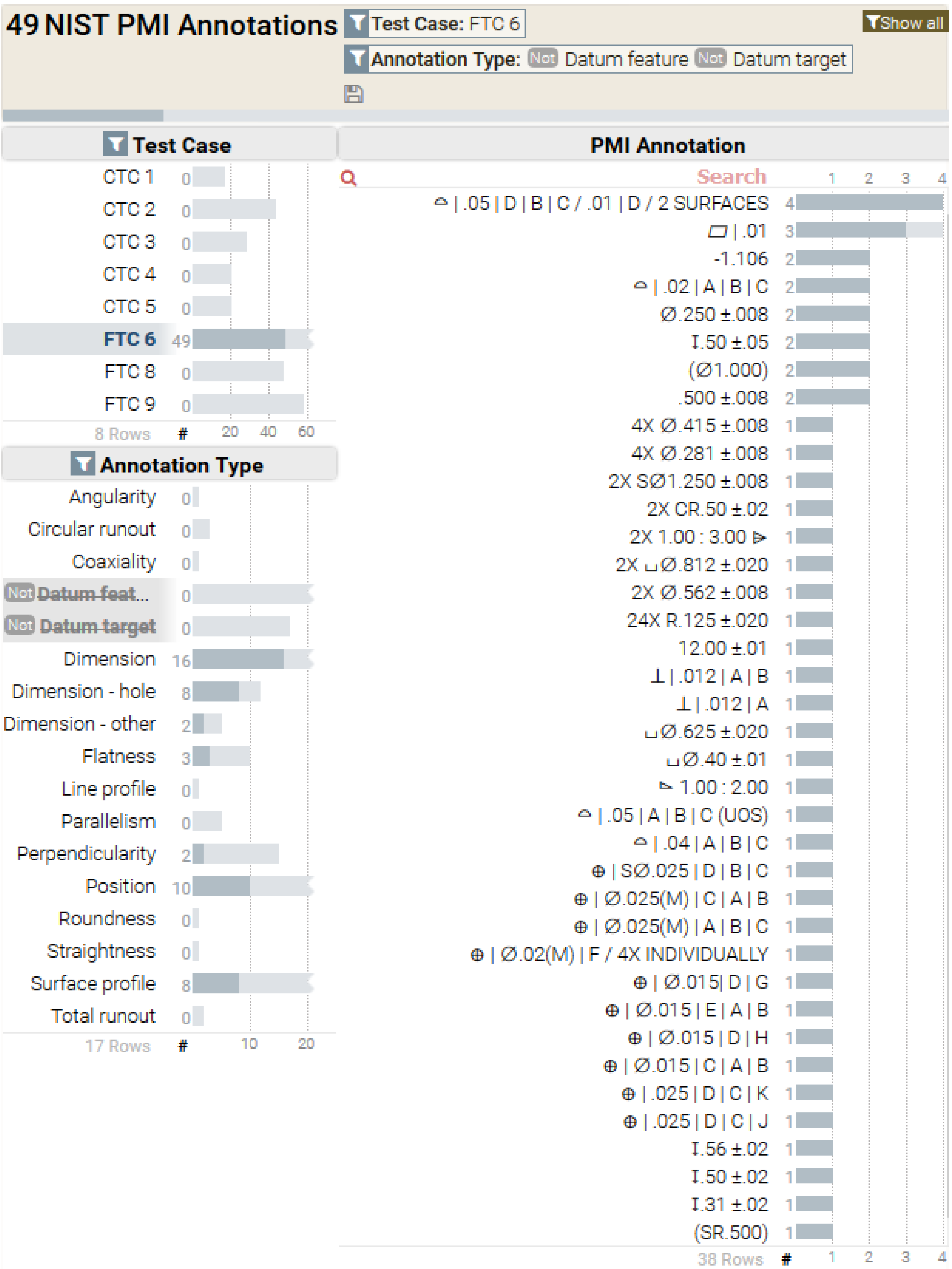

Figure 19: PMI annotations for FTC 6 excluding datum features and datum targets

Figure 20 shows the distribution of PMI annotations and types for FTC 8 excluding datum features.

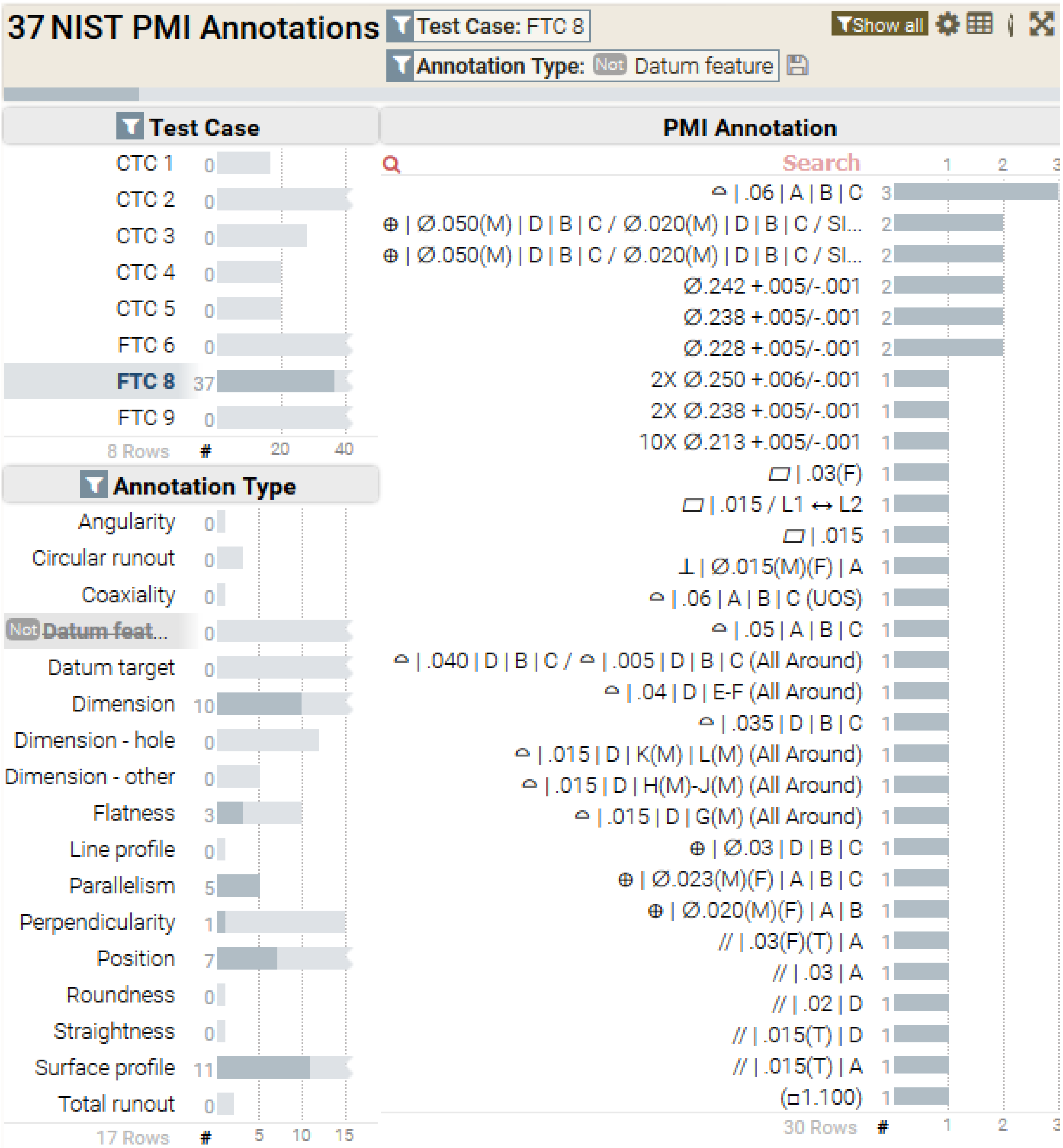

Figure 20: PMI annotations for FTC 8 excluding datum features

Figure 21 shows the distribution of PMI annotations and types for FTC 9 excluding datum features.

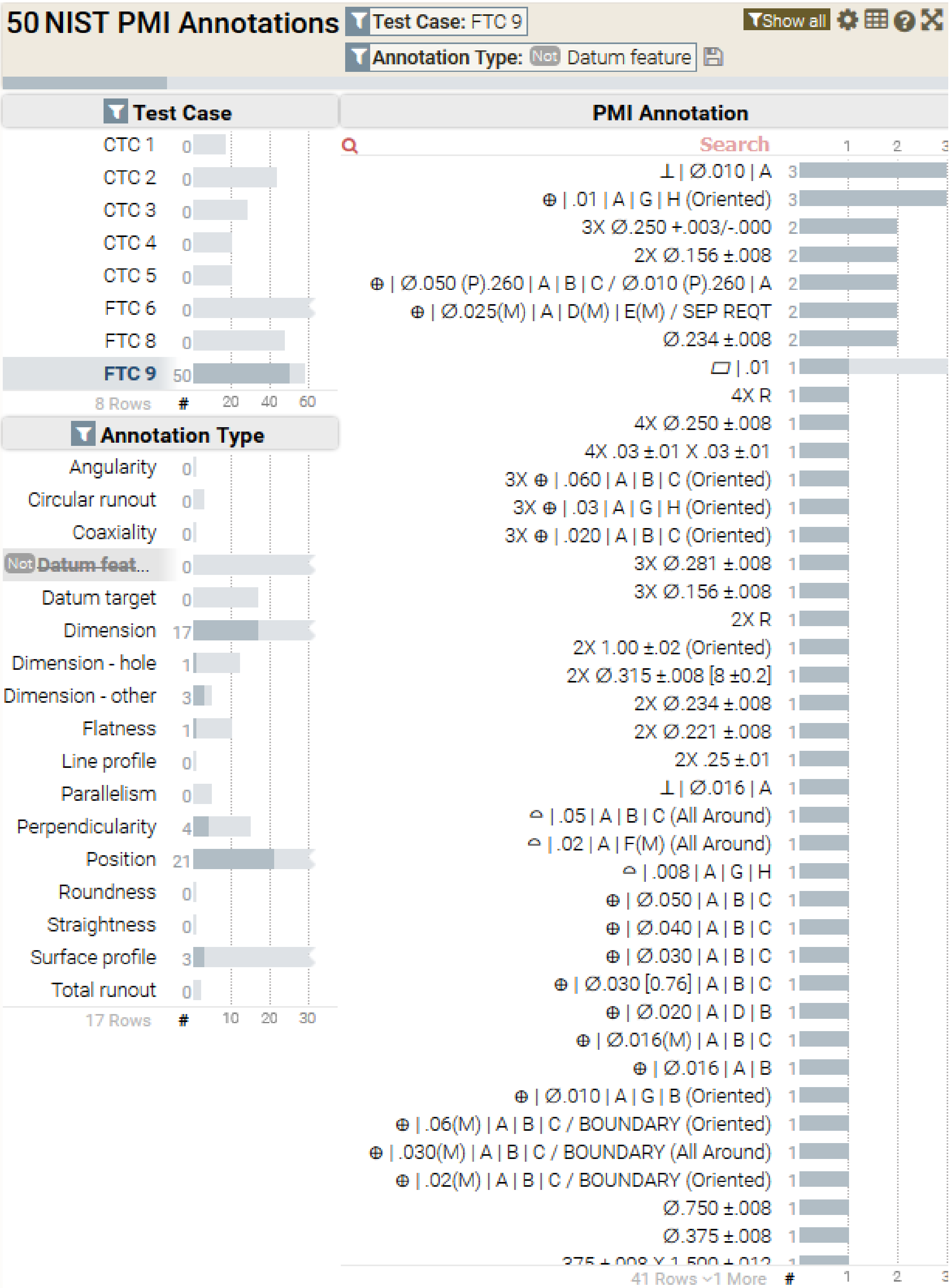

Figure 21: PMI annotations for FTC 9 excluding datum features

2.4.3 Distribution of PMI Annotations by Type

By selecting multiple Annotation Types in the Keshif display, only the PMI Annotations are shown for those types and their count in the test cases. Figure 22 shows that most tolerance types with five or less occurrences are in CTC 5 and FTC 8.

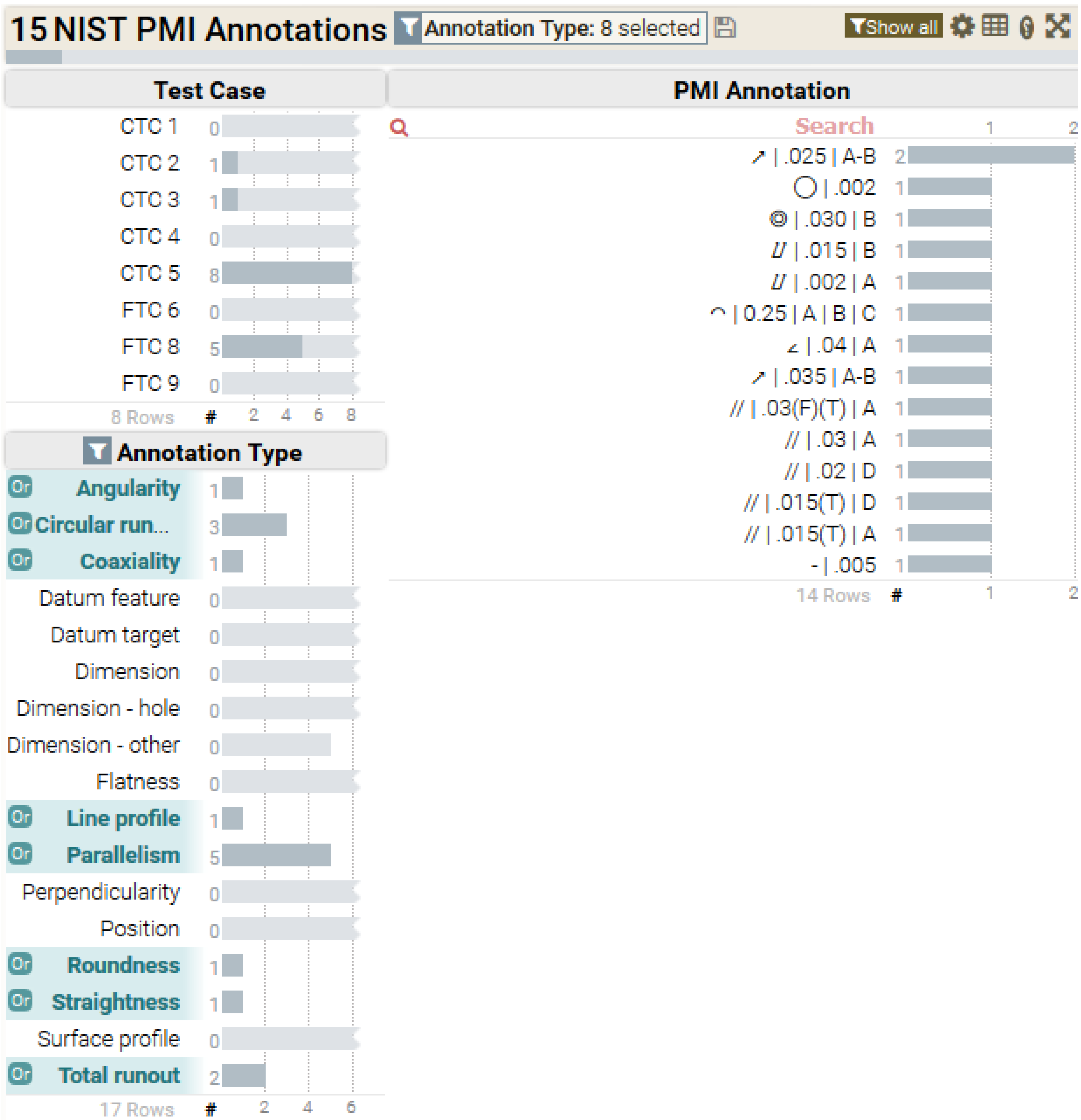

Figure 22: PMI annotations for tolerances with five or less occurrences in the test cases

Figure 23 shows that hole (depth, counterbore, countersink, hole thread) and other (slope, conical taper, radius) dimensions are used only in CTC 4, FTC 6, and FTC 9.

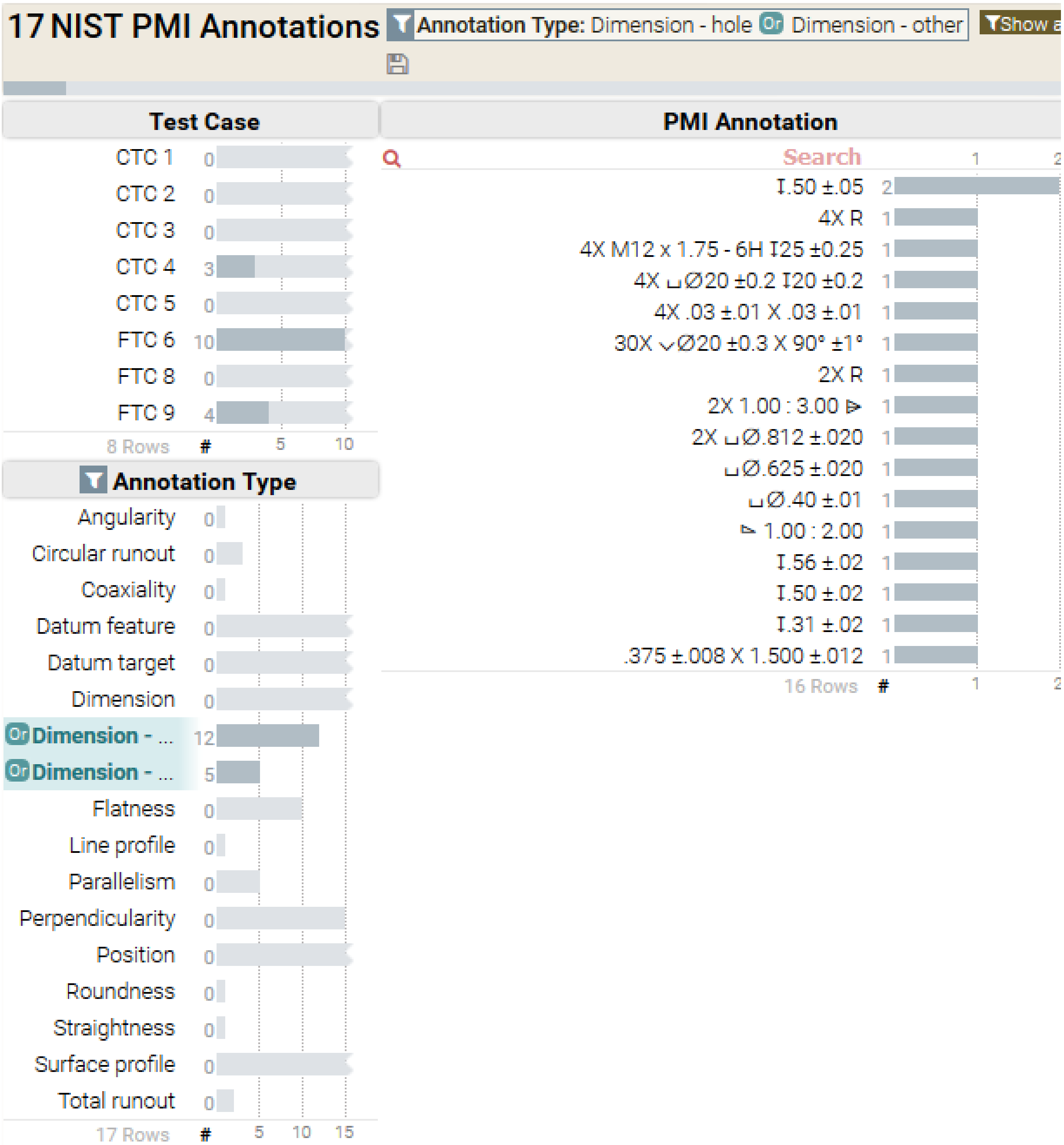

Figure 23: PMI annotations for hole and other dimensions

Figure 24 shows all position tolerances in the test cases and that none are found in CTC 5.

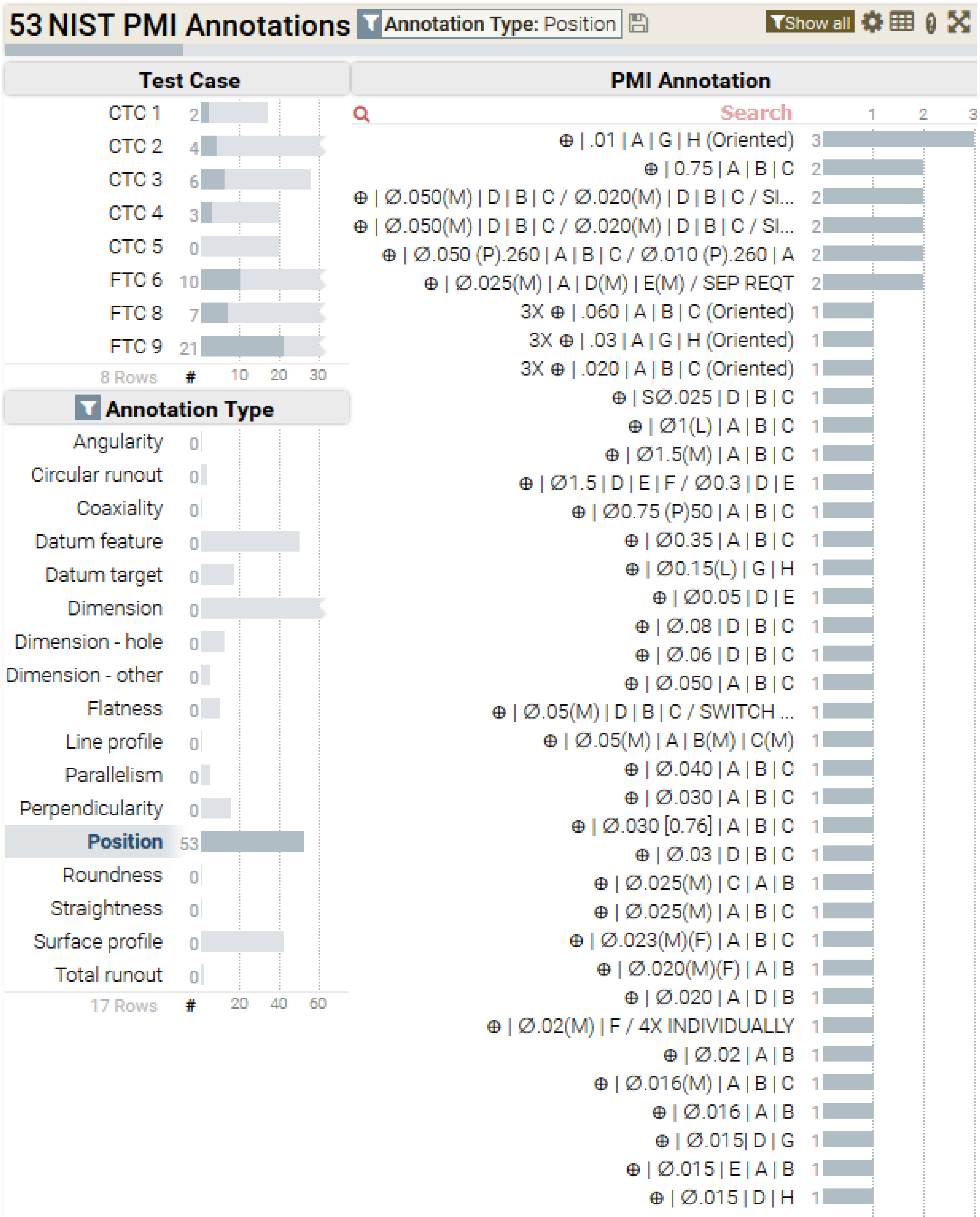

Figure 24: PMI annotations for position tolerances

2.4.4 Filtering PMI Annotations by Text String

The Keshif display characteristics can also be filtered by a text string. Figure 25 shows PMI annotations filter by the text string "oriented" which shows position tolerances and dimensions with an orientation. They are found only in CTC 3 and FTC 9.

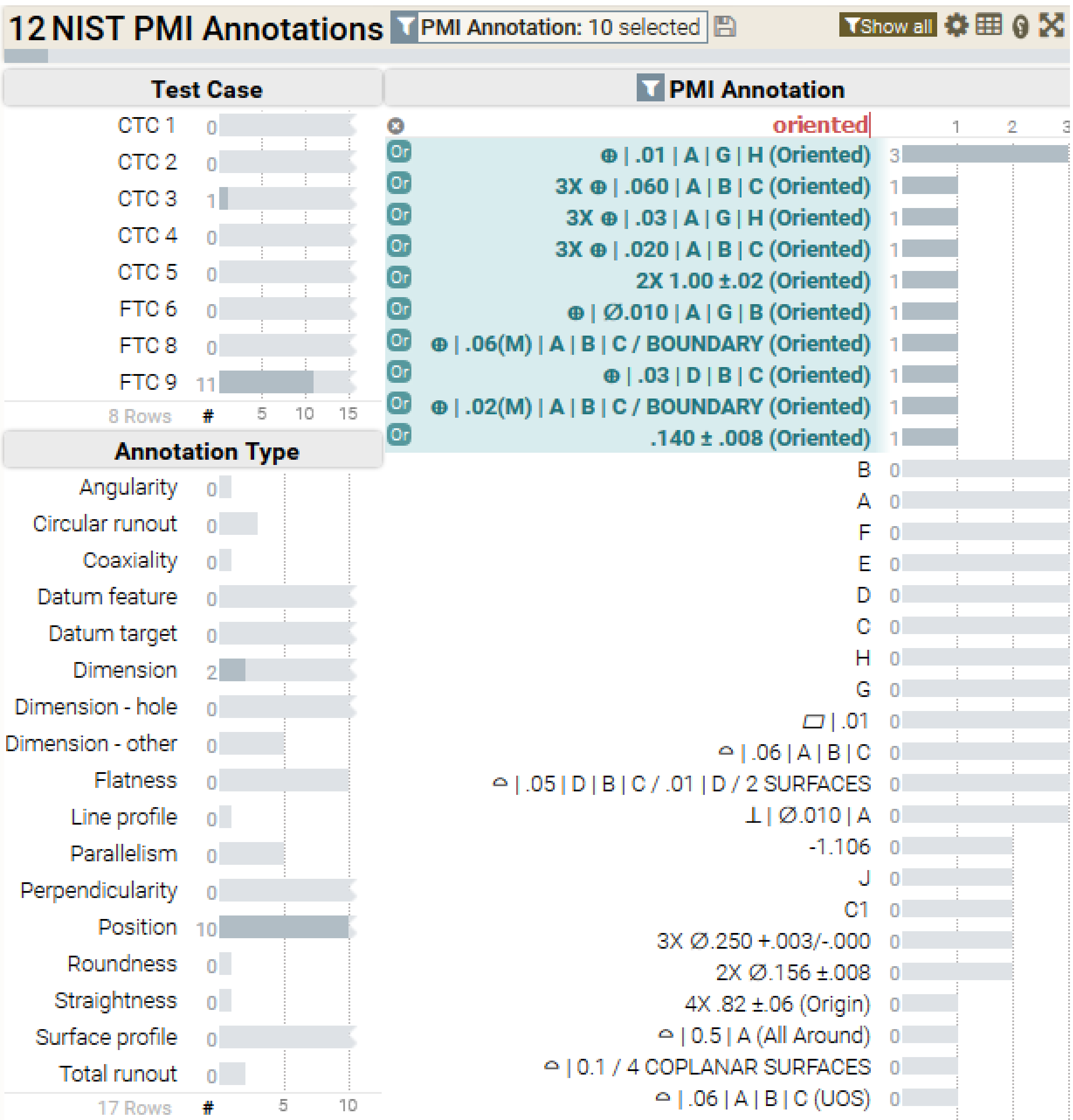

Figure 25: PMI annotations for dimensions and tolerances with an orientation

Figure 26 shows PMI annotations filter for the maximum material modifier (shown as an (M) in the annotation) in the datum reference frame or tolerance zone.

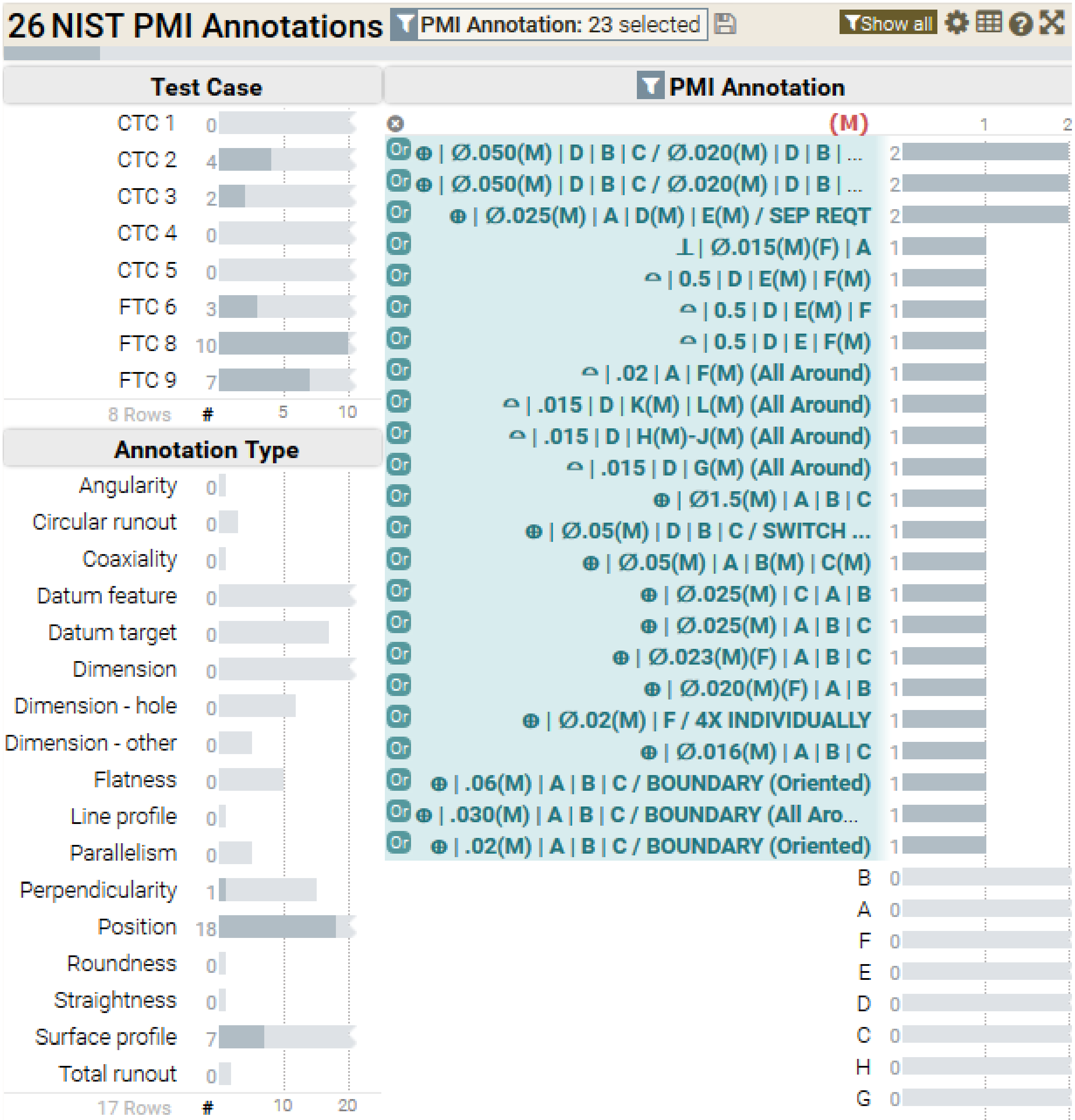

Figure 26: PMI annotations with a maximum material modifier in the datum reference frame or tolerance zone

All of the previous figures that were generated from Keshif can be reproduced with the online version of the Keshif display for the distribution of PMI annotations: https://pages.nist.gov/CAD-PMI-Testing/models.html

3 Original Verification Testing Results

The verification testing of the CAD systems, described in the project reports [4, 6], involved modeling the PMI annotations in CTC and FTC (Section 2.2) in the four CAD systems (Section 2.1) as best as possible with a preference given to PMI representation (semantic PMI) over PMI presentation (graphic PMI). The resulting semantic and graphic PMI information in each CAD model was compared to the corresponding information in a test case drawing. This was performed in a semi-automated way with the CAD validation software CADIQ[3]. Some of the verification testing results for the CTC are reproduced here to help understand the basis for the new analysis of the verification testing results described in Section 4.

The verification and validation testing results related to the PMI in the test cases were generated based on the 2012 and 2015 versions of the CAD systems. Issues identified for the semantic and graphic representation of PMI in each CAD system may have been resolved since the original testing took place.

Errors (limitations) of PMI representation and presentation were compiled for all of the test case PMI annotations in the four CAD systems. In the project reports, the errors were classified by various characteristics of PMI representation and presentation shown in Table 6 and Table 7. In addition to characteristics of the annotations, errors related to coordinate systems, supplemental geometry, and saved views were also considered. Errors related to PMI representation affect the automated consumption and exchange of that information in downstream design, manufacturing, and inspection processes. Errors related to PMI presentation affect the human interpretation of that information on drawings and 3D CAD models [4].

Table 6: Characteristics of PMI representation [4]

Annotation structure
Annotation parameters
Annotation geometry
Coordinate system structure
Coordinate system parameters
Supplemental geometry structure
Supplemental geometry parameters

Table 7: Characteristics of PMI presentation [4]

Annotation visibility
Annotation color
Annotation name
Annotation layout
Annotation location
Annotation orientation
Annotation lines
Annotation text
Coordinate system visibility
Coordinate system color
Coordinate system name
Coordinate system text
Supplemental geometry visibility
Supplemental geometry color
Saved view structure
Saved view name
Saved view frustum

[3] https://www.iti-global.com/cadiq

3.1 Representation and Presentation Limitations

Table 8 and Table 10 show the PMI representation and presentation limitations (errors), respectively, for the CTC. There are other similar verification testing results for the FTC [6]. Table 9 is a key to the abbreviations used in the tables.

Table 8: CTC Representation limitation counts by characteristic and type [4]

Representation Limitations	96
Annotation structure	19
Countersink diameter DIM not defined	1
DIM defined as part of DTS	4
FCF extension line defined as separate DIM	9
FCF projected tolerance zone defined as separate DIM	1
FCF text defined as separate note	3
Threaded hole depth DIM not defined	1
Annotation parameters	11
DIM origin not defined	1
DIM parameter defined with encoded text	3
FCF between-basis defined with encoded text	4
FCF parameter defined with encoded text	3
Annotation geometry	18
DIM associated with extra face	1
DIM not associated with complete set of faces	4
DTS associated with extra face	1
DTS not associated with face	1
DTS not associated with SG point	3
FCF associated with extra face	5
FCF not associated with SG curve	3
Coordinate system structure	48
CS not linked to FCF DRF	48

Table 9: PMI entity abbreviations [4]

Abbrev	Definition
AN	Annotation
CS	Coordinate system
DFS	Datum feature symbol
DIM	Dimension
DRF	Datum reference frame
DTS	Datum target symbol
FCF	Feature control frame
PG	Product geometry
SG	Supplemental geometry
VW	View

Table 10: CTC Presentation limitation counts by characteristic and type [4]

Presentation Limitations	**108**
Annotation visibility	**7**
DFS is extraneous when DTS is defined	2
DFS not visible in specified view	1
DIM not visible in specified view	1
DTS visible in wrong view	3
Annotation layout	**20**
Counterbore DIM defined as two separate DIM's	4
Countersink DIM defined as two separate DIM's	4
DIM limits displayed in reversed order	1
DIM limits not displayed horizontally	2
DTS target area diameter defined as separate DIM	1
FCF text displayed above rather than below	2
FCF text displayed on right rather than below	3
Threaded hole DIM defined as two separate DIM's	3
Annotation location	**12**
DFS not attached to FCF	8
DFS overlaps DIM graphics	1
DFS partially buried in solid	1
FCF partially buried in solid	2
Annotation orientation	**4**
DIM text orientation is wrong	1
DTS text is backwards in this view	3
Annotation lines	**10**
DFS has no extension line	10
Annotation text	**22**
DIM has extraneous space	11
DTS text is extraneous	2
FCF missing note text	2
FCF missing projected tolerance zone length	1
FCF text is extraneous	6

Figure 27 shows an example of a representation limitation (semantic annotation error) where the unequally-disposed symbol is only defined by encoded text rather than a semantic representation. This limitation would affect the automated consumption of this information by downstream applications. The limitation appears in Table 8 under the Annotation parameters category. More examples of representation and presentation limitations are found in Appendices D and E of the verification reports [4, 6].

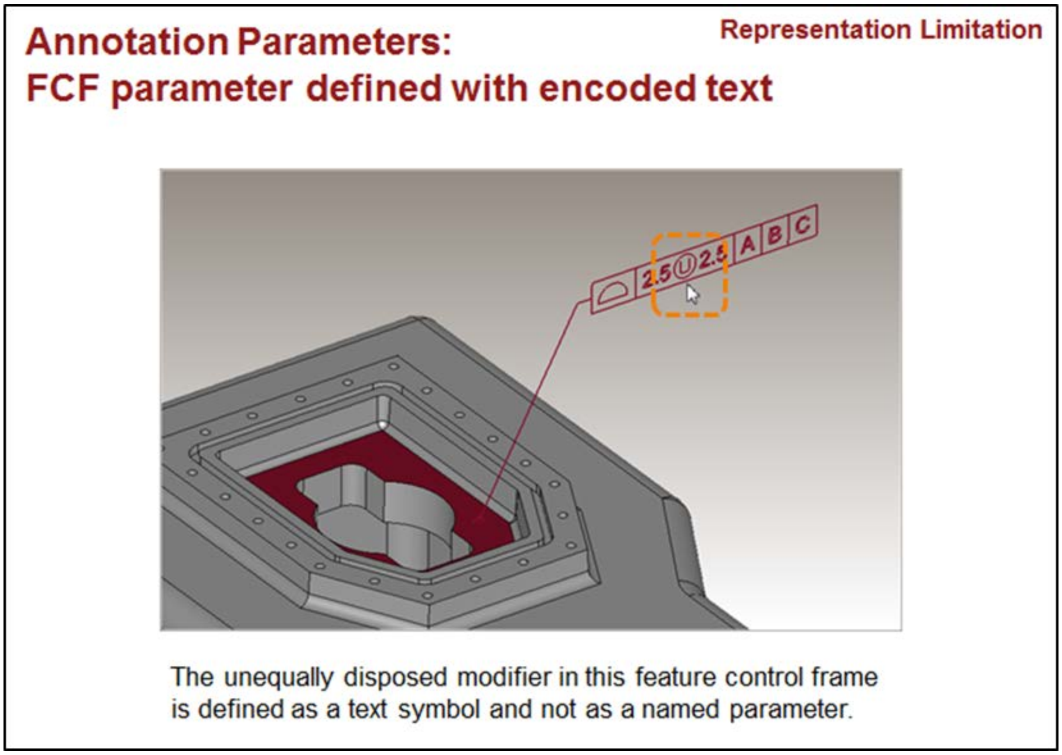

Figure 27: PMI representation limitation: feature control frame defined with encoded text [4]

Figure 28 shows an example of a presentation limitation (graphic annotation error) where a dimension has an extra space. This would not affect the human interpretation of the dimension. Figure 29 shows an example of a presentation limitation where the feature control frame is missing the projected tolerance zone length. This would affect the human interpretation of the tolerance zone. The projected tolerance zone length may or may not be missing as semantic PMI information. These limitations appear in Table 10 under the Annotation text category.

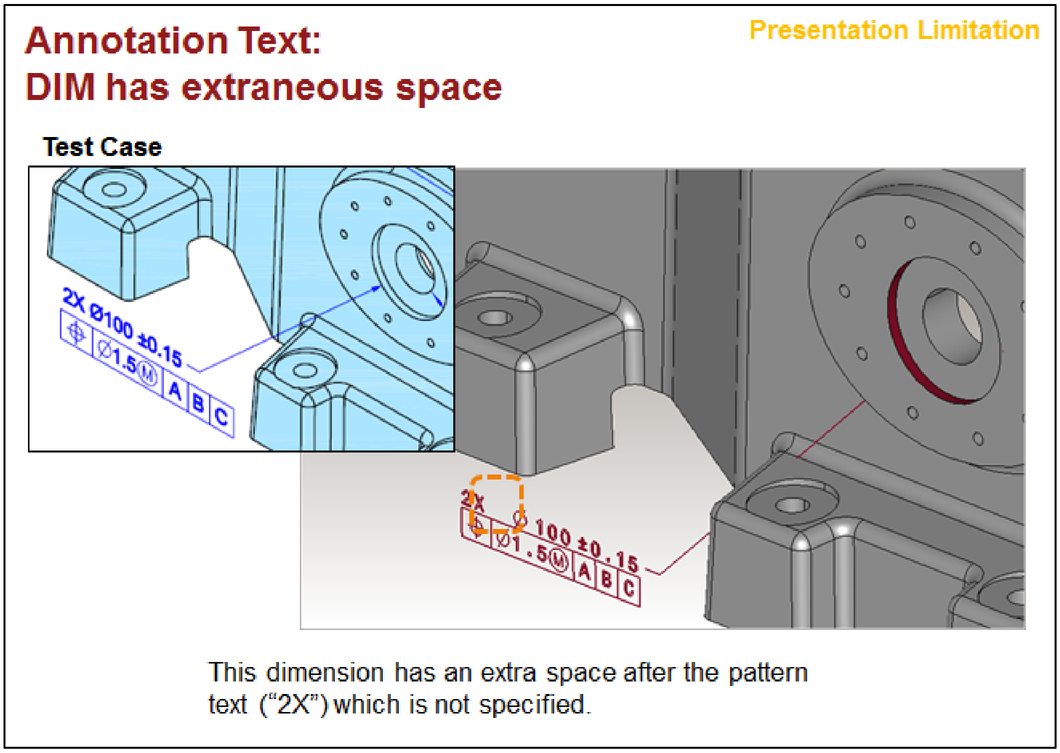

Figure 28: PMI presentation limitation: dimension has extraneous space [4]

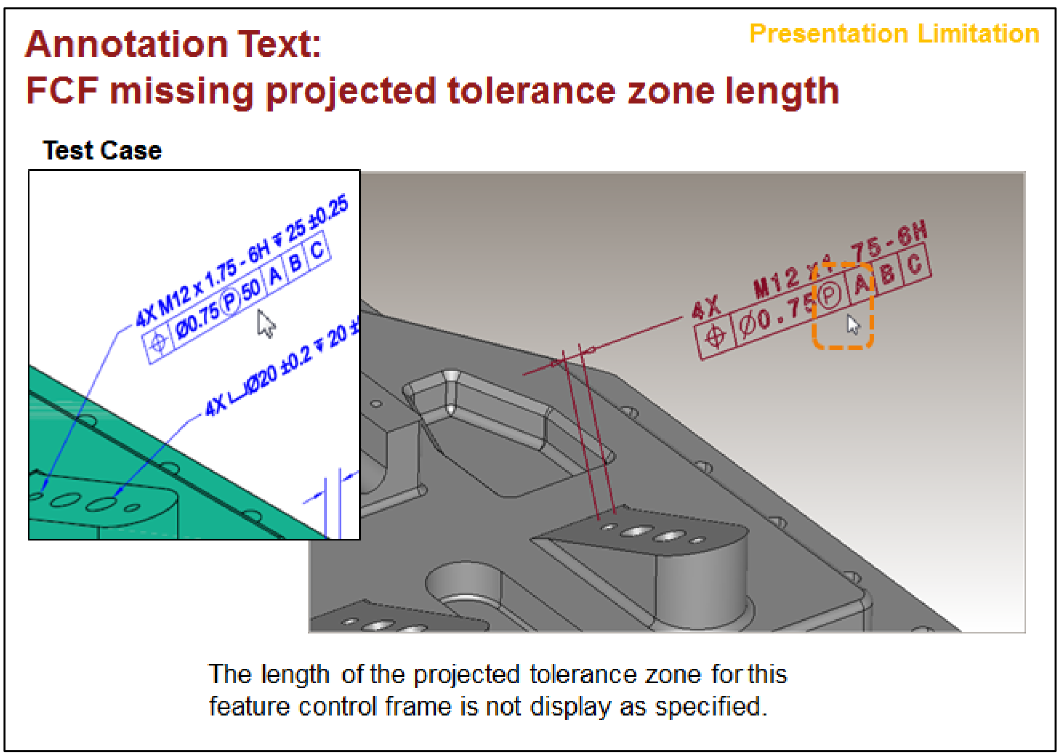

Figure 29: PMI presentation limitation: feature control frame missing projected tolerance zone length [4]

3.2 Verification Percentages by Characteristic and CAD System

Table 11 and Table 12 present the "verification percentage" for each characteristic of PMI representation and presentation limitation in the CTC. Table 13 and Table 14 show the verification percentages for the FTC. The verification percentage is the percent of PMI annotations (element count) that have no limitations for a particular annotation, coordinate system, supplemental geometry, or saved view characteristic. An individual PMI annotation might have multiple representation and presentation limitations. In general, the CAD systems performed well; however, any type of limitation might have significant consequences for the downstream human or automated consumption of that information.

Table 11: CTC PMI representation limitations by characteristic and CAD system [4]

Representation Limitations	**Element Count**	**CAD A**	**CAD B**	**CAD C**	**CAD D**
Annotation structure	127	98%	94%	98%	95%
Annotation parameters	127	96%	99%	98%	98%
Annotation geometry	127	100%	96%	98%	92%
Coordinate system structure	12	**0%**	**0%**	**0%**	**0%**
Coordinate system parameters	12	100%	100%	100%	100%
Supplemental geometry structure	6	100%	100%	100%	100%
Supplemental geometry parameters	6	100%	100%	100%	100%

Table 12: CTC PMI presentation limitations by characteristic and CAD system [4]

Presentation Limitations	**Element Count**	**CAD A**	**CAD B**	**CAD C**	**CAD D**
Annotation visibility	127	100%	99%	96%	99%
Annotation color	127	100%	100%	100%	100%
Annotation name	127	100%	100%	100%	100%
Annotation layout	127	98%	96%	93%	98%
Annotation location	127	99%	100%	94%	98%
Annotation orientation	127	100%	100%	98%	99%
Annotation lines	127	100%	97%	96%	99%
Annotation text	127	98%	**89%**	100%	96%
Coordinate system visibility	12	100%	100%	100%	**67%**
Coordinate system color	12	100%	100%	100%	100%
Coordinate system name	12	100%	100%	**83%**	100%
Coordinate system text	12	100%	100%	100%	**67%**
Supplemental geometry visibility	6	100%	100%	100%	**0%**
Supplemental geometry color	6	100%	100%	100%	100%
Saved view structure	8	100%	100%	100%	**0%**
Saved view name	8	100%	100%	100%	100%
Saved view frustum	8	100%	100%	100%	**0%**

Table 13: FTC PMI representation limitations by characteristic and CAD system [6]

Representation Limitations	Element Count	CAD A	CAD B	CAD C	CAD D
Annotation structure	182	97%	**89%**	97%	99%
Annotation parameters	182	96%	92%	95%	91%
Annotation geometry	182	97%	95%	100%	**86%**
Coordinate system parameters	33	100%	100%	100%	100%
Supplemental geometry structure	16	100%	100%	100%	100%
Supplemental geometry parameters	16	100%	100%	100%	100%

Table 14: FTC PMI presentation limitations by characteristic and CAD system [6]

Presentation Limitations	Element Count	CAD A	CAD B	CAD C	CAD D
Annotation visibility	182	100%	100%	100%	98%
Annotation color	182	100%	100%	100%	100%
Annotation name	182	100%	100%	100%	100%
Annotation layout	182	96%	91%	96%	94%
Annotation location	182	100%	99%	92%	98%
Annotation orientation	182	99%	98%	99%	99%
Annotation lines	182	99%	97%	98%	97%
Annotation text	182	96%	91%	99%	92%
Coordinate system visibility	33	100%	100%	100%	**42%**
Coordinate system color	33	100%	100%	100%	100%
Coordinate system name	33	100%	100%	100%	100%
Coordinate system text	33	100%	100%	100%	100%
Supplemental geometry visibility	16	100%	100%	100%	**0%**
Supplemental geometry color	16	100%	100%	100%	100%
Saved view structure	11	100%	100%	100%	**0%**
Saved view name	11	100%	100%	100%	100%
Saved view frustum	11	100%	100%	100%	**0%**

4 Analysis of Verification Testing Results

The analysis of the verification testing results aims to supplement the original analysis and provide a deeper dive into the cause of some of the errors. The original analysis did not break down the errors by annotation type (dimension, geometric tolerance, datum feature, datum target) or by test case (CTC, FTC).

The new analysis considers the verification testing results as a scientific experiment where observations are made about the PMI annotations and whether they pass or fail various criteria. Only the PMI representation and presentation limitation characteristics for annotations (Table 6, Table 7) are used for the new analysis. The limitations for coordinate systems, supplemental geometry, and saved views are ignored. Limiting the new analysis to only the annotation characteristics yields nine types of error characteristics that can be observed for each PMI annotation. The nine error types are divided between three types of semantic annotation errors (structure, parameters, geometry) and six types of graphic annotation errors (visibility, layout, location, orientation, lines, text).

An individual PMI annotation is observed 36 times (9x4) for annotation limitations, once for each of nine error types in four CAD systems in which it was modeled. Given that there are 297 individual PMI annotations in the five CTC and three FTC (6, 8, 9) that were tested, and that they are observed 36 times for annotation limitations, then there are 10,692 total observations (297x36) of the PMI annotations.

4.1 PMI Errors for All Test Cases and CAD Systems

The Keshif web-based data exploration visualization environment was used to produce the following figures. The results can be reproduced with the online version: https://pages.nist.gov/CAD-PMI-Testing/results.html The online Keshif browser only shows the "Fail Responses" as described below.

Figure 30 is different from the previous Keshif figures in that it includes information related to the verification testing results: CAD System (upper left), PMI Error (center), Response (top right), and Error Type (middle right).

- The four CAD Systems A, B, C, and D are differentiated by the version of CAD system, 2012 or 2015 as described in Section 2.1.
- The Error Types are the nine annotation characteristics for PMI representation and presentation in Table 6 and Table 7 respectively. The other characteristics are not considered.
- The PMI Errors are all of the errors for all test cases (CTC and FTC) and CAD systems are the errors found in Table 8 and Table 10.
- The Response, Pass or Fail, is the observation of a PMI Annotation for an Error Type. The PMI Error information is relevant when the Response is Fail. The online version does not include the Pass Response.

In total, there are 10,692 observations (Keshif incorrectly reports 10693 at the top of Figure 30) from 297 individual PMI annotations in the five CTC and three FTC as described above. There are 411 Fail Responses out of 10692 observations yielding a Pass rate for all observations of approximately 96%.

An example of a PMI annotation with 36 observations can be seen highlighted in the last row of the Annotation Type (bottom left of Figure 30) for the straightness tolerance. There is only one straightness tolerance in all of the test cases (see Figure 12); therefore, there are only 36 observations of that straightness tolerance (4 CAD Systems, 9 possible Error Types).

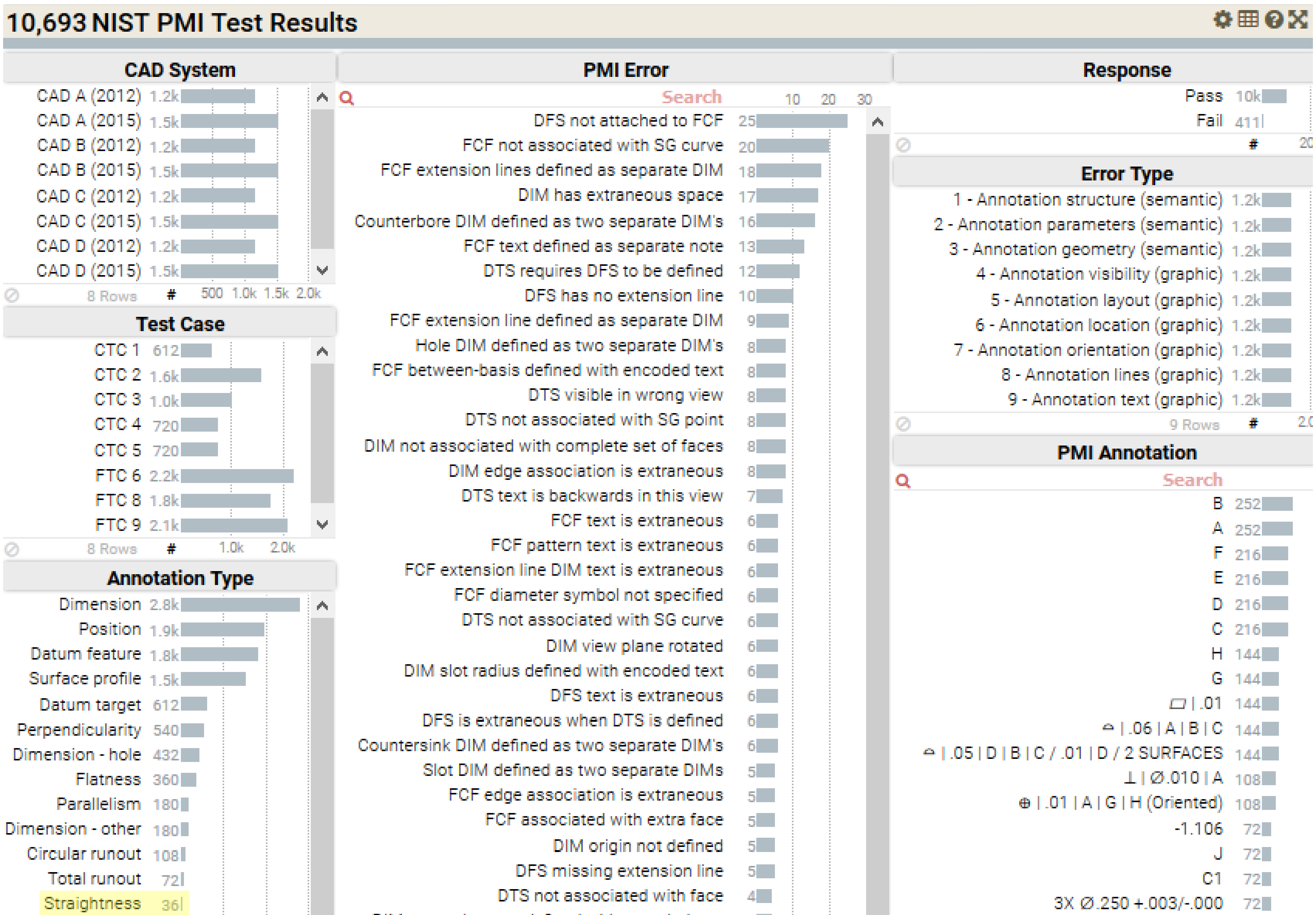

Figure 30: All PMI error observations

By selecting the Fail Response highlighted in Figure 31, the distribution of the 411 total errors is shown per CAD System, Test Case, Annotation Type, Error Type, and PMI Annotation. The following sections will explore some observations about the errors:

- In general, there are more errors for the 2015 versions of the CAD systems because they were used to model the FTC which have more PMI annotations than the CTC that were modeled in the 2012 versions of the CAD systems (see Figure 12).
- CAD C (2012) and CAD C (2015) have almost the same number of errors, 49 and 51, respectively. This might be caused by the 2012 version having more errors than expected relative to the other 2012 CAD systems or the 2015 version having less errors than expected relative to the other 2015 CAD systems.
- CTC 2 and 4 have more errors than the other CTC.
- FTC 8 has fewer errors than FTC 6 and 9.
- Error Type errors are split almost equally between semantic annotation errors (204) and graphic annotation errors (207).
- The first annotation under PMI Annotations, an oriented position tolerance, has 24 errors for three instances of that tolerance (see Figure 25).
- Four "oriented" annotations (see Figure 25) appear in the top eight annotations with errors.

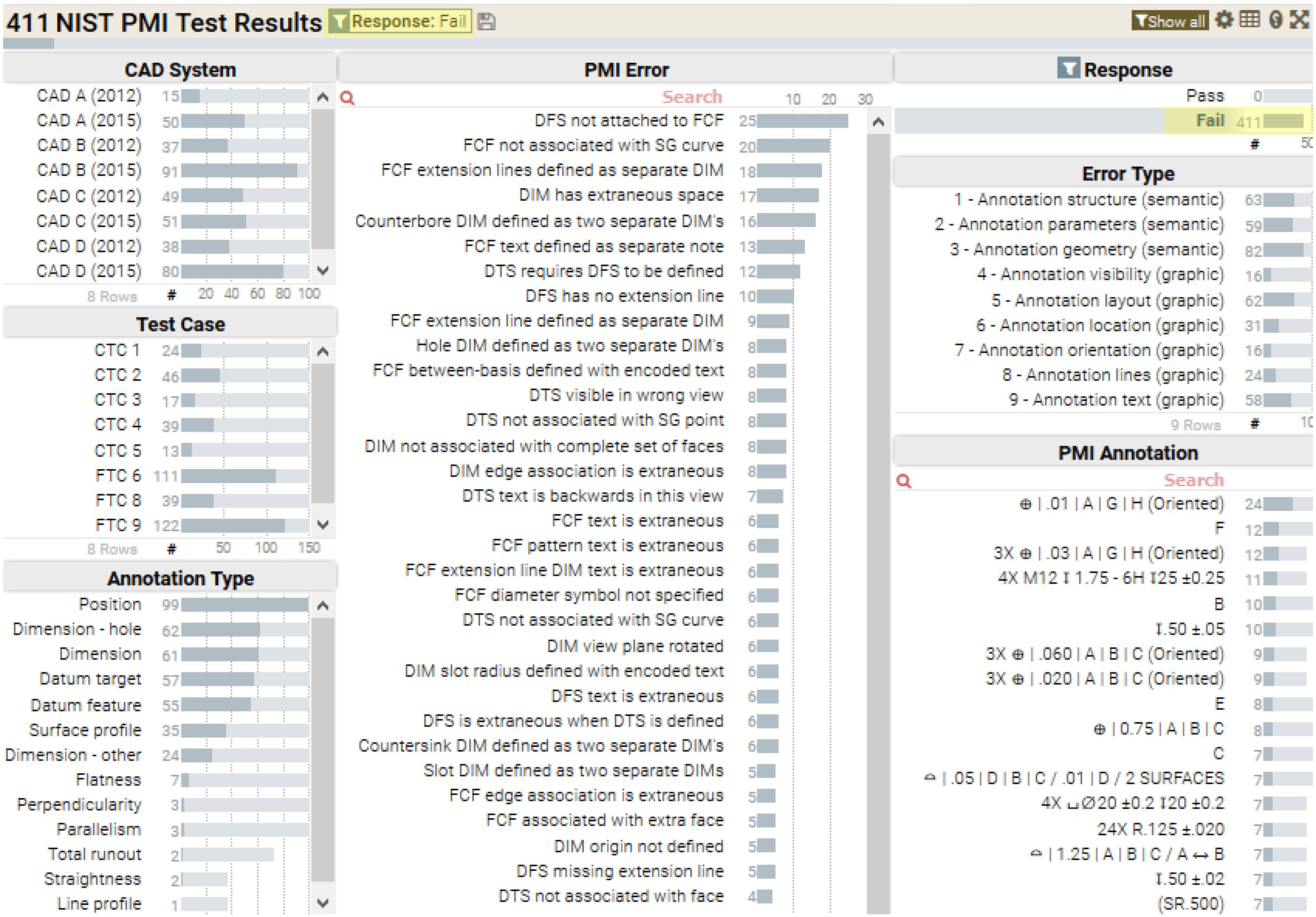

Figure 31: PMI errors for all CAD systems and test cases

4.1.1 PMI Errors for CAD System C

CAD systems A, B, and D have significantly more errors for 2015 versions than for 2012 versions. This is to be expected since the FTC modeled in the 2015 versions have more PMI annotations, therefore more potential errors. However, CAD C (2012) and CAD C (2015) have almost the same number of errors, 49 and 51, respectively.

Figure 32 shows the PMI errors for CAD C (2012). Most of the PMI errors are related to CTC 2, datum targets, datum features, and annotation graphics (Error Type). In the lower left of Figure 33, datum target is highlighted in Annotation Type. This shows that 19 of the 26 errors in CTC 2 are related to datum target and annotation graphics. CTC 2 is the only CTC with any datum targets (see Figure 15). Therefore, if a CAD system has errors with datum targets and since there are so many datum targets in CTC 2, it will skew that CAD system to seem more error prone as is the case with CAD C. This accounts for the large number of errors in CAD C (2012) relative to the other CAD (2012) systems in Figure 31.

Figure 34 shows the PMI errors for CAD C (2015). Datum features have more errors than any other annotation type. In the lower left of Figure 35, datum feature is highlighted in Annotation Type. The datum feature errors are associated with all of the FTC and annotation graphics. Nine of the eleven errors for FTC 8 are related to datum features. The datum features in the FTC do not skew the results for CAD C (2015) as do the datum targets in the CTC for CAD C (2012).

Based on this analysis, CAD C (2012) had more errors than expected relative to the other 2012 CAD systems due to the large number of datum targets in CTC 2.

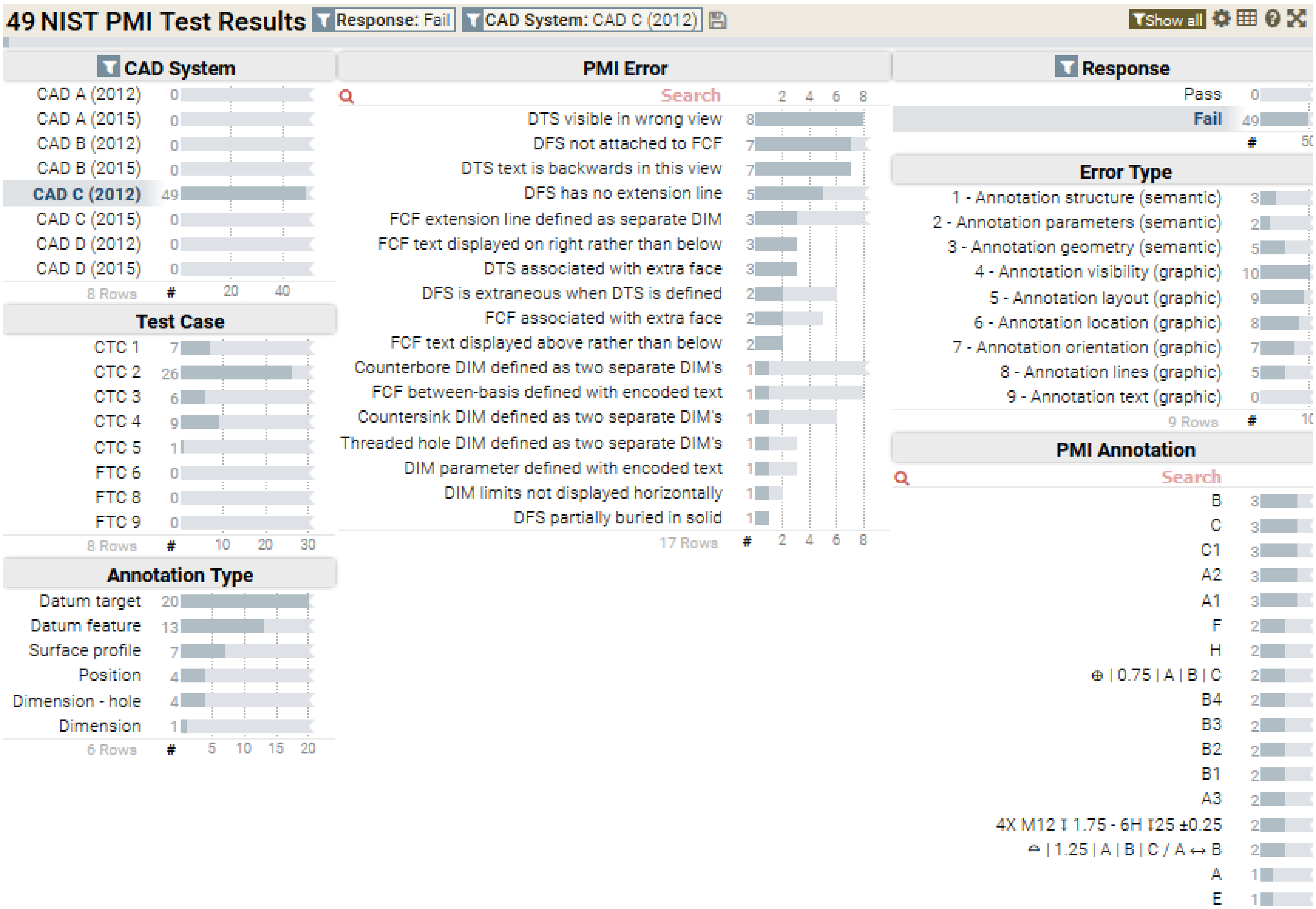

Figure 32: PMI errors for CAD system C (2012 version)

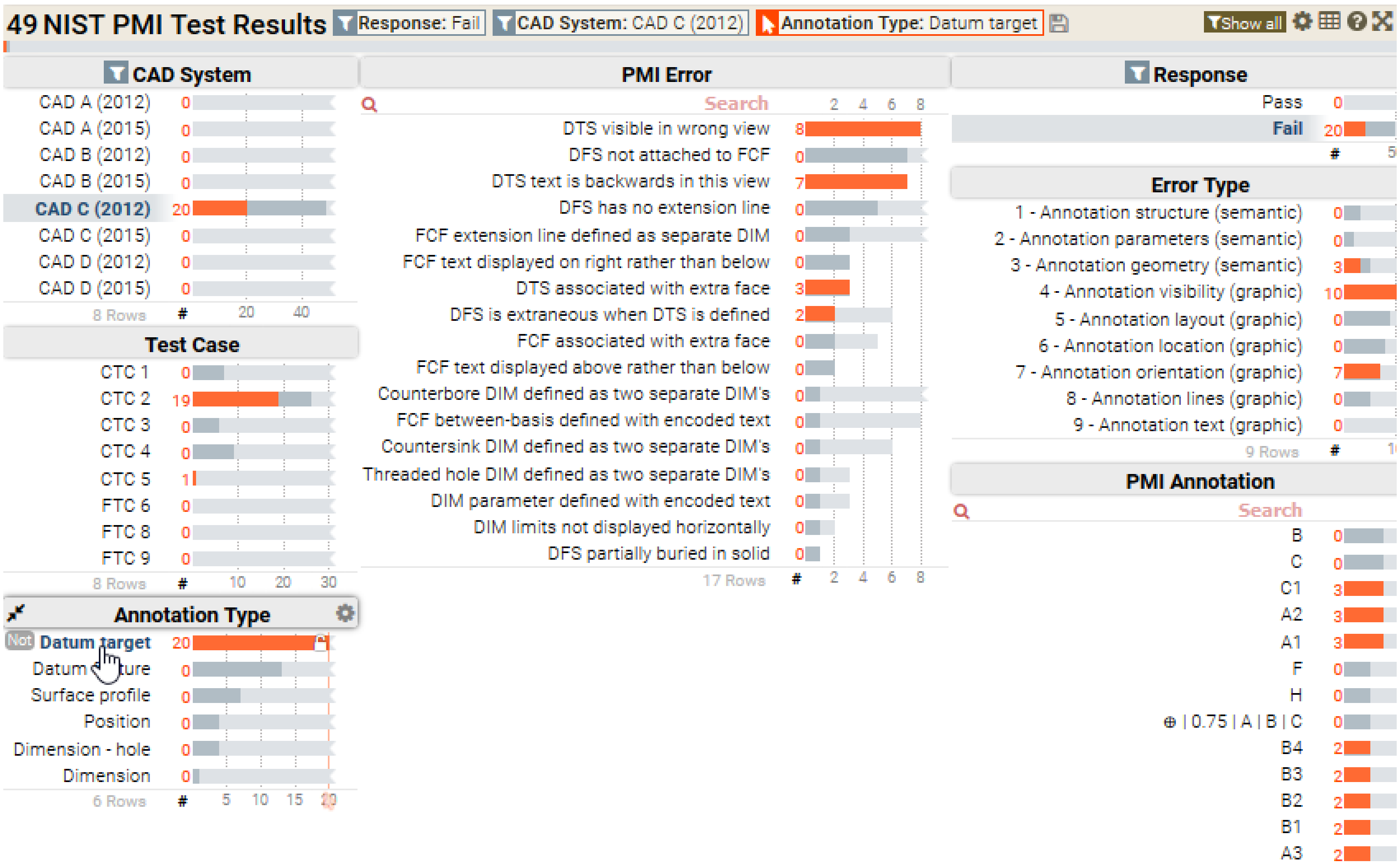

Figure 33: PMI errors for CAD system C (2012 version) related to datum target

Figure 34: PMI errors for CAD system C (2015 version)

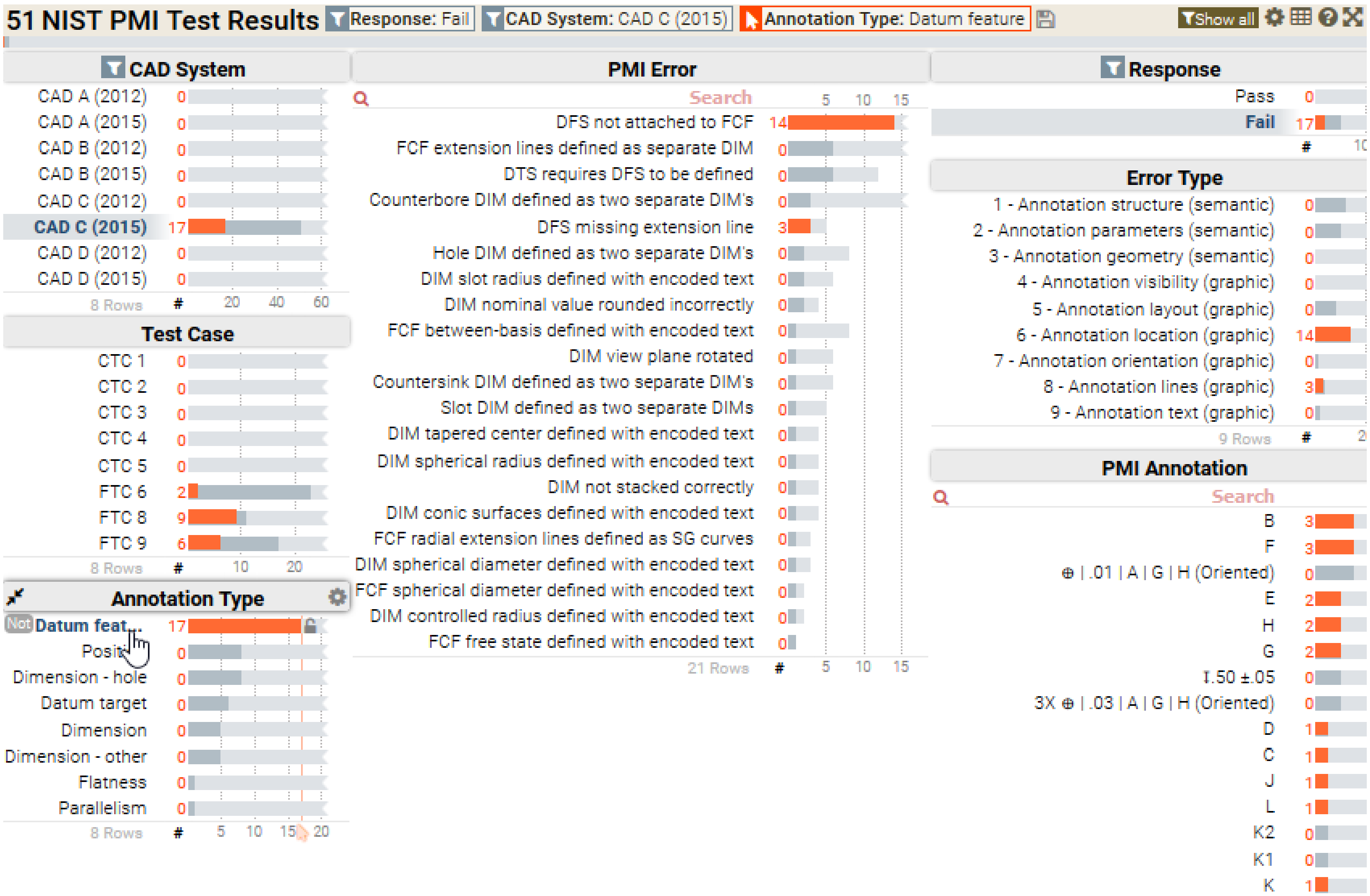

Figure 35: PMI errors for CAD system C (2015 version) related to datum feature

4.1.2 Semantic PMI Errors

Figure 36 shows all of the semantic PMI errors by selecting Annotation structure, Annotation parameters, and Annotation geometry in the Error Type section. The 2015 versions of the CAD systems have more semantic errors because the FTC have more PMI annotations, although FTC 8 has fewer semantic errors than FTC 6 and 9. Position tolerances exhibit the most semantic errors.

Figure 37 shows all semantic and graphic errors for position tolerances by selecting Position in the Annotation Type section. Semantic errors account for 75 (41 annotation structure, 10 annotation parameters, and 24 annotation geometry errors in the Error Type section) of the total of 99 errors for position tolerances.

Figure 38 shows the PMI annotations filtered by the text string “oriented” where most of the errors are semantic errors (Error Type section) with oriented position tolerances found in FTC 9 (Test Case section).

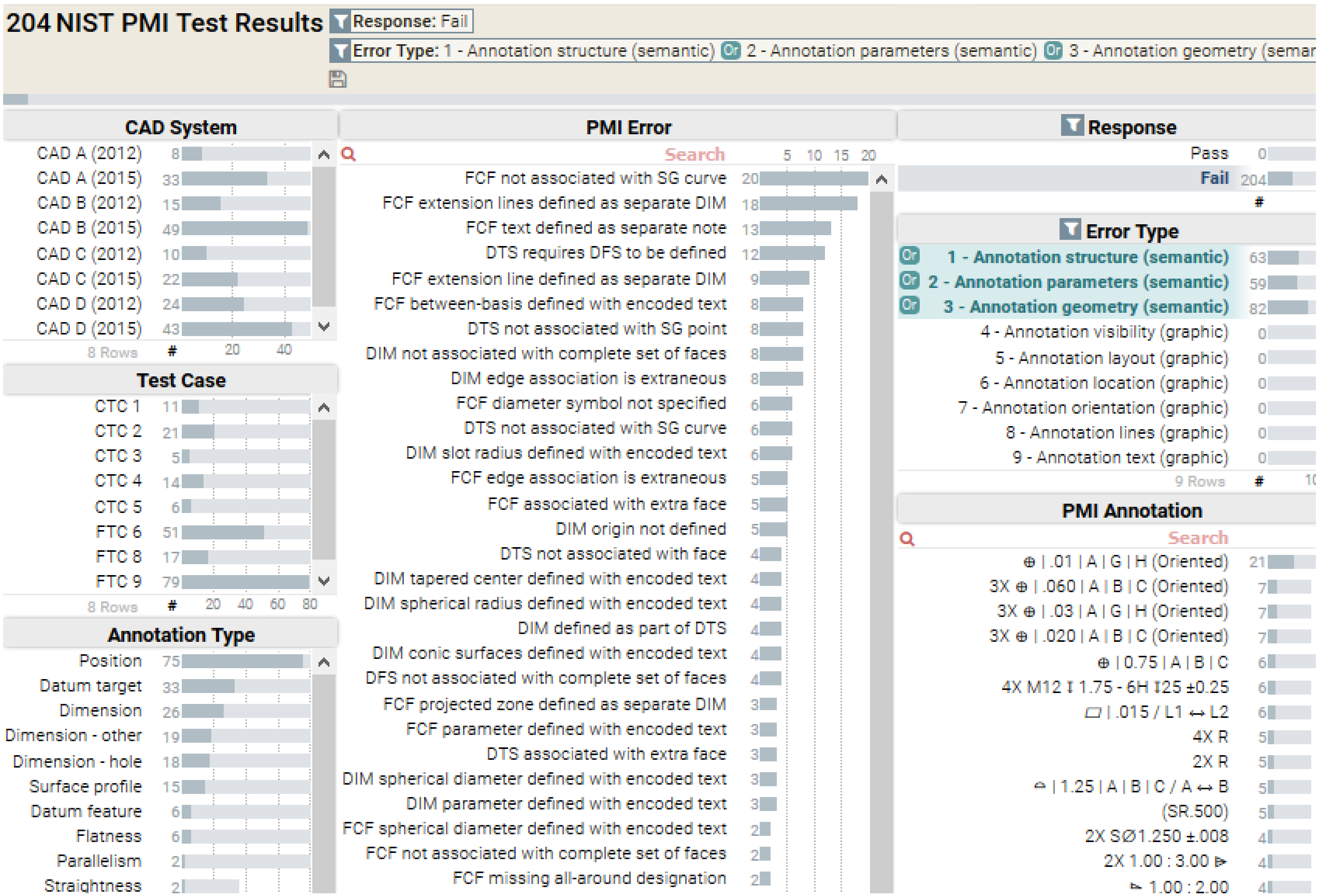

Figure 36: Semantic PMI errors for all CAD systems and test cases

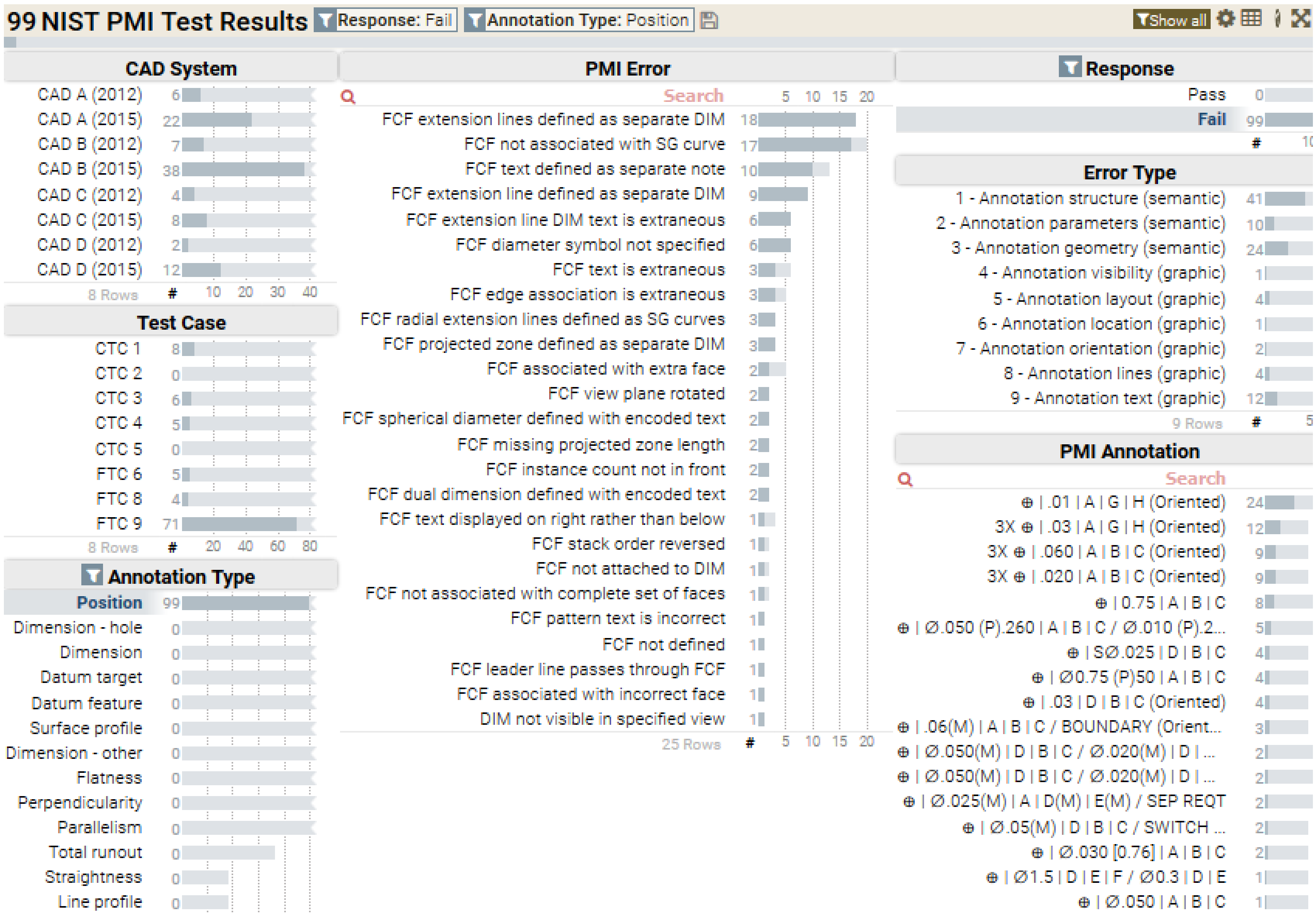

Figure 37: PMI errors for position tolerances

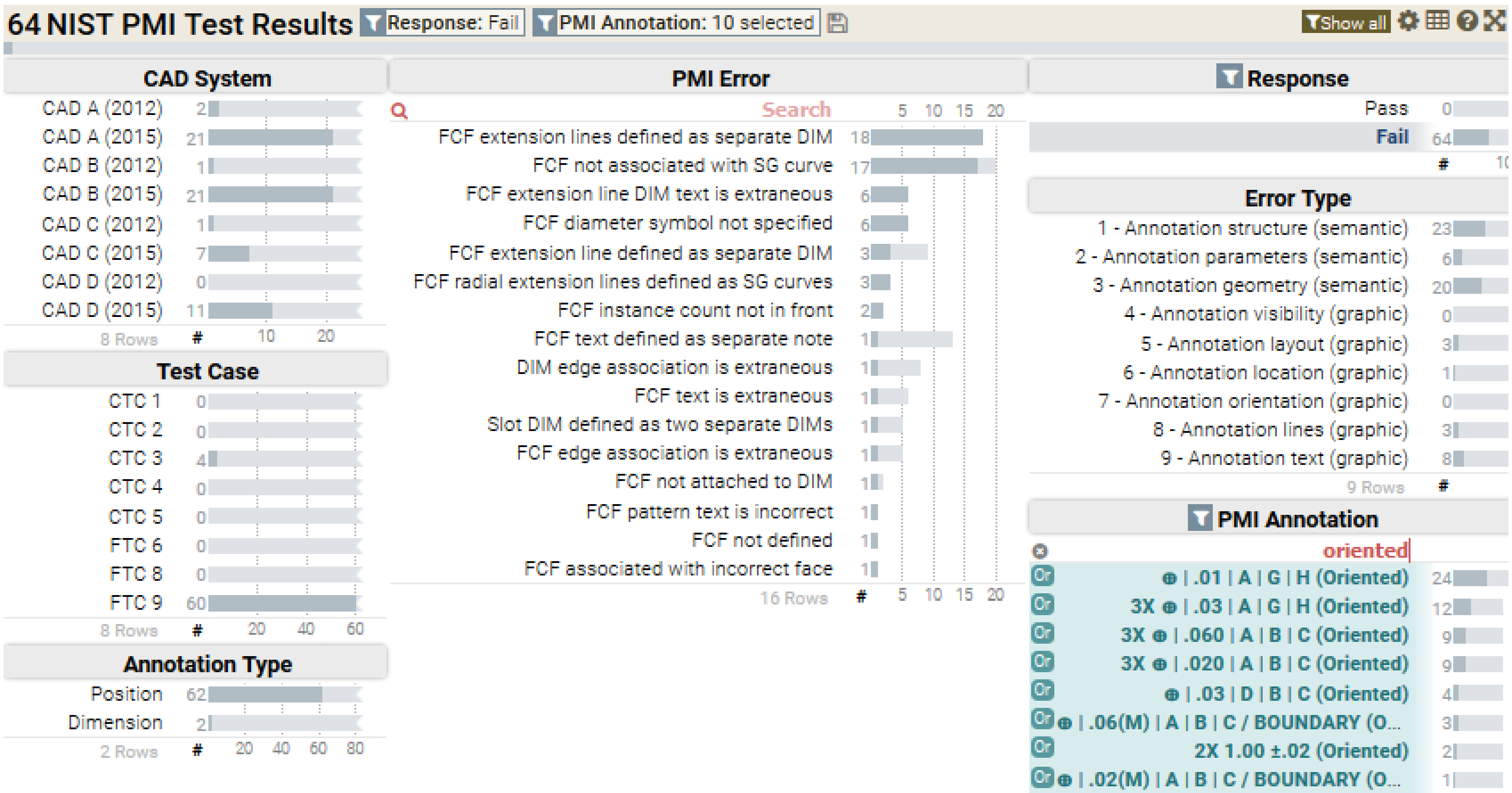

Figure 38: PMI errors for “oriented” annotations

4.1.3 Graphic PMI Errors

Figure 39 shows all of the graphic PMI errors. The 2015 versions of the CAD systems have more errors than the 2012 versions except for CAD C as discussed in Section 4.1.1. The second most common graphic PMI error is "dimension has extraneous space" shown in Figure 28.

Figure 40 shows that this type of error is most common in both the 2012 and 2015 versions of CAD B. However, as discussed in Section 3.1, an extra space in an annotation would not affect its readability or interpretation.

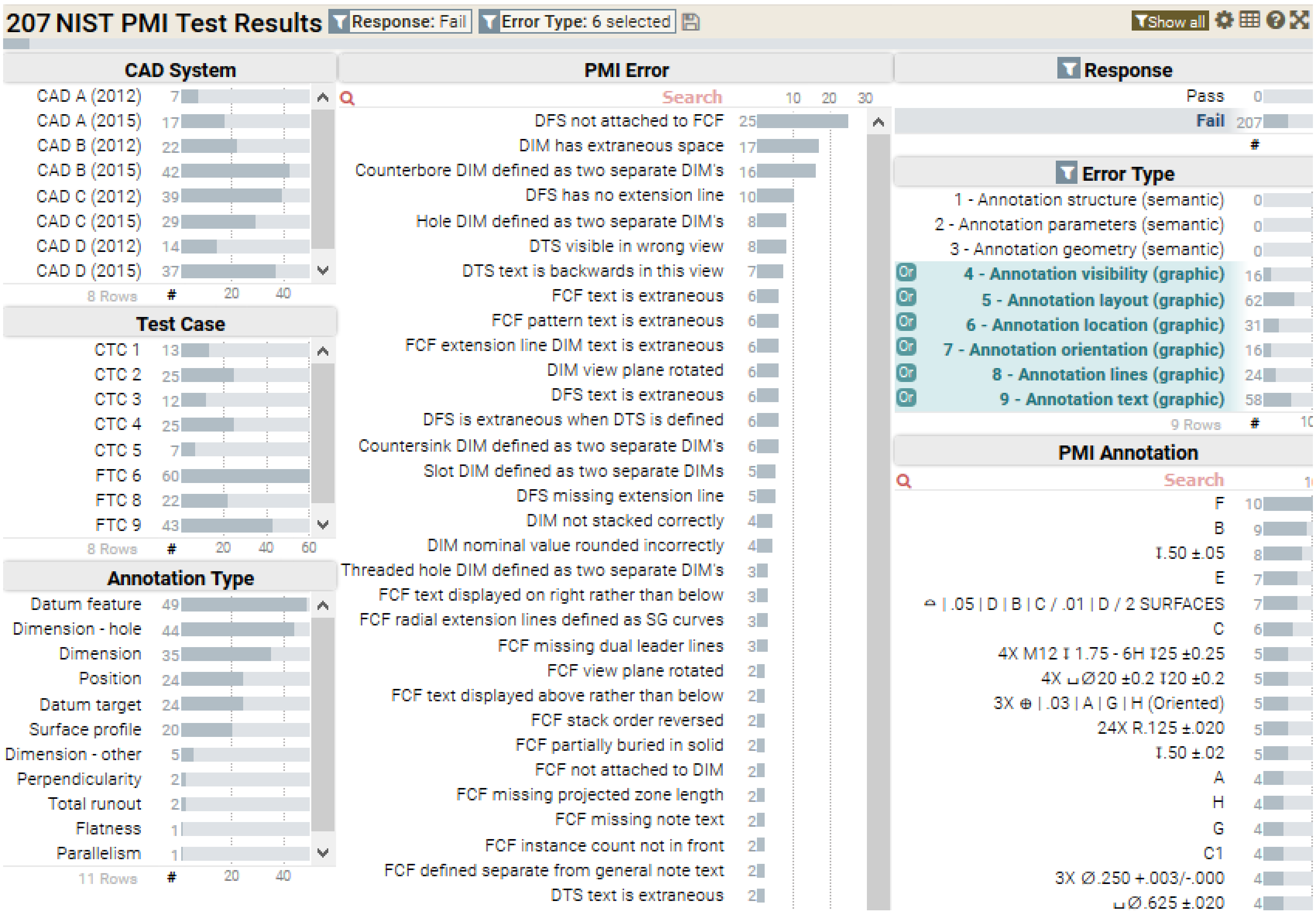

Figure 39: Graphic PMI errors for all CAD systems and test cases

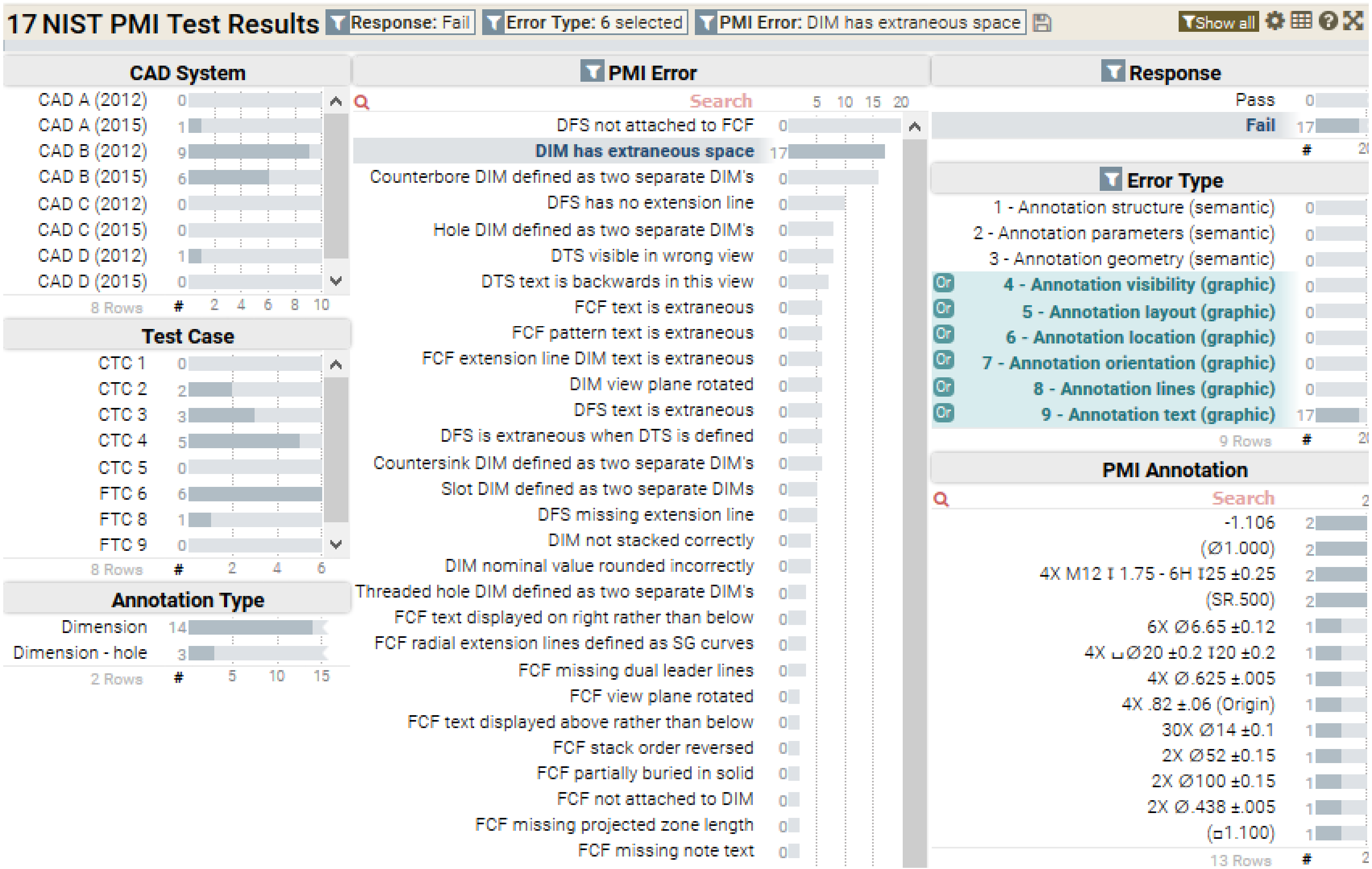

Figure 40: PMI errors for dimension has an extraneous space

4.1.4 PMI Errors by Test Case

Figure 41 through Figure 48 shows the distributions of errors for each test case. The following observations are made about PMI errors in the test cases:

- CAD C (2012) has the most errors with datum targets in CTC 2 (Figure 42, see Section 4.1.1).
- CAD B and C (2012) have the most errors for CTC 3 (Figure 43).
- Dimensions related to holes (depth, counterbore, countersink, hole thread) have the most errors for CTC 4 (Figure 44).
- CAD D (2012) has the most errors for CTC 5 (Figure 45).
- CAD A, B, and C (2012) have no errors or one error for CTC 5 (Figure 45).
- Hole dimensions, dimensions, and datum targets have the most errors for FTC 6 (Figure 46).
- CAD A (2015) has only one error for FTC 8 (Figure 47).
- Datum features have the most errors for FTC 8 (Figure 47).
- Oriented positions tolerances have the most errors for FTC 9 (Figure 48).

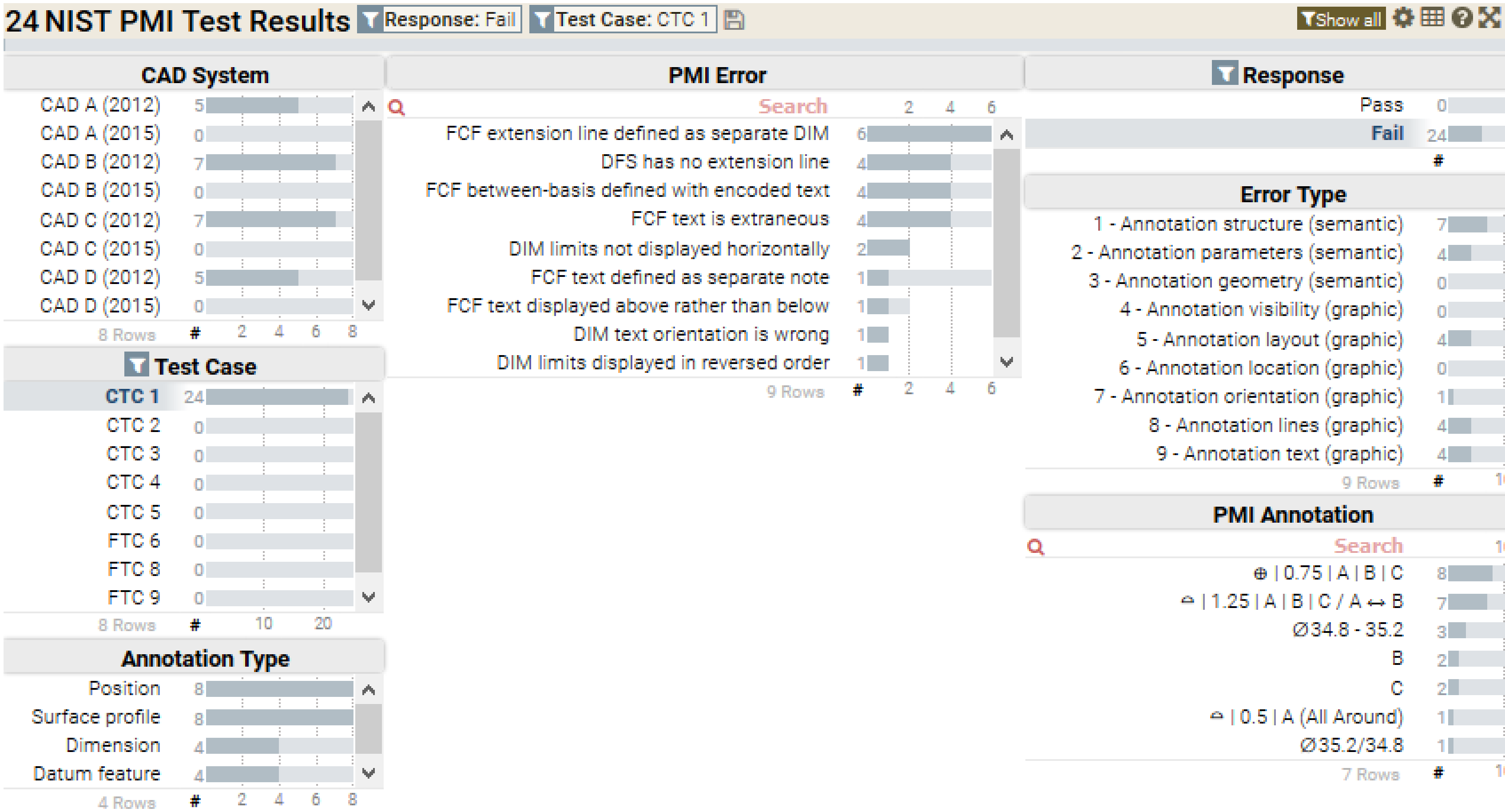

Figure 41: PMI errors for CTC 1

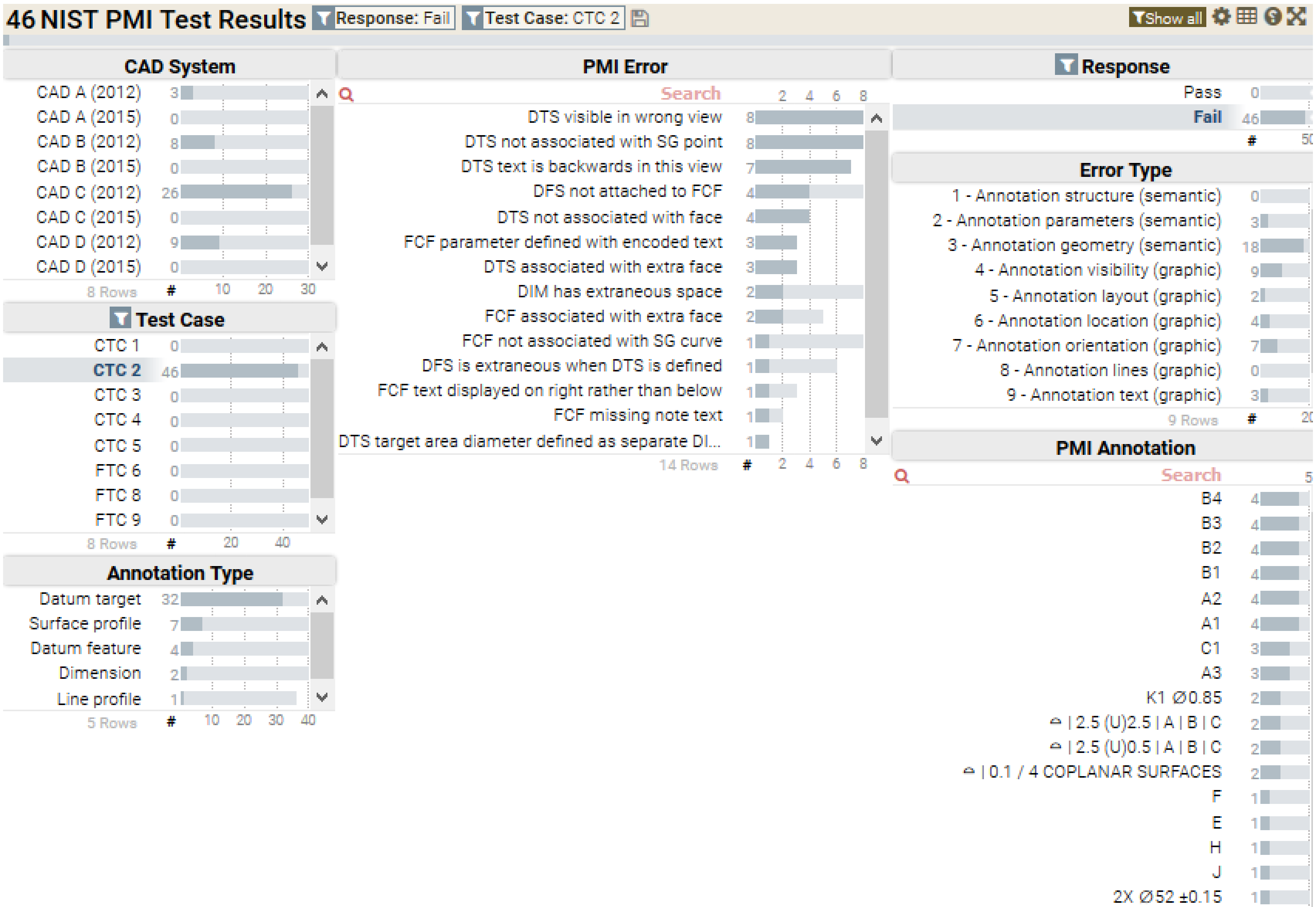

Figure 42: PMI errors for CTC 2

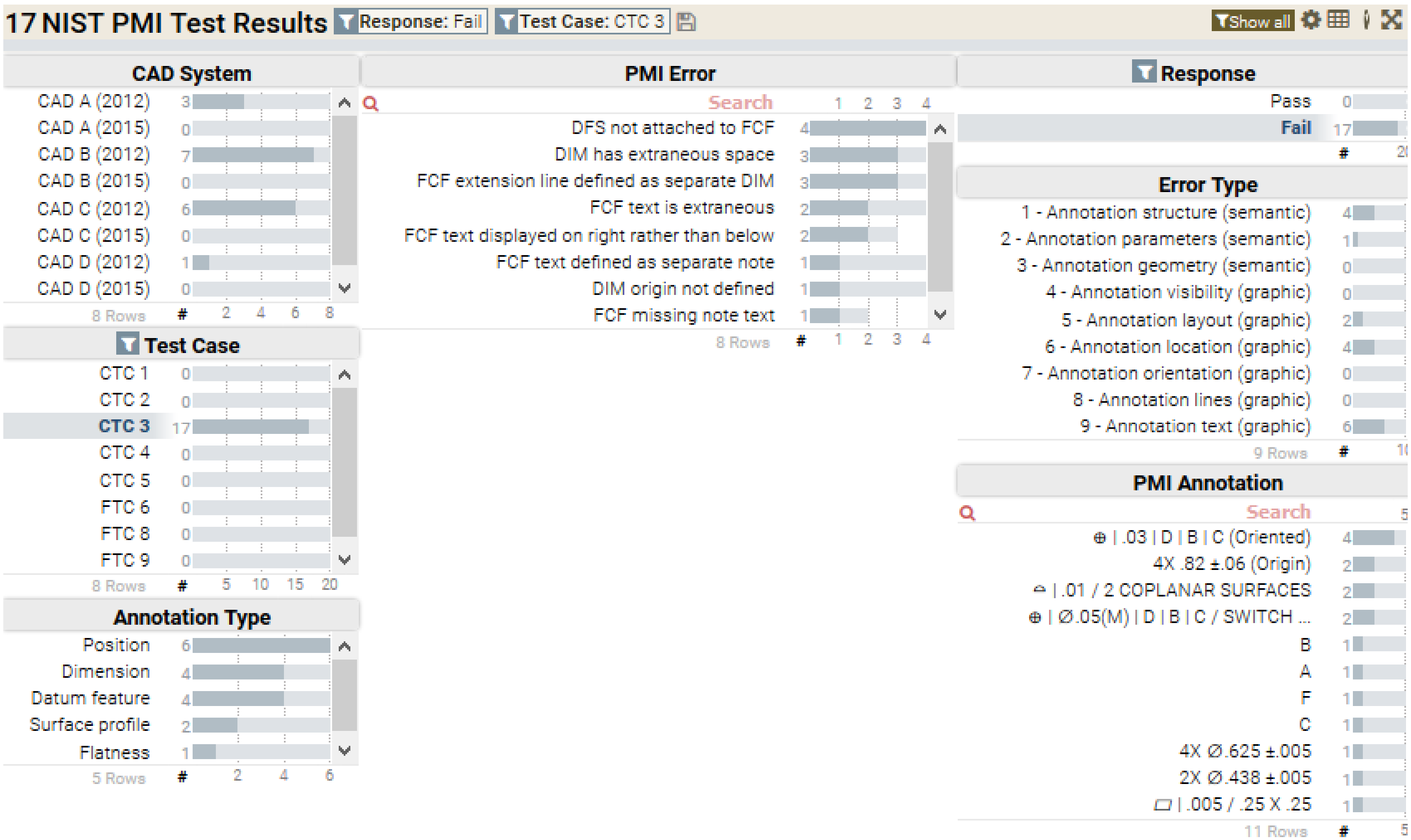

Figure 43: PMI errors for CTC 3

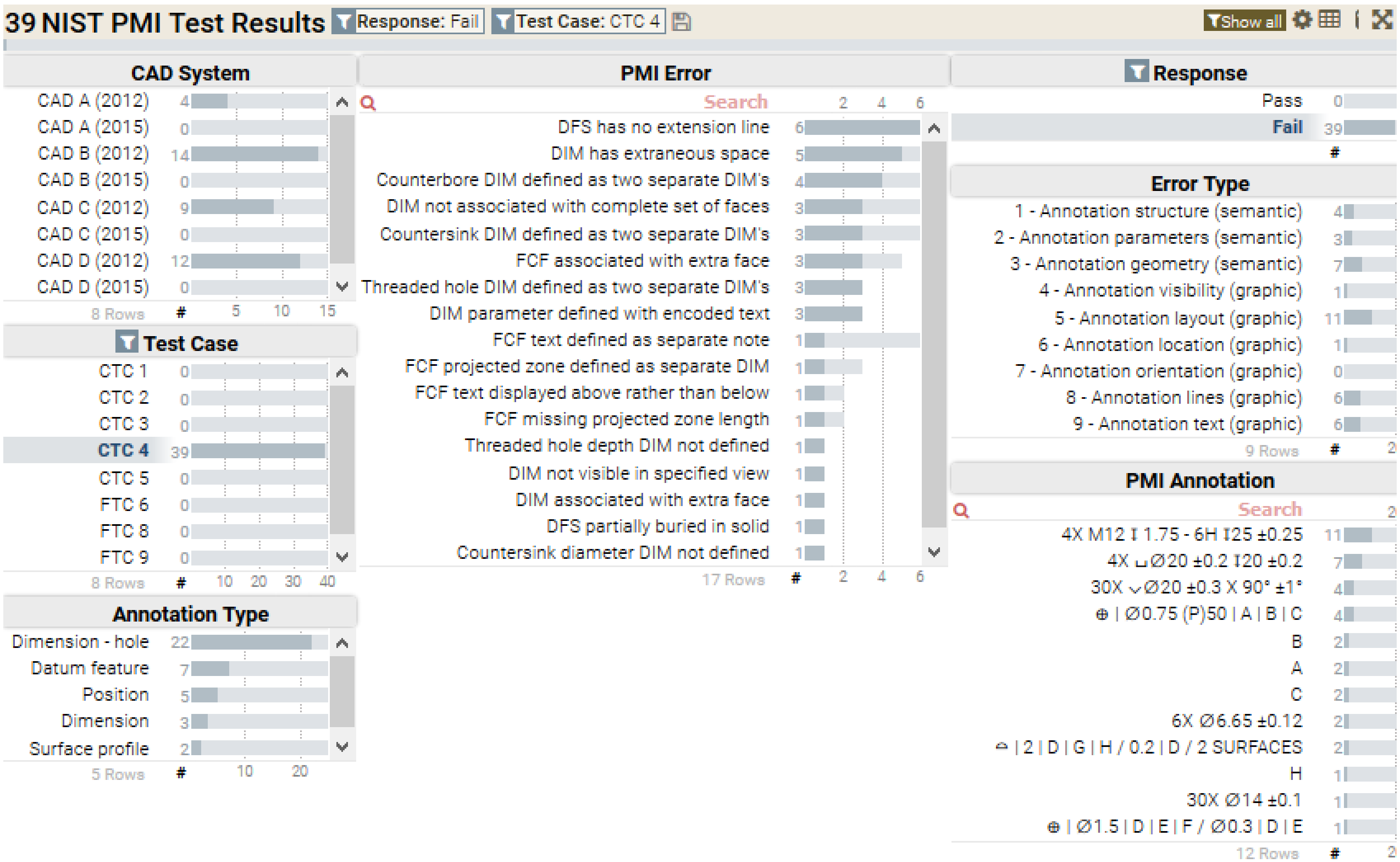

Figure 44: PMI errors for CTC 4

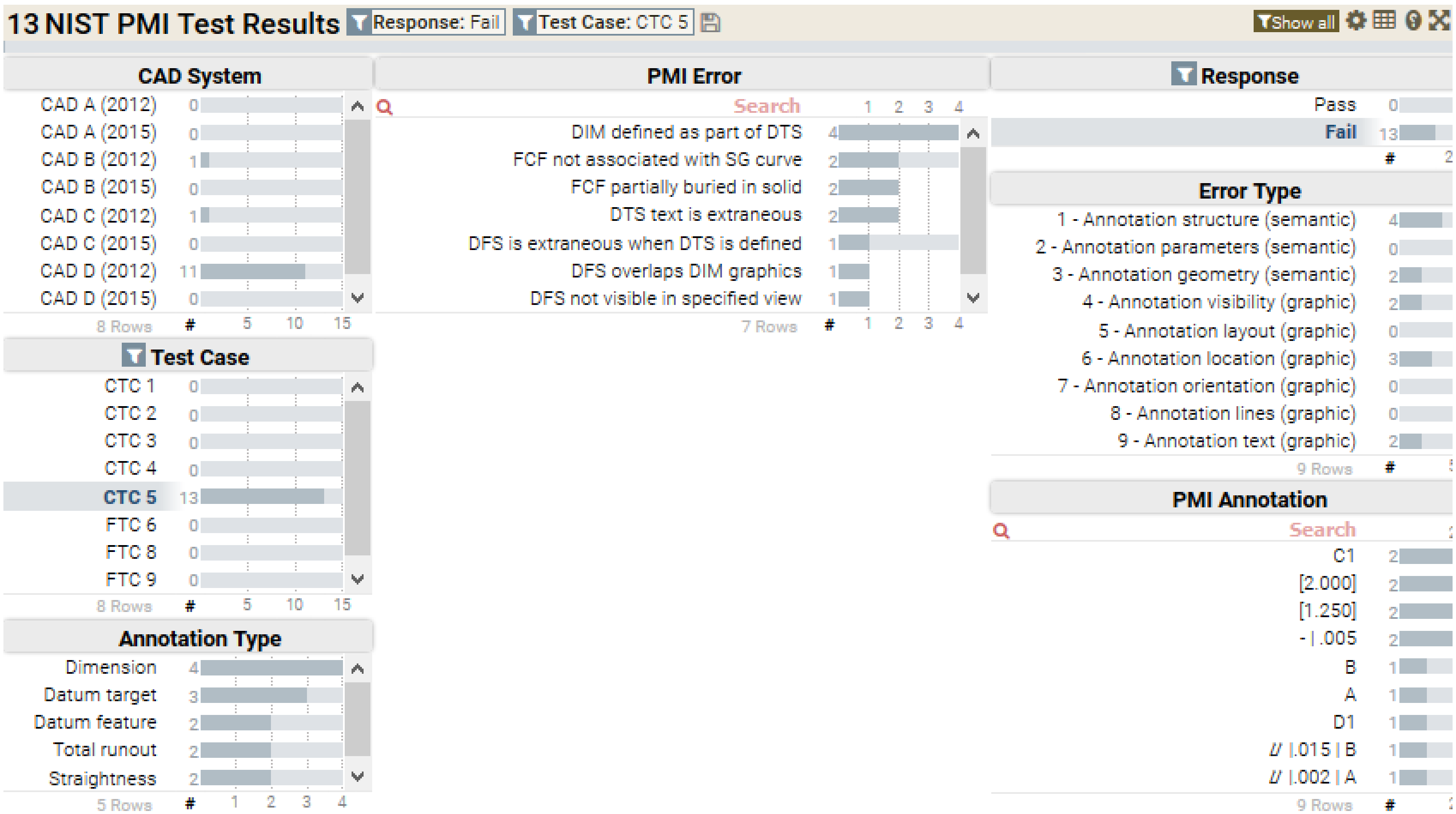

Figure 45: PMI errors for CTC 5

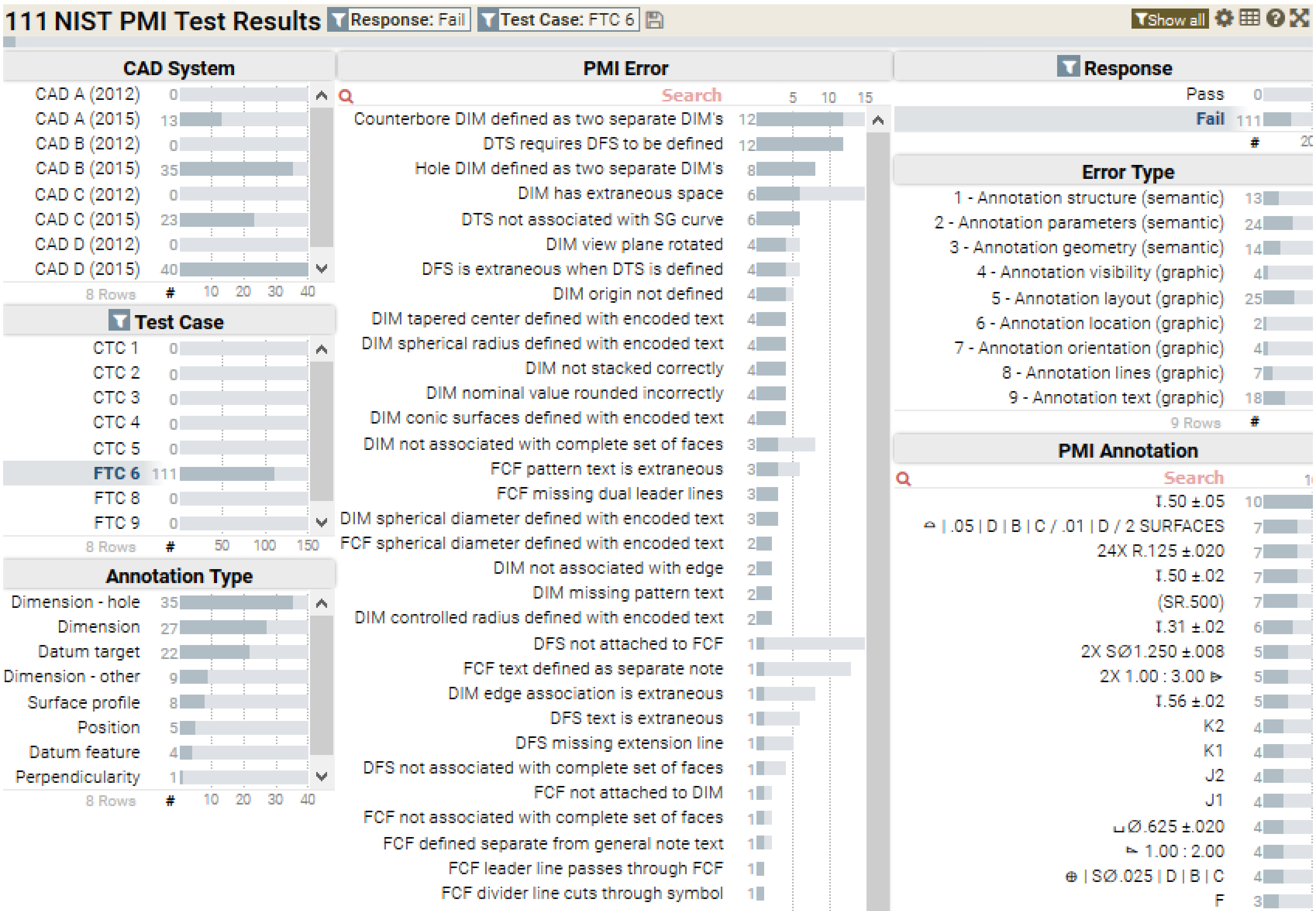

Figure 46: PMI errors for FTC 6

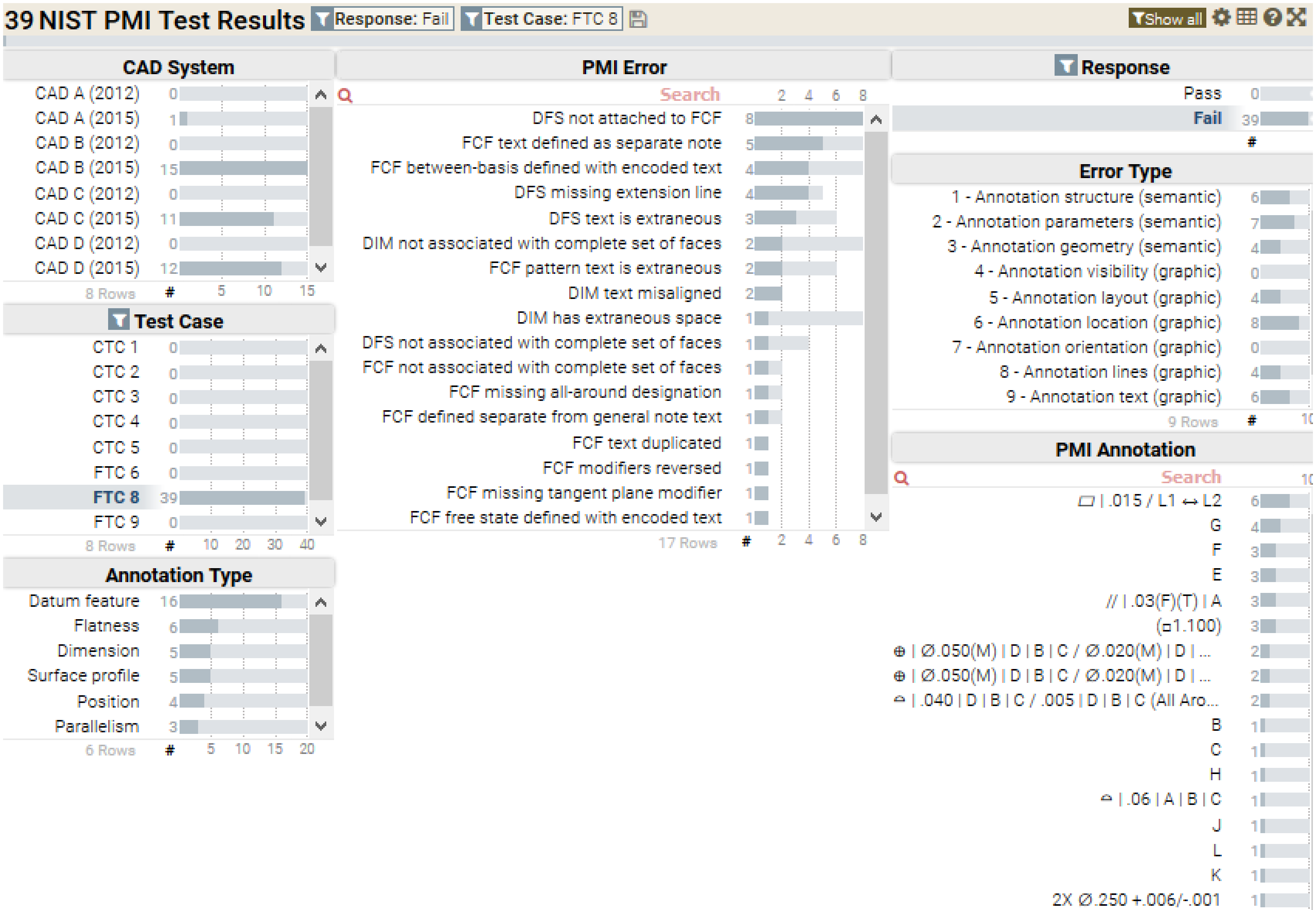

Figure 47: PMI errors for FTC 8

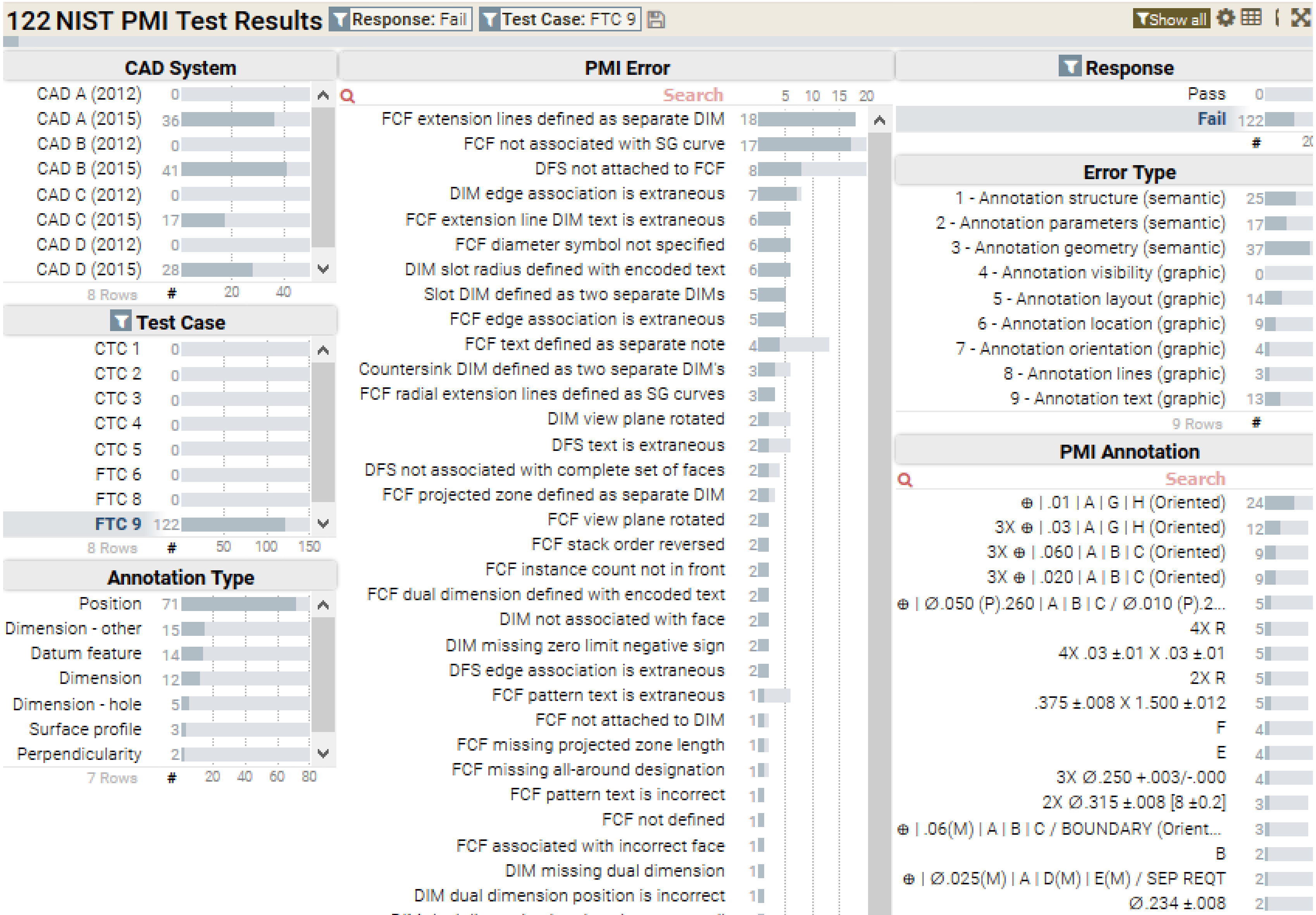

Figure 48: PMI errors for FTC 9

4.1.5 PMI Errors by Annotation Type

The following three figures are a small sampling of PMI errors by annotation type. Figure 49 shows the distributions of errors for hole (depth, counterbore, countersink, hole thread) and other (slope, conical taper, radius) dimensions found in CTC 4 and FTC 6 and 9. The most common error type is graphic layout.

Figure 50 shows the distributions of errors for datum targets and datum features. Both versions of CAD A have few problems with those types of annotations.

Figure 51 shows the distributions of errors for projected tolerance zones found mostly in both versions of CAD B.

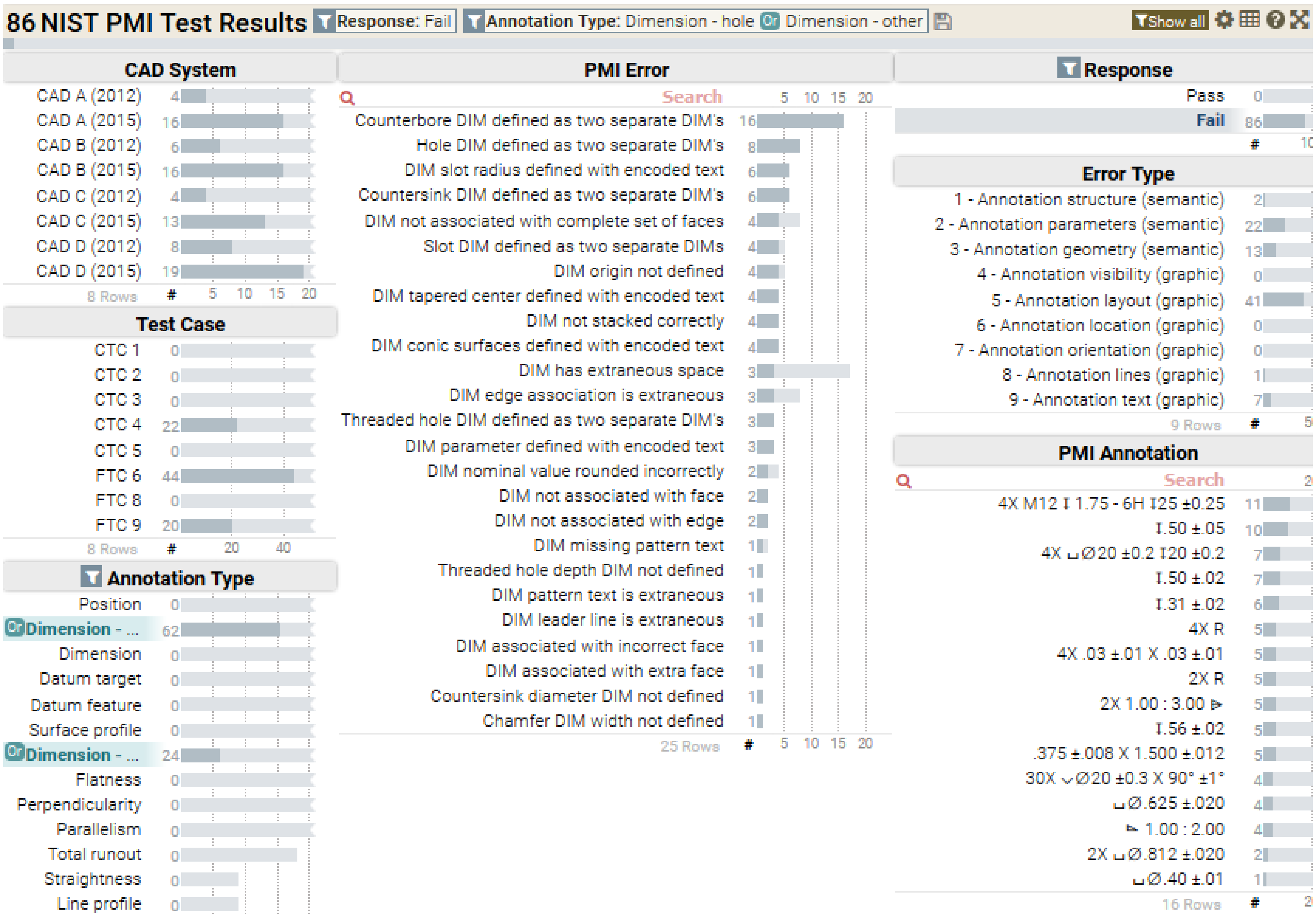

Figure 49: PMI errors for hole and other dimensions

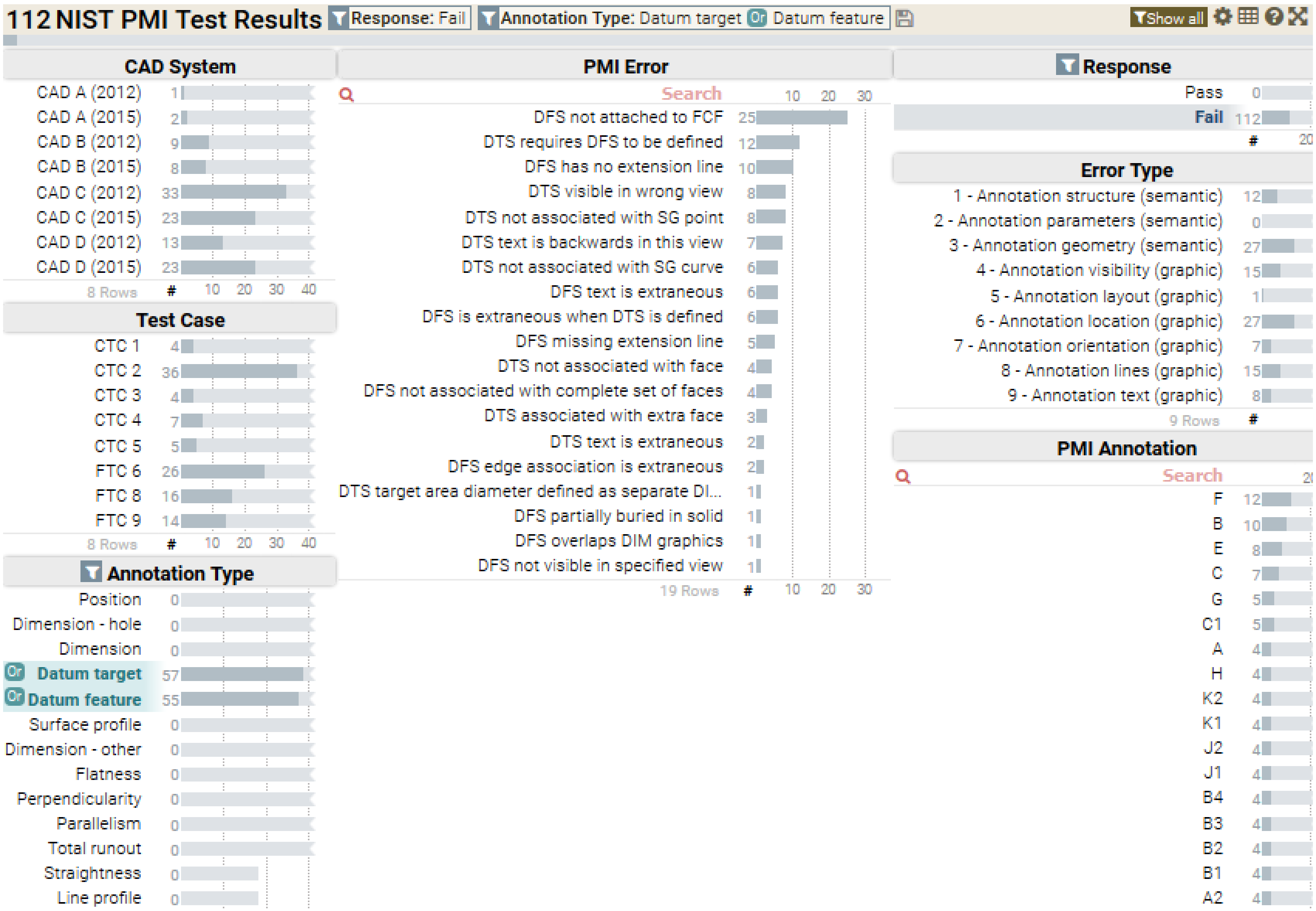

Figure 50: PMI errors for datum target and datum feature

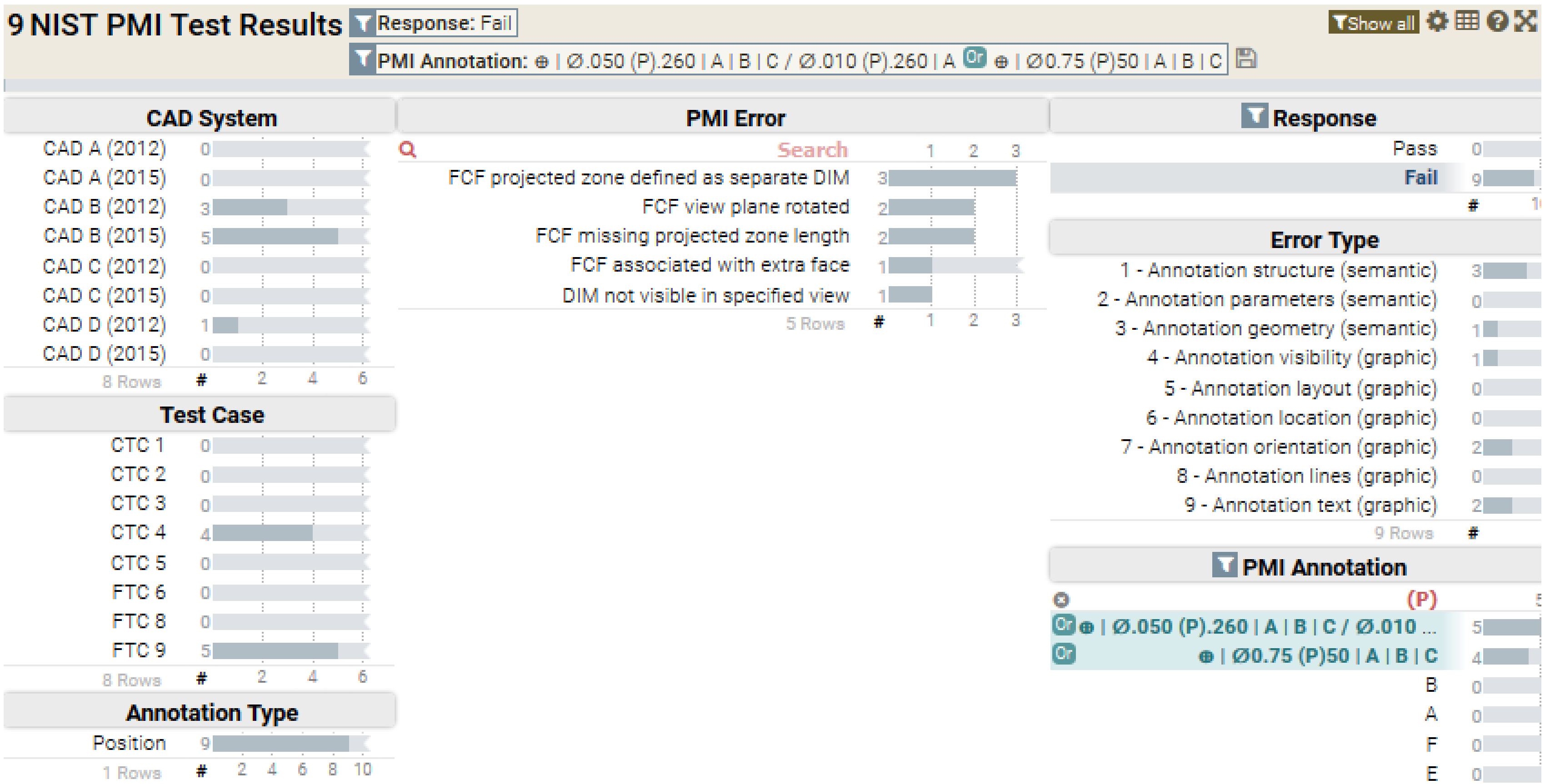

Figure 51: PMI errors for projected tolerance zone

5 Exploratory Data Analysis

An exploratory data analysis (EDA) of the verification testing results provides a different way to look at the testing results and gain additional insights. An exploratory data analysis [10] is an approach for data analysis that uses a variety of mostly graphical techniques to

1. maximize insight into a data set;
2. uncover underlying structure;
3. determine important parameters and interactions;
4. detect outliers and anomalies;
5. test underlying assumptions;
6. develop simple but effective predictive models; and
7. determine optimal parameter settings.

Dataplot was used for the exploratory data analysis. Dataplot is a free, public-domain software system for statistical analysis developed by the Statistical Engineering Division at NIST [11, 12].

The EDA uses the same verification testing results as the Keshif analysis in Section 4.1, which considers that each PMI annotation has 36 observations for errors (nine error categories in each of four CAD systems.) The primary statistical graphical technique used for this EDA is a block plot [10]. A block plot is "an EDA tool for assessing whether the factor of interest is statistically significant (yes/no) and whether that conclusion about the primary factor is robustly valid over all other factor settings in the experiment" [10]. A conclusion about a factor's significance which is valid over a broad set of all other factors is stronger and more desirable than one which is valid only over a limited set of conditions. In the first case, the conclusion is known to be "robust" or global. In the second case, the conclusion is known to be conditional or local.

The factor used to assess significance is known as the "primary" factor. All other factors used to assess the consistency of that primary factor conclusion are known as "robustness" factors. For a set of experimental results, any parameter can be chosen as the primary factor. Although broad conclusions are desirable, if the primary factor conclusion is not robust over other factors, then by definition, the primary factor and these other robustness factors depend on each other and "interact".

Assessing robustness is an important first step in analyzing an experimental system. If need be, estimating interactions is an important second step in understanding and appreciating the nuances of a system. The block plot is an invaluable tool and is used sequentially to focus on all factors in the system.

A secondary statistical graphic technique used for the EDA is a main effects plot also known as a design of experiments (DOE) mean plot [10]. A main effects plot shows the mean values for all factors and can quickly identify which factors have a large or small variation about the mean. Factors with deviations large about the mean are more important than other factors.

5.1 Exploratory Data Analysis Factors

Five factors are considered for the exploratory data analysis in the following block and mean effects plots:

1. CAD System (X1),
2. Test Case (X5),
3. Annotation Type (X4),
4. Error Type (X3), and
5. PMI Annotation (X2).

The X1-X5 notation is a characteristic of Dataplot. X2 is not used in the block plots because there are many PMI annotations in all of the test cases, block plots using this factor is too cluttered to be useful. PMI annotation errors (X6) is also not used in the block plots for the same reason.

CAD systems (X1) are labeled A, B, C, and D in the block plots. Test cases (X5) are labeled 1-5 for the CTC and 6, 8, and 9 for the FTC. The CTC were modeled in the 2012 versions of the CAD systems. The FTC were modeled in the 2015 versions of the CAD systems (Section 2.1). Table 15 and Table 16 shows the integer values, used in the block plots, that are assigned to the 17 annotation types (X4) and nine error types (X3).

Table 15: EDA factor X4 - Annotation Type

1	Dimension	10	Angularity
2	Dimension - hole	11	Line profile
3	Dimension - other	12	Parallelism
4	Datum feature	13	Total runout
5	Datum target	14	Circular runout
6	Position	15	Coaxiality
7	Surface profile	16	Roundness
8	Flatness	17	Straightness
9	Perpendicularity		

Table 16: EDA factor X3 - Error Type

1	Semantic structure
2	Semantic parameters
3	Semantic geometry
4	Graphic visibility
5	Graphic layout
6	Graphic location
7	Graphic orientation
8	Graphic lines
9	Graphic text

Table 17 shows the combinations of primary and robustness factors used in the block plots. Some combinations of factors are not analyzed because the block plots were too cluttered to provide meaningful results.

Table 17: Primary and robustness factor combinations

Primary factor	Robustness factor
CAD System (X1)	Test Case (X5)
Test Case (X5)	CAD System (X1)
CAD System (X1)	Annotation Type (X4)
Test Case (X5)	Annotation Type (X4)
CAD System (X1)	Error Type (X3)
Test Case (X5)	Error Type (X3)

5.2 CTC Main Effects Plot

The main effects plot for the CTC test cases is shown in Figure 52. The vertical axis of the block plot is the "Mean Probability of Success". The mean is determined by the number of "pass" responses to the observation of a PMI annotation for an error (Section 4.1). Along the horizontal axis are the five factors being considered. The 'x' marks for a particular factor are the mean values for each setting within that factor and are connected by a line across the factor settings. For CAD system (X1) there are four CAD systems, thus the four 'x' marks. The number of 'x' marks for the first four factors are described in previous section. There are 129 PMI annotations (X2) for the last factor, thus the very dense appearance of the many 'x' marks and connecting lines.

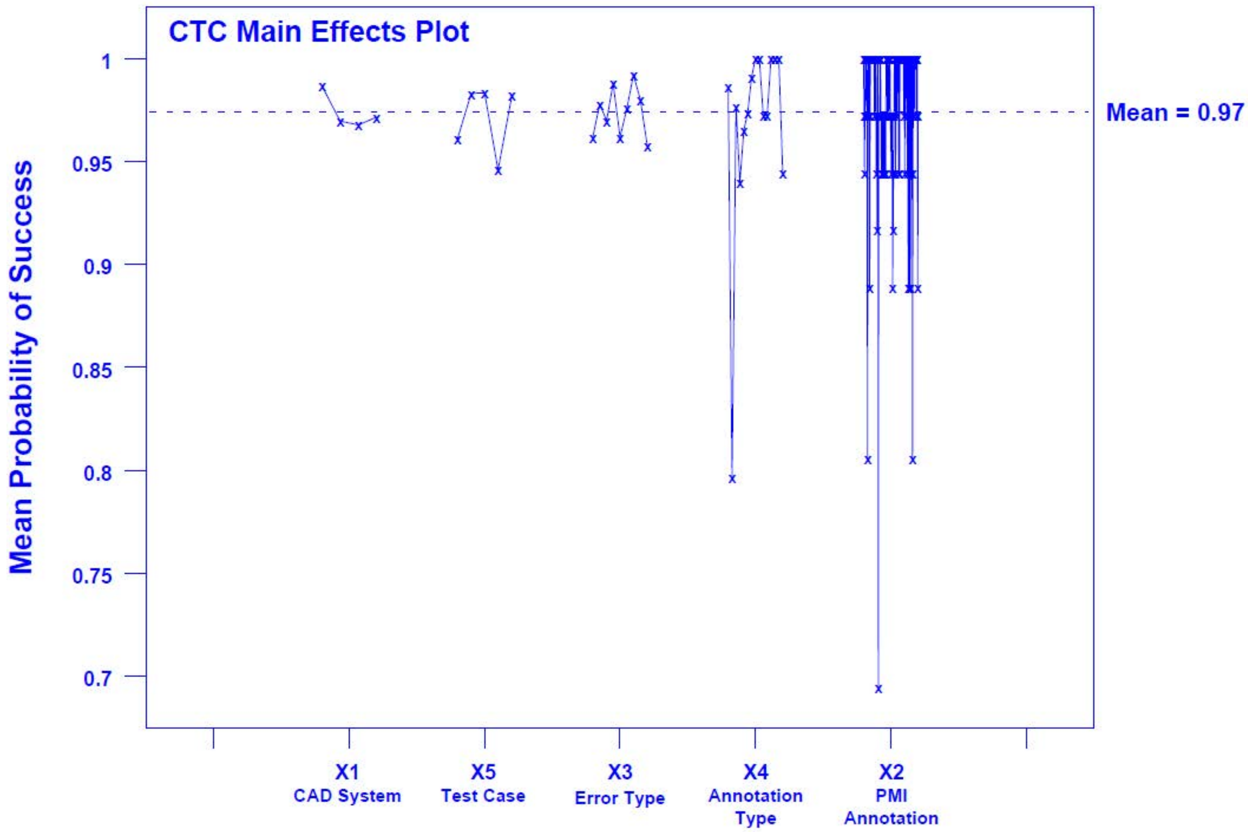

Figure 52: CTC main effects plot

Conclusions from the main effects plot are:

- CAD A (first 'x' for X1) performs better than the other CAD systems.
- CTC 2, 3, and 5 (X5) perform similarly and better than CTC 1 and 4.
- Three error types (X3) perform significantly worse than the mean while two error types perform much better than the mean.
- Hole dimensions (X4, annotation type 2, second 'x') perform significantly worse than the other annotation types.
- Many PMI annotations (X2) perform near or above the mean while there are several outliers with much worse performance.

5.3 CTC Block Plots

The following sections show the mean block plots for the combinations of primary and robustness factors in Table 17 for the CTC test cases. For a mean block plot, the vertical axis is the mean response, the horizontal axis is the settings of the robustness factor, and the plot character is the settings of the primary factor.

5.3.1 CTC – CAD System (X1) and Test Case (X5)

Figure 53 is a mean block plot for the primary factor CAD system (X1) and the robustness factor test case (X5). For this figure:

- The vertical axis of the block plot is the "Mean Probability of Success" as described in the previous section. Although the mean values appear high, any failure could have consequences for downstream human or automated consumption of PMI information.
- The horizontal axis is the Test Case for the five CTC, labeled 1-5.
- The plot character is the CAD System for the four CAD systems, labeled A-D. The position of the letters A-D within a block is the mean value for that combination of CAD system and test case.
- Block mean values (described below) are displayed just above the horizontal axis.
- The number of annotations per test case is also displayed just above the horizontal axis.

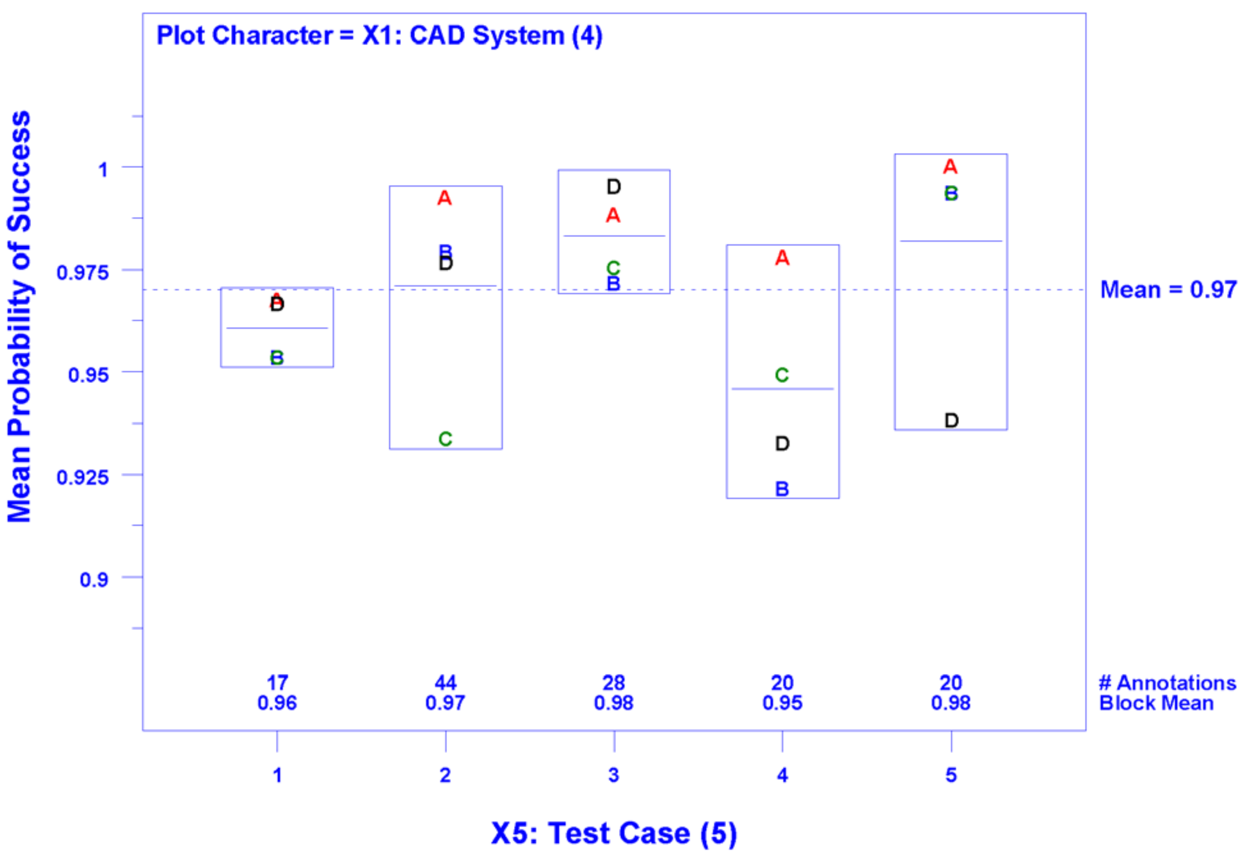

Figure 53: CTC mean block plot for CAD system (X1) and test case (X5)

For a given test case (robustness factor), the four CAD systems (primary factor) are enclosed by a block to emphasize the purpose of the block plot, namely to focus attention on behavior within a block, as opposed to between blocks. Noting which blocks are high or low relative to one another conveys information about the test cases (robustness factor) along the horizontal axis. The block plot mainly addresses whether the four levels of the primary factor (CAD System) are statistically equivalent or not. If similar behavior occurs across all or most block implies robustness, else it implies interaction. For example, in Figure 53 CAD A performs best for four of five blocks and second best for one block; therefore, its performance is robust, i.e., it does not depend on the test case. CAD D's performance ranges from best to worse across the test cases; therefore, there is an interaction (dependency) between CAD D and the test case.

The vertical position of the letters A through D in each block is the "mean probability of success" for that combination of CAD system and test case. Each letter, corresponding to a CAD system, has a different color and sometimes overlap each other which visually implies equivalence. For example, the block for CTC 5 (rightmost block of Figure 53), CAD A has a mean probability of success of 1.0 meaning that there were no PMI annotation errors. CAD B and C, with a mean probability of success of about 0.99, overlap each other just below CAD A. CAD D appears as a local "outlier" with a much lower mean probability of success of about 0.94.

The height of a block corresponds to the variation of the CAD systems for a test case. Smaller heights imply more equivalence among the four CAD systems while larger heights indicate greater disparity. In the block plot, CTC 1 has the smallest block height (the four CAD systems perform similarly). CTC 2, 4, and 5 each have large block heights indicating that the four CAD Systems are performing differently for those test cases.

The dotted line across the entire plot is the "grand mean" across all CAD systems and test cases. In this example, the grand mean is 0.97. The solid line in each block is the "block mean" value for the four CAD systems for a test case. CAD systems above the solid line are "better" than the block mean. The value of the block mean is shown at the bottom of the plot inside the horizontal axis. The block mean values correspond to the 'x' marks associated with CAD system for the mean effects plot in Figure 52.

For a given test case, the location of the block relative to the grand mean indicates whether a particular test case leads to good results (block mean values near 1) or to poor results (block mean values considerably less than 1. In general, test cases with block mean values greater than the grand mean would be considered to perform better than test cases with block mean values less than the grand mean. CTC 3 and 5 have blocks that appear higher and have block mean values better than the grand mean. CTC 1 and 4 have blocks that appear lower and have block mean values worse than the grand mean. CTC 2 has a block mean value similar to the grand mean.

Conclusions from this block plot are:

- CAD A performs best or almost best for all five test cases. This is a robust conclusion.
- CAD B performs the worst for CTC 1, 3, and 4.
- CAD C performs worst or almost worst for CTC 1, 2, and 3.
- CAD D performs the best for CTC 3 and the worst for CTC 5.
- CTC 1 performs poorly with all CAD systems having values below the grand mean.
- CTC 2 performs much worse than the block and grand means for CAD C, meaning that CTC 2 was more difficult to model in CAD C. For the other four test cases, CAD C performs either above the block mean or grand mean. A conclusion about CAD C performing poorly is not robust; therefore, an interaction between CAD C and the test cases exists.
- CTC 3 is the least problematic test case shown by the highest block mean, smallest block height, and all CAD systems above the grand mean.
- CTC 4 also performs poorly with the smallest block mean and largest height.

- CTC 5 performs the best, except for CAD D that has the lowest block mean value as confirmed by Section 4.1.4.

This and the following block plots show detailed information that help gain insight and understanding of the testing results.

5.3.1.1 Correspondence to Keshif visualizations

The information in this block plot corresponds to the CAD System characteristic in the Keshif visualizations in Figure 41 through Figure 45. Those figures show the total number of errors per CAD system for a CTC. In Figure 41 for errors with CTC 1, CAD A and D have the same number of errors (5), thus the overlapping A and D in the leftmost block. CAD B and C also have the same number of errors (7), thus the overlapping B and C in the leftmost block. The block plot shows a relative comparison of the "pass" responses (probability of success) of the CAD systems between all of the CTC.

The Test Case characteristic from the Keshif visualization in Figure 31 shows the total number of errors for each of the five CTC (24, 46, 17, 39, 13). More errors per CTC does not necessarily imply a lower block mean. CTC 2 (second block) has 46 errors with a block mean just above 0.97 while CTC 4 (fourth block) has 39 errors but the lowest block mean of all the CTC.

This is only one example of the correspondence between the Keshif visualizations and EDA block plots. There are other similar relationships between the following block plots and the Keshif visualizations.

5.3.1.2 Sorted block plots

Figure 54 and Figure 55 are similar to Figure 53 except the blocks have been sorted by the block mean and block height, respectively. The letters for each CAD system are connected across the blocks. Sorting the blocks provides visual feedback for which test case performed better overall (CTC 3) and which test case has the least (CTC 1) variation and most (CTC 5) between the CAD systems. The curve for CAD A is consistently high (no up and down variation) showing that it perform well for all test cases. The EDA sorted block plot methodology is demonstrated only for this combination of primary and robustness factors.

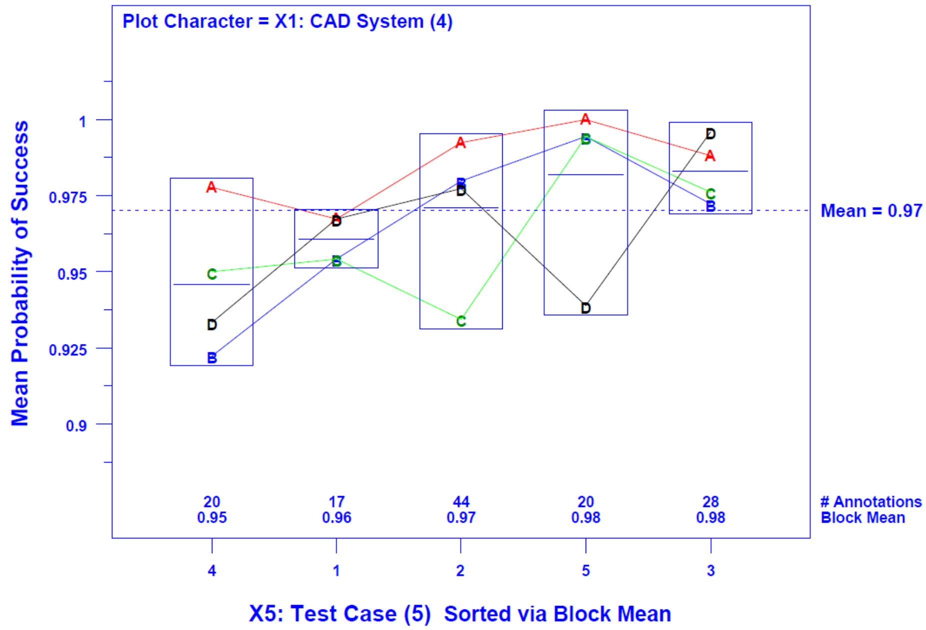

Figure 54: CTC mean block plot for CAD system (X1) and test case (X5), sorted by block mean

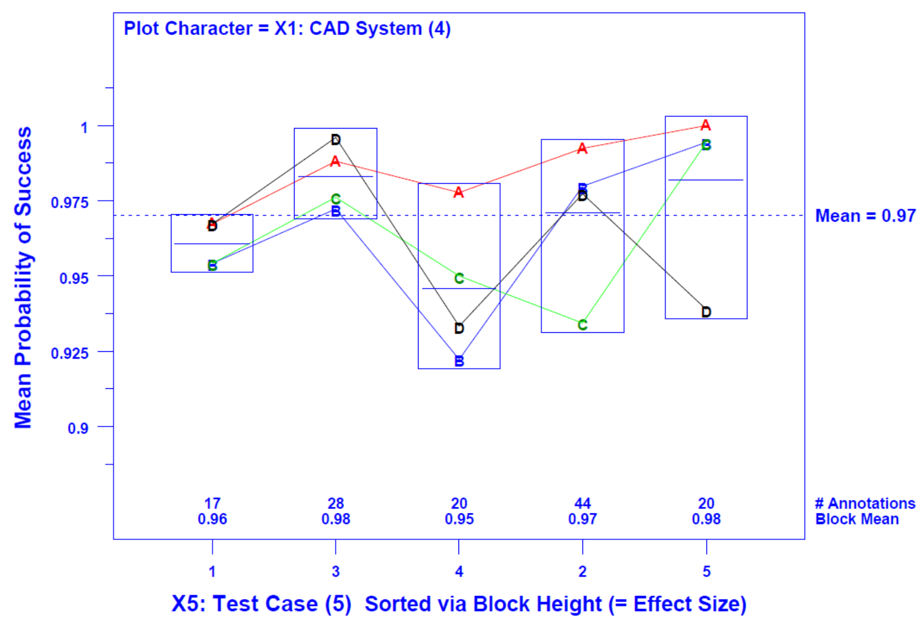

Figure 55: CTC mean block plot for CAD system (X1) and test case (X5), sorted by block height

5.3.2 CTC – Test Case (X5) and CAD System (X1)

Figure 56 flips the primary and robustness factor from Figure 53. Test Case (X5) is now the primary factor and the test case numbers 1 through 5 appear within the blocks. CAD System (X1) is now the robustness factor and the letters A through D appear on the horizontal axis. For a given CAD system, the block mean is the solid line within the block and its value is shown above the horizontal axis. Above the block mean value is the corresponding actual number of failures of observations for that CAD system. For CAD A, the block mean is .99 and the observed number of failures is 15.

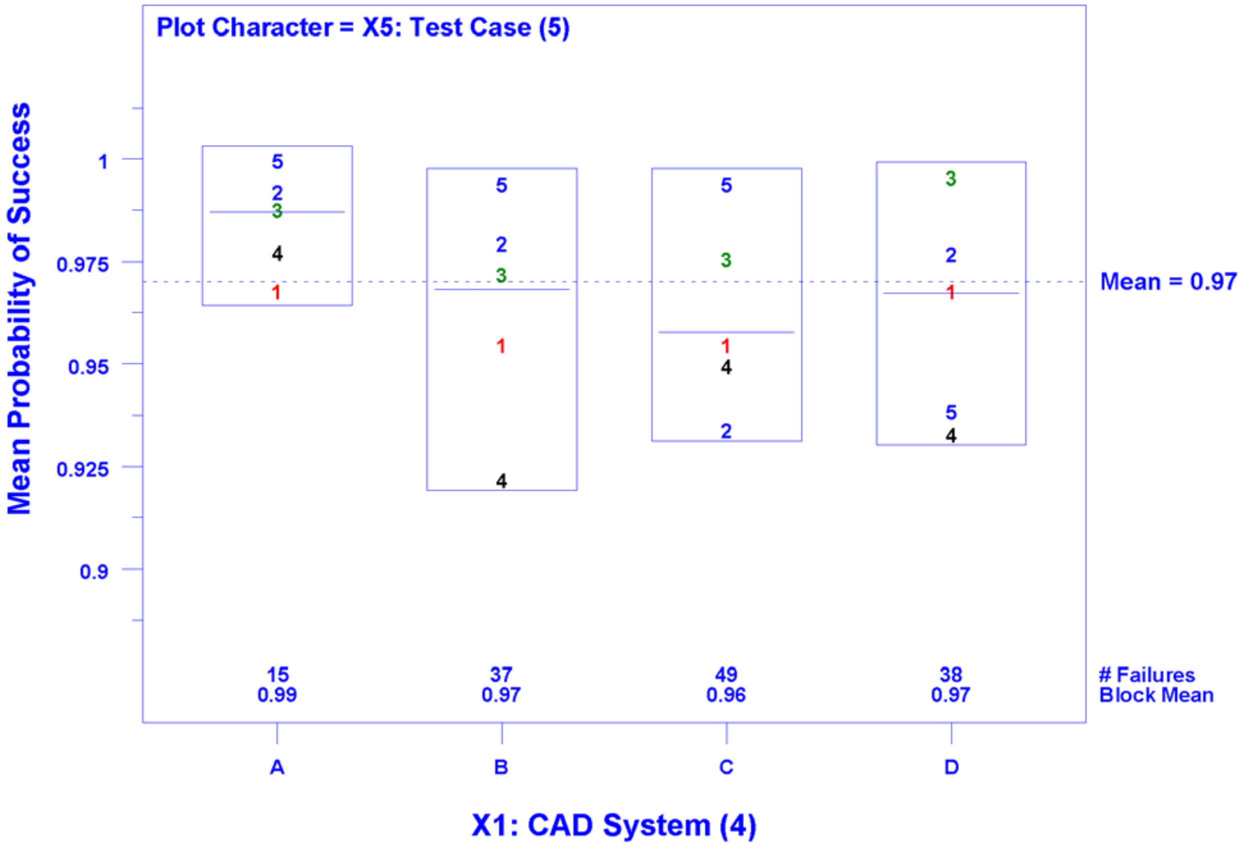

Figure 56: CTC mean block plot for test case (X5) and CAD system (X1)

Some conclusions from this block plot are:

- CTC 1 performs worse than the grand mean for all CAD systems.
- CTC 2 performs better than the grand and block means except for CAD C.
- CTC 3 performs better than the grand and three of four block means for all CAD systems.
- CTC 4 for CAD B has the lowest mean value of about 0.92.
- CTC 5 performed better than the other four test cases except for CAD D, as confirmed by Figure 53 and Figure 45.
- CAD A performs better (higher block mean, shortest block height) than the other CAD systems.
- CAD C performs poorly (lowest block mean) and especially for CTC 2 as previously confirmed by the Keshif visualizations in Figure 32 and Figure 42.

5.3.3 CTC – CAD System (X1) and Annotation Type (X4)

Figure 57 shows the mean probability of success where the primary factor is CAD system (X1) and the robustness factor is annotation type (X4). Table 15 shows the correspondence between the annotation type number (1-17) and the annotation type (dimension, datum feature, geometric tolerance, etc.). There are no values for annotation types 3 and 12 (dimension–other and parallelism) because none exist in the CTC. Just above the block plot mean values on the horizontal axis are the number of annotations per annotation type. For example, there are eight perpendicularity tolerances (annotation type 9).

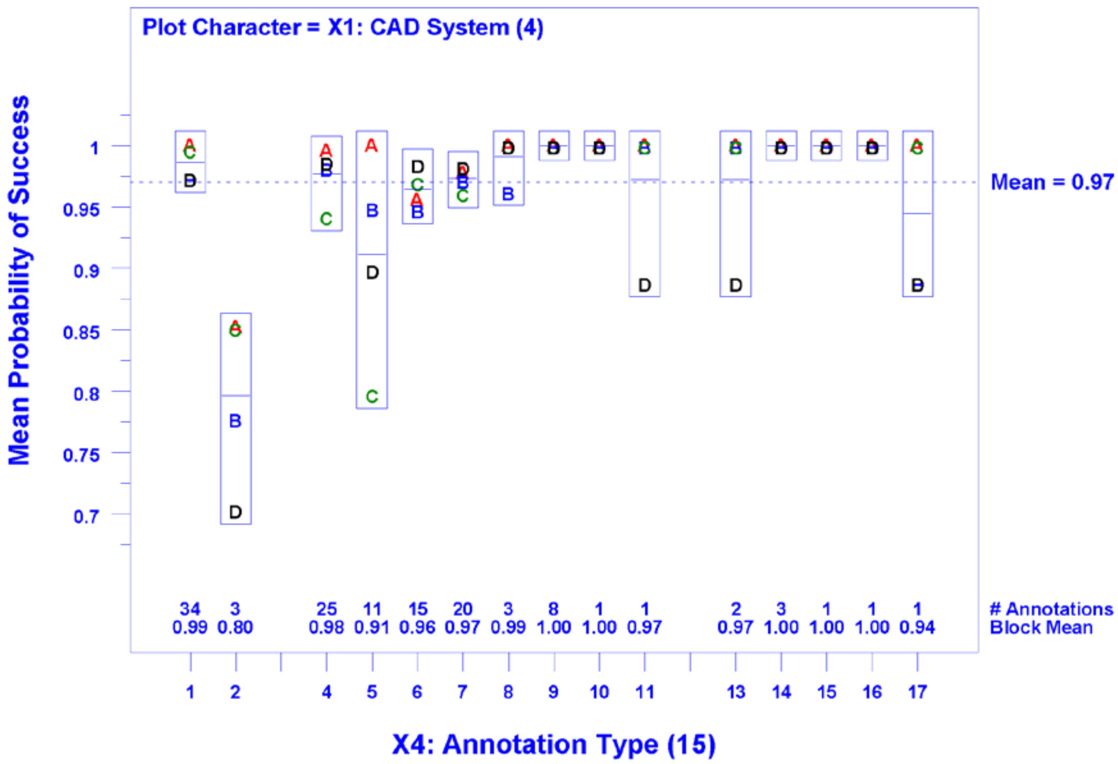

Figure 57: CTC mean block plot for CAD system (X1) and annotation type (X4)

Some conclusions from the block plot are:

- CAD A performs the best for 14 out of the 15 annotation types. The exception is for position tolerances (annotation type 6) where CAD D is the best.
- CAD D for annotation types 2, 5, 11, 13, and 17 performs the worst. For two of those types (11, 13) the other CAD systems performed perfectly.
- Hole dimensions (annotation type 2) perform poorly for all CAD systems as confirmed by the Keshif visualization in Figure 49 although there are only three dimensions related to holes for all CTC.
- Datum targets (annotation type 5) perform poorly for all CAD systems except CAD A as confirmed by the Keshif visualization in Figure 50.
- Perpendicularity, angularity, circular runout, coaxiality, and roundness (annotation types 9, 10, 14, 15, 16) have no errors in the CTC for all CAD systems (overlapping letters) although there are relatively few of those types of annotations.
- Line profile and total runout (annotation types 11, 13) only have errors in CAD D although there is only one of each of those annotations in CTC 5 (Figure 18).

5.3.4 CTC – Test Case (X5) and Annotation Type (X4)

Figure 58 is similar to Figure 57 except that the primary factor is test case (X5). The block means are the same as Figure 57. Some blocks only have a single test case number because those annotation types only have a single occurrence in the CTC. There are no values for annotation types 3 and 12 (dimension–other and parallelism) because none exist in the CTC.

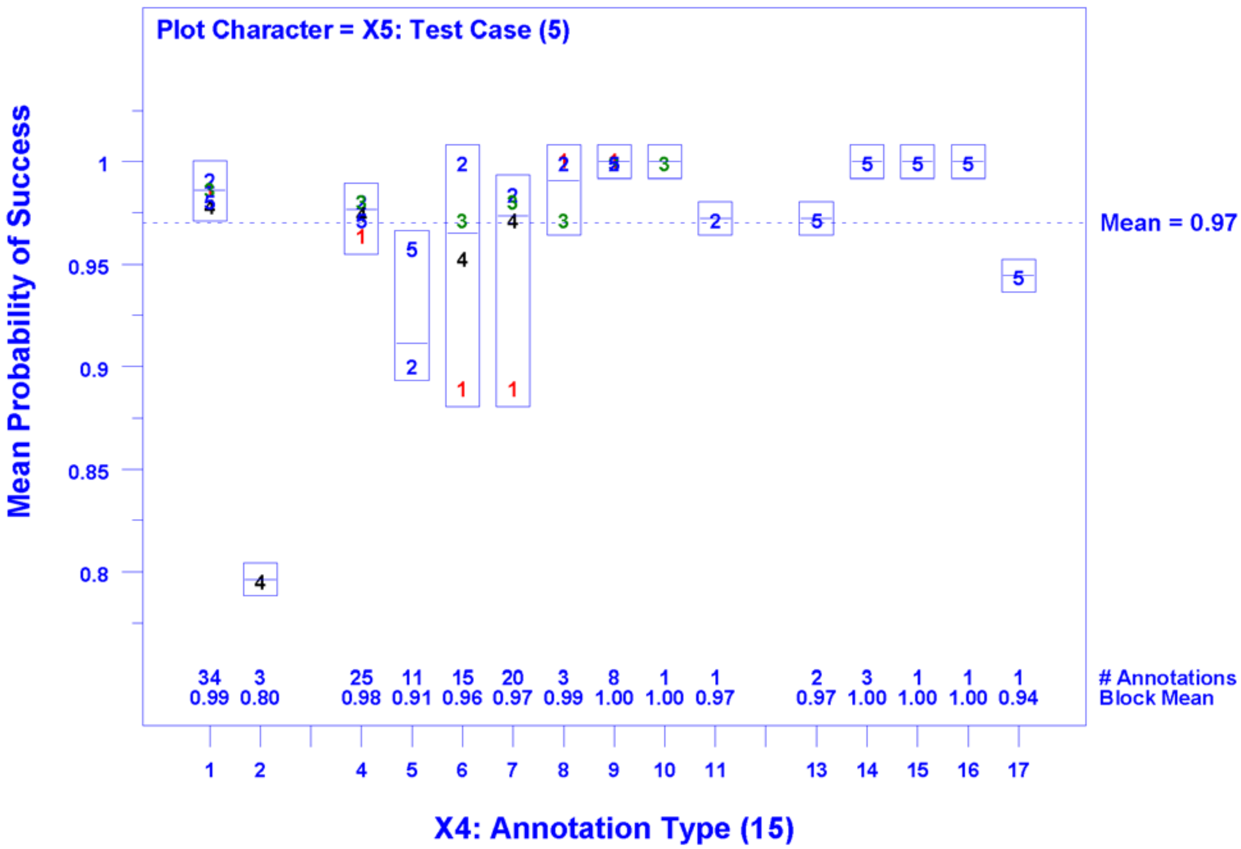

Figure 58: CTC mean block plot for test case (X5) and annotation type (X4)

Some conclusions from the block plot are:

- CTC 1 performs poorly with position and surface profile tolerances (annotation types 6 and 7).
- CTC 2 performs poorly with datum targets (annotation type 5).
- CTC 4 performs the worst with hole dimensions (annotation type 4). The other CTCs have no holes.
- For datum targets (annotation type 5) the block mean is closer to CTC 2 than CTC 5 because there are more datum targets that cause problems in CTC 2 than in CTC 5.
- Position and surface profile tolerances (annotation types 6, 7) have the widest ranges of performance (tallest blocks).

5.3.5 CTC – CAD System (X1) and Error Type (X3)

Figure 59 is a mean block plot where the primary factor is CAD system (X1) and the robustness factor is Error Type (X3). There are nine error types (Table 16), the first three being semantic annotation errors, thus the vertical dotted line between error types 3 and 4 to differentiate between the three semantic and six graphic error types. Just above the block mean values on the horizontal axis is the number of failures for each error type. In general, there are more failures for semantic errors. These results are confirmed in Keshif visualizations in Figure 36 and Figure 39 with errors per the 2012 CAD systems for all semantic and graphic error types, respectively.

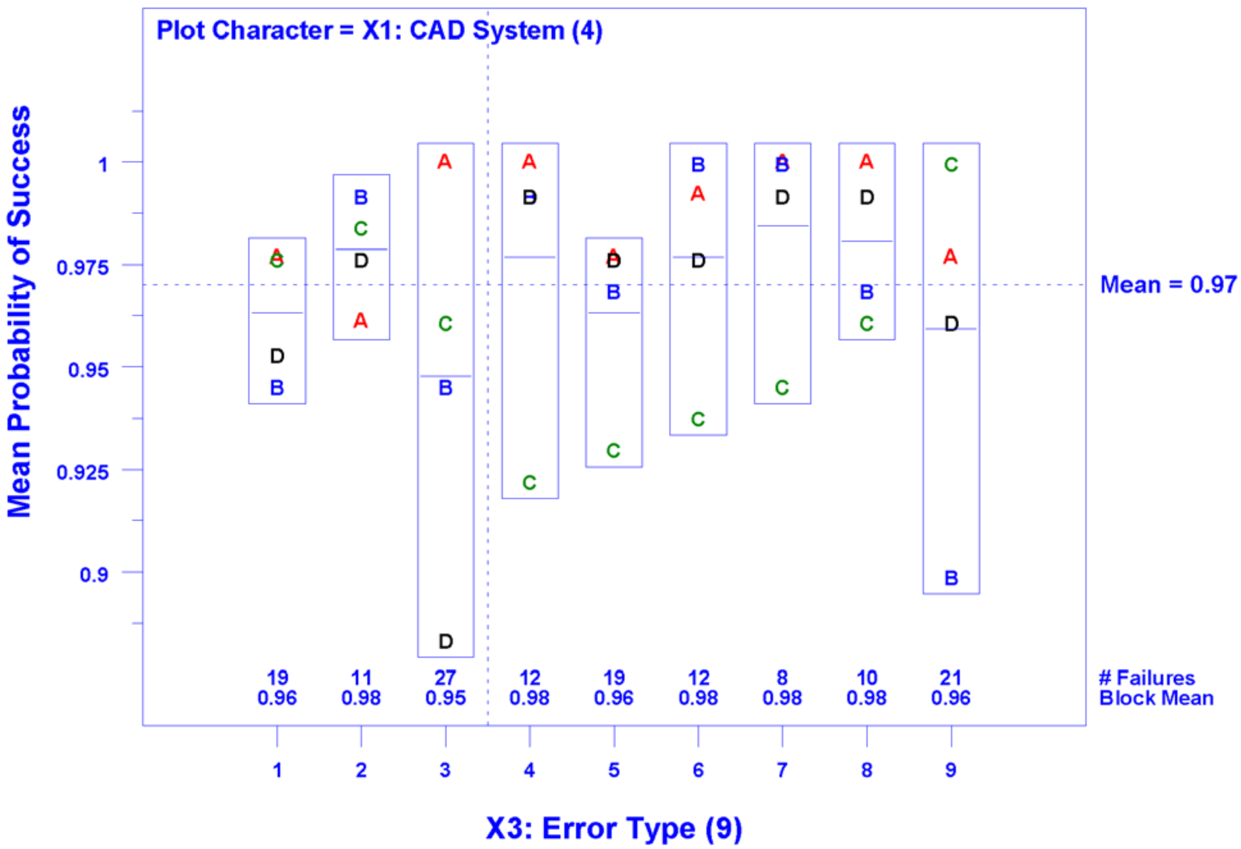

Figure 59: CTC mean block plot for CAD system (X1) and error type (X3)

Some conclusions from the block plot are:

- CAD A performs the best or next best for eight of the nine error types except for error type 2 (semantic parameters) where it performs the worst.
- CAD C performs worse than the other CAD systems for graphic annotation errors types 4-9.
- CAD D has the lowest performance for any CAD system for error type 3 (semantic geometry).
- Semantic geometry (error type 3) has the widest range of performance (tallest block) and the lowest block mean.
- Graphic text (error type 9) has the next lowest block mean and CAD B has the next lowest performance for any CAD system and error type.

5.3.6 CTC – Test Case (X5) and Error Type (X3)

Figure 60 is a mean block plot were the primary factor is test case (X5) and the robustness factor is error type (X3). The block means are the same as Figure 59. These results correspond to the Error Type characteristic for the Keshif visualizations in Figures 41-45 for each CTC.

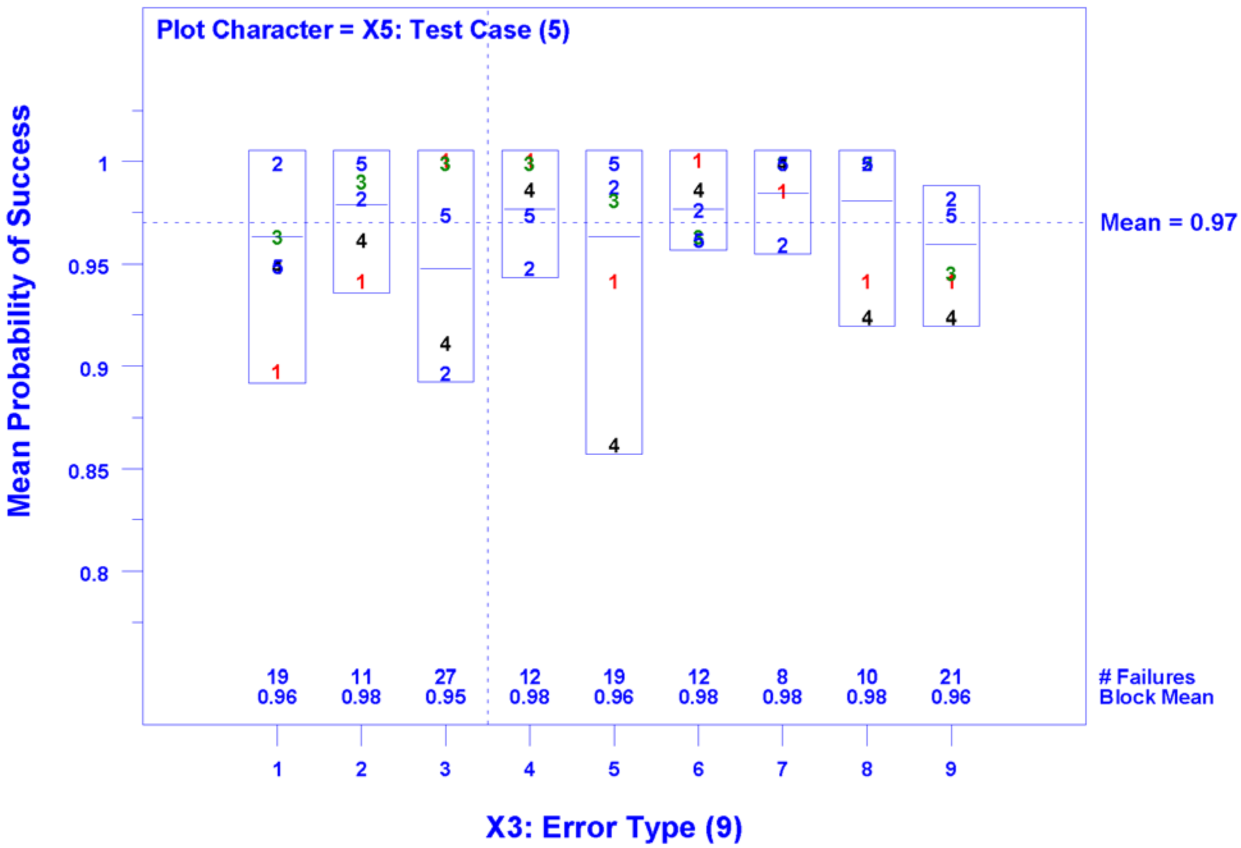

Figure 60: CTC mean block plot for test case (X5) and error type (X3)

Some conclusions from the block plot are:

- CTC 1 performed the best in semantic PMI error type 3 and the worst with error types 1 and 2.
- CTC 2 had opposite results for those semantic PMI error types.
- CTC 4 performed worse than the overall mean and block mean for graphical PMI error types 5, 8, and 9.
- Semantic geometry (error type 3) has the worst block mean although CTC 1 and 3 performed perfectly.
- Graphic text (error type 9) is the only error type for which none of the test cases had a perfect score.

5.4 FTC Main Effects Plot

The main effects plot for the FTC test cases is shown in Figure 61 and is similar to the CTC main effects plot in Figure 52. The vertical axis of the block plot is the "Mean Probability of Success". Along the horizontal axis are the five factors being considered. The 'x' marks are the mean values for a particular factor and are connected across an individual factor. For CAD system (X1) there are four CAD systems, thus the four 'x'. The number of 'x' for the first four factors are described in previous section. There are 168 PMI annotations (X2) for the last factor, thus the very dense appearance of the many 'x' and connecting lines.

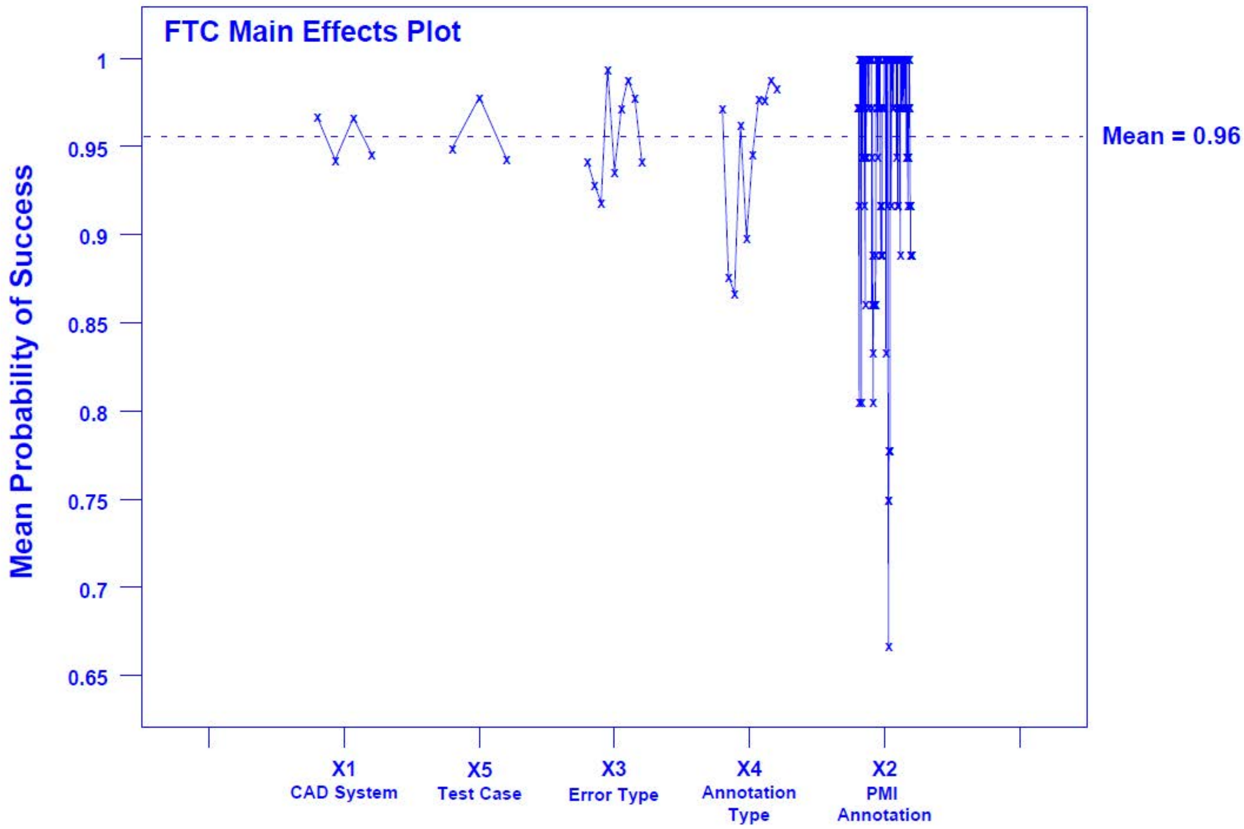

Figure 61: FTC main effects plot

Conclusions from the main effects plot are:

- CAD A and C (X1) perform better than the other CAD systems.
- CTC 8 (X5) performs better than the other test cases.
- Five error types (X3) perform significantly worse than the mean while four error types perform much better than the mean. All three semantic errors types (first three 'x') perform worse than the mean.
- Many PMI annotations (X2) perform near or above the mean while there are several outliers with much worse performance.

5.5 FTC Block Plots

Similar to the EDA of the CTC in the previous section, the following figures are the exploratory data analysis block plots for the three FTC test cases. The explanation of the setup of the block plots for the CTC EDA in Figures 53-60 apply to the corresponding block plots for the FTC.

5.5.1 FTC – CAD System (X1) and Test Case (X5)

Figure 62 is analogous to the block plot in Figure 53 for the CTC. The primary factor is CAD system (X1) and the robustness factor is test case (X5). There are only three test cases for the FTC labeled 6, 8, and 9.

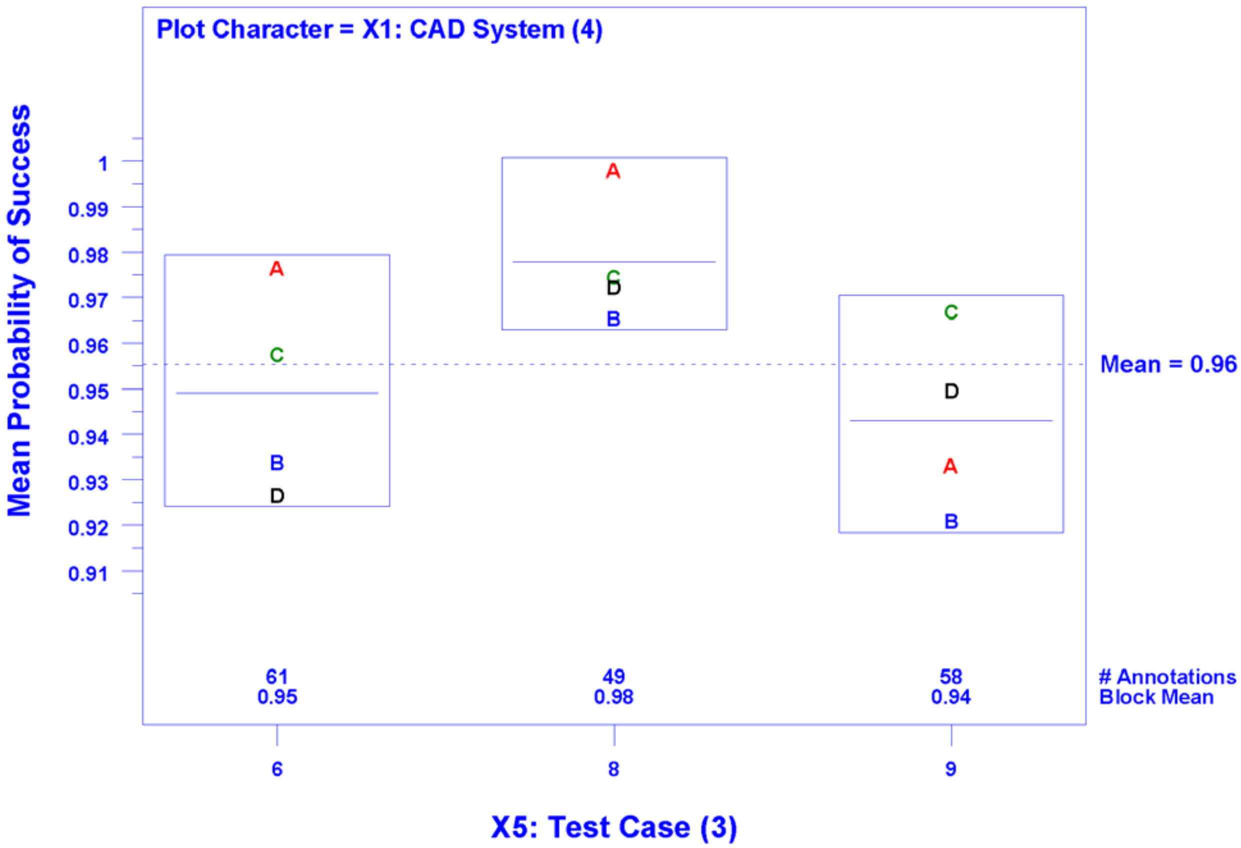

Figure 62: FTC mean block plot for CAD system (X1) and test case (X5)

Some conclusions from the block plot are:

- All of the CAD systems performed better than the grand mean for FTC 8.
- Only CAD C performed better than the grand mean for all test cases.
- For FTC 6 and 8, CAD A performed the best, however, for FTC 9 CAD A performed worse than the grand mean and block mean.
- CAD B performed worse than the block mean for all test cases and is the worst or next to worst for all three test cases.

5.5.2 FTC – Test Case (X5) and CAD System (X1)

Figure 63 flips the primary and robustness factor from
Figure 62 and is similar to the block plot in Figure 56 for the CTC where the primary factor is test case (X5) and the robustness factor is CAD system (X1). Just above the block mean values along the horizontal axis are the number of failures for each CAD system.

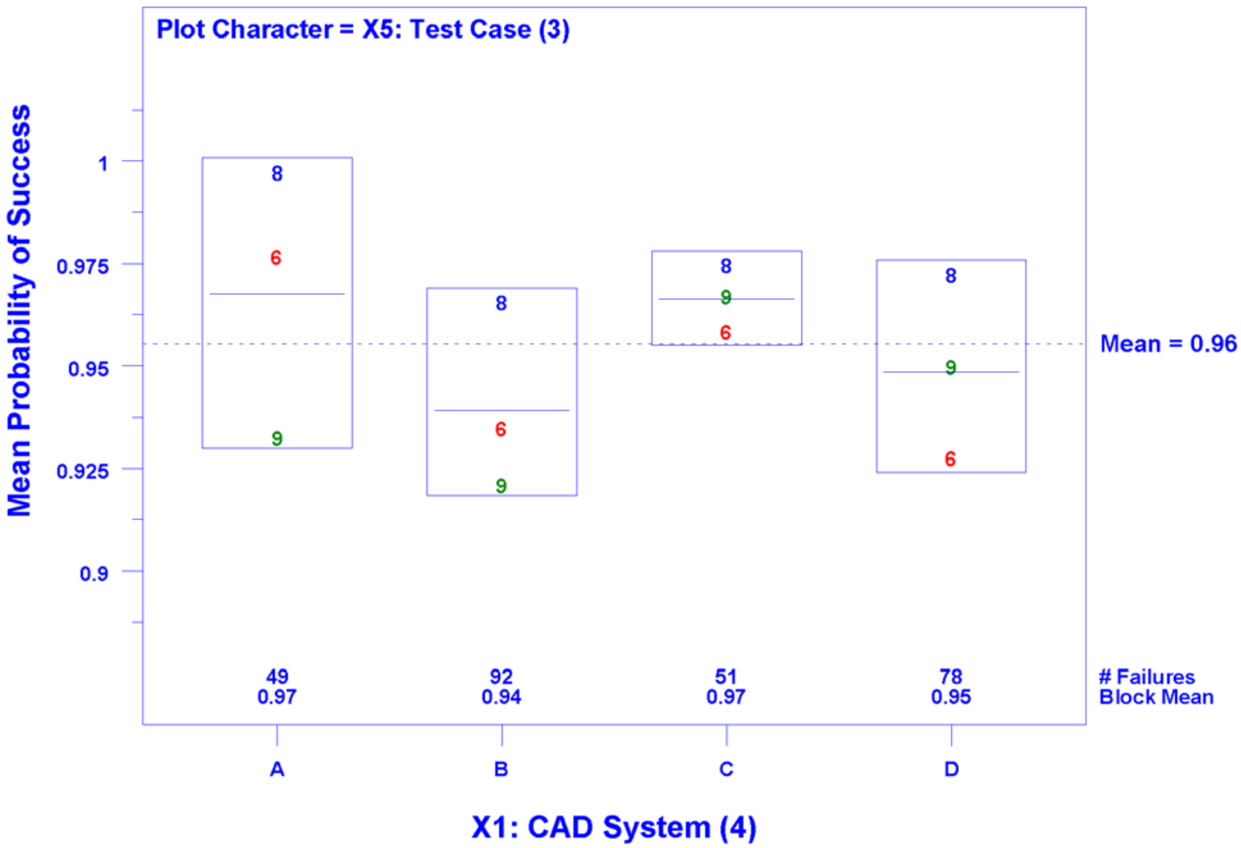

Figure 63: FTC mean block plot for test case (X5) and CAD system (X1)

Some conclusions from the block plot are:

- FTC 8 is best with the highest mean for all CAD systems.
- CAD C performed better (higher block mean and shortest block) than the other CAD systems for the test cases.
- CAD A performed with best for any test case with FTC 8.

5.5.3 FTC – CAD System (X1) and Annotation Type (X4)

Figure 64 is analogous to the block plot in Figure 57 for the CTC. The primary factor is CAD system (X1) and the robustness factor is annotation type (X4). The annotation type values are described in Table 15. Above the block plot mean value along the horizontal axis is the number of annotations per annotation type. There are no values for annotation types 10, 11, and 13 through 17 because none exist in the FTC.

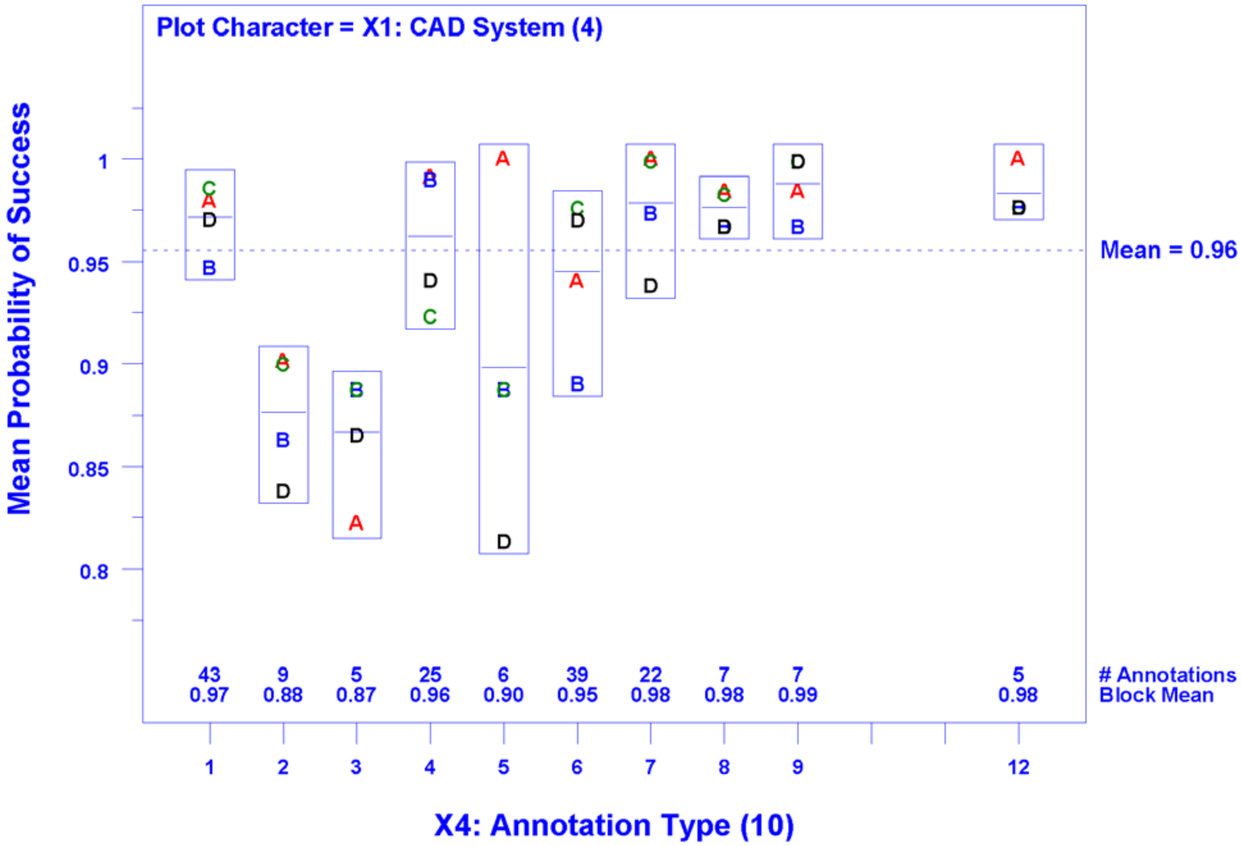

Figure 64: FTC mean block plot for CAD system (X1) and annotation type (X4)

Some conclusions from the block plot are:

- CAD A and C performed better than the block mean for 7 out of the 10 annotation types.
- Comparing this figure and Figure 57 for the CTC, datum targets (annotation type 5) in each figure have the widest range of performance (tallest block) for all CAD systems. For both the CTC and FTC, CAD A performed the best.
- CAD B performed worse than the block mean for 8 out of the 10 annotation types.
- Hole and other dimensions (annotation types 2 and 3) perform poorly for all CAD systems as confirmed by Figure 49.
- Datum targets (annotation type 5) have the widest range of performance (tallest block) for all CAD systems. Datum targets also have the widest range of performance for the CTC in Figure 57
- Flatness, perpendicularity, and parallelism (annotation types 8, 9, 12) all performed above the mean in the FTC for all CAD systems (overlapping letters), although there are relatively few of these types of annotations.

5.5.4 FTC – Test Case (X5) and Annotation Type (X4)

Figure 65 is analogous to Figure 58 for the CTC where the primary factor is test case (X3) and the robustness factor is annotation type (X4). The block means are the same as Figure 64. Any number 6, 8, or 9 that does not appear in a block means that that type of annotation does not exist in that FTC.

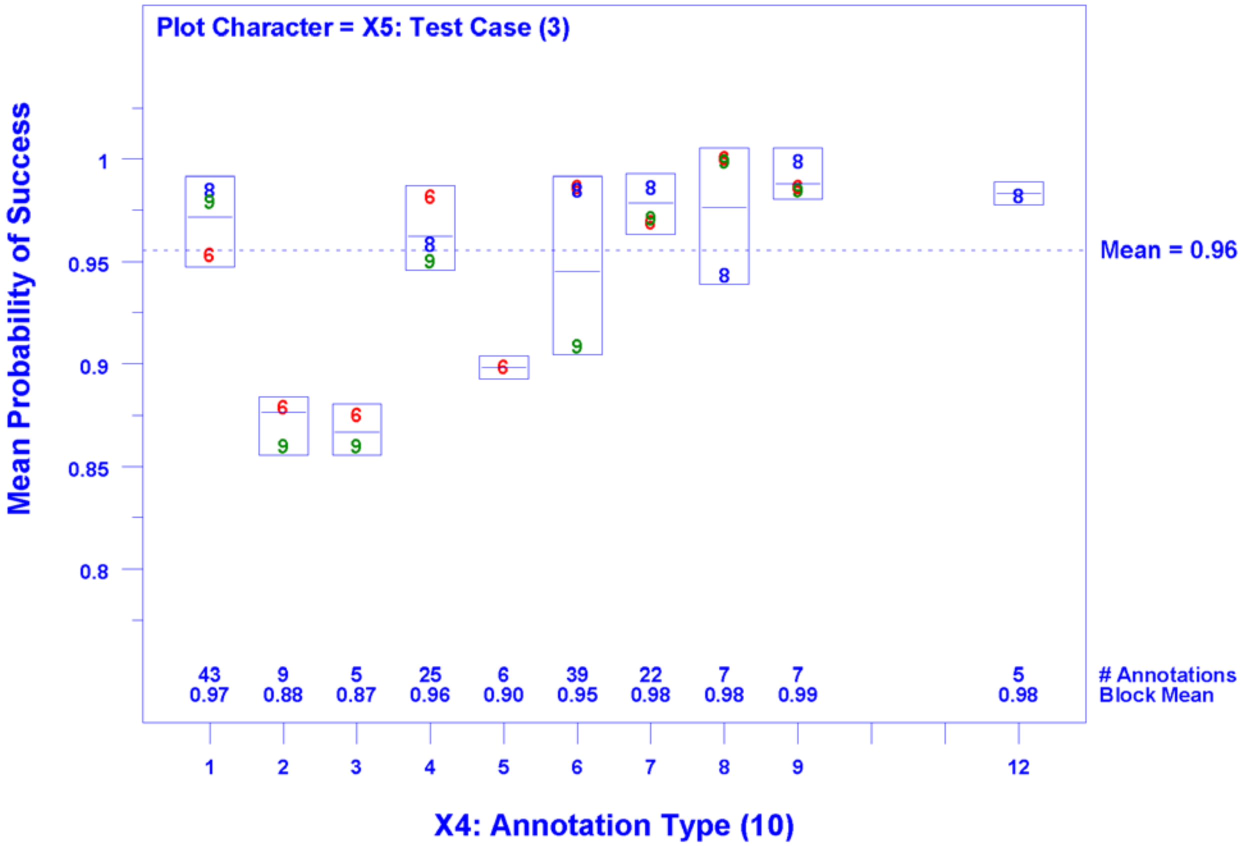

Figure 65: FTC mean block plot for test case (X5) and annotation type (X4)

Some conclusions from the block plot are:

- FTC 8 performs better than the mean for all annotations except flatness (annotation type 8).
- FTC 9 performs better than the block mean for only position and flatness (annotation types 1, 8).
- Dimension-hole, dimension-other, and datum target (annotation types 2, 3, 5) are the most difficult with the lowest blocks and block means.

5.5.5 FTC – CAD System (X1) and Error Type (X3)

Figure 66 is a mean block plot where the primary factor is CAD system (X1) and the robustness factor is error type (X3). It is analogous to Figure 59 for the CTC. There are nine error types, the first three being semantic annotation errors and the next six are graphic annotation errors. Just above the block mean values on the horizontal axis is the number of failures for each error type.

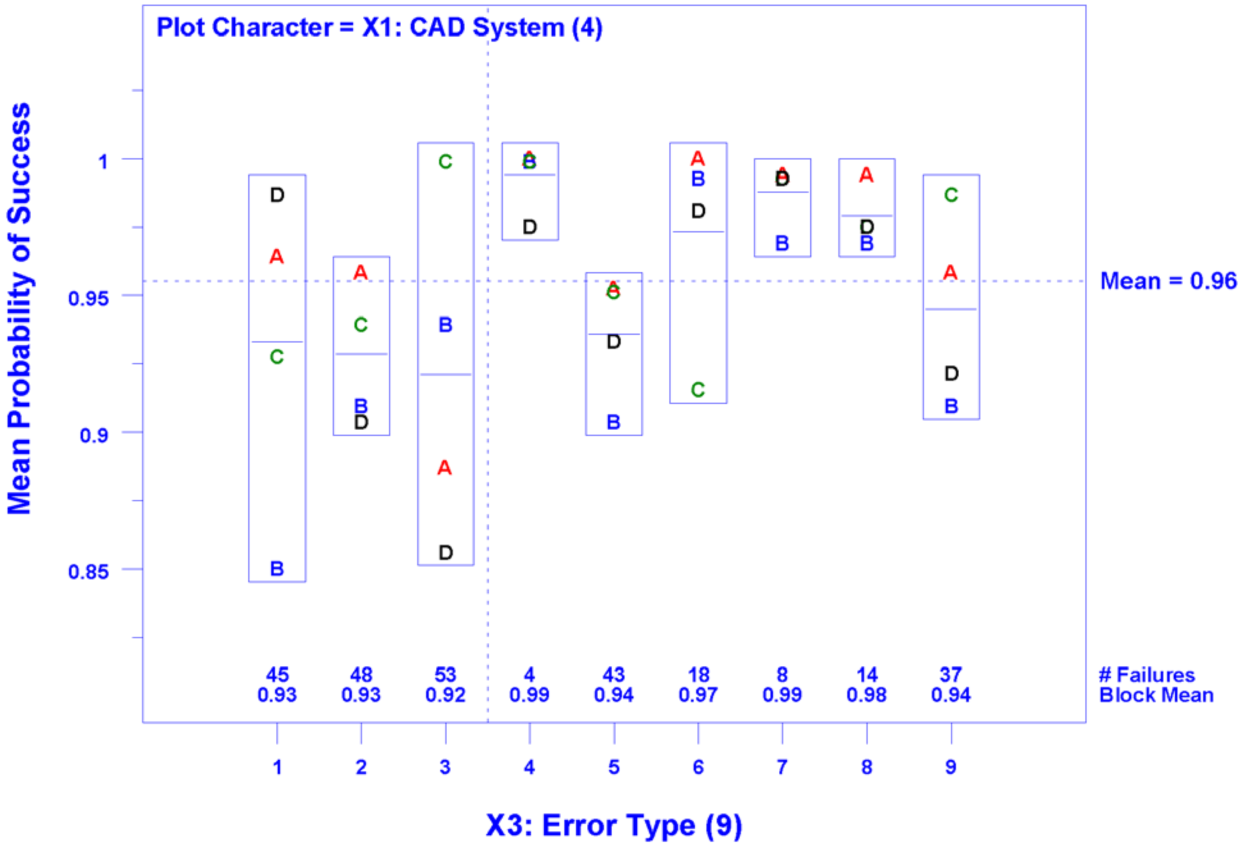

Figure 66: FTC mean block plot for CAD system (X1) and error type (X3)

Some observations from the block plot are:

- In general, CAD A performs better than the other CAD systems for all error types except for the error types 3 and 9.
- CAD B is the worst in five of the nine error types (1, 5, 7, 8, 9) yet performs well for error types 4 and 6.
- CAD D performs that best for semantic structure error types (first block) yet the worst for the other two semantic error types.
- Error types 4, 7, and 8 all perform well for all CAD systems with minimal variations (small block height).
- Error types 1 and 3 have the widest variation in performance (tallest blocks).
- Error types 2 and 5 are the most problematic with only CAD A for error type 2 being above the grand mean.

5.5.6 FTC – Test Case (X5) and Error Type (X3)

Figure 67 is a mean block plot were the primary factor is test case (X5) and the robustness factor is error type (X3). It is analogous to Figure 60 for the CTC. The block means are the same as Figure 66. These results correspond to the Keshif visualizations for Error Type characteristic in Figures 46-48 for each FTC.

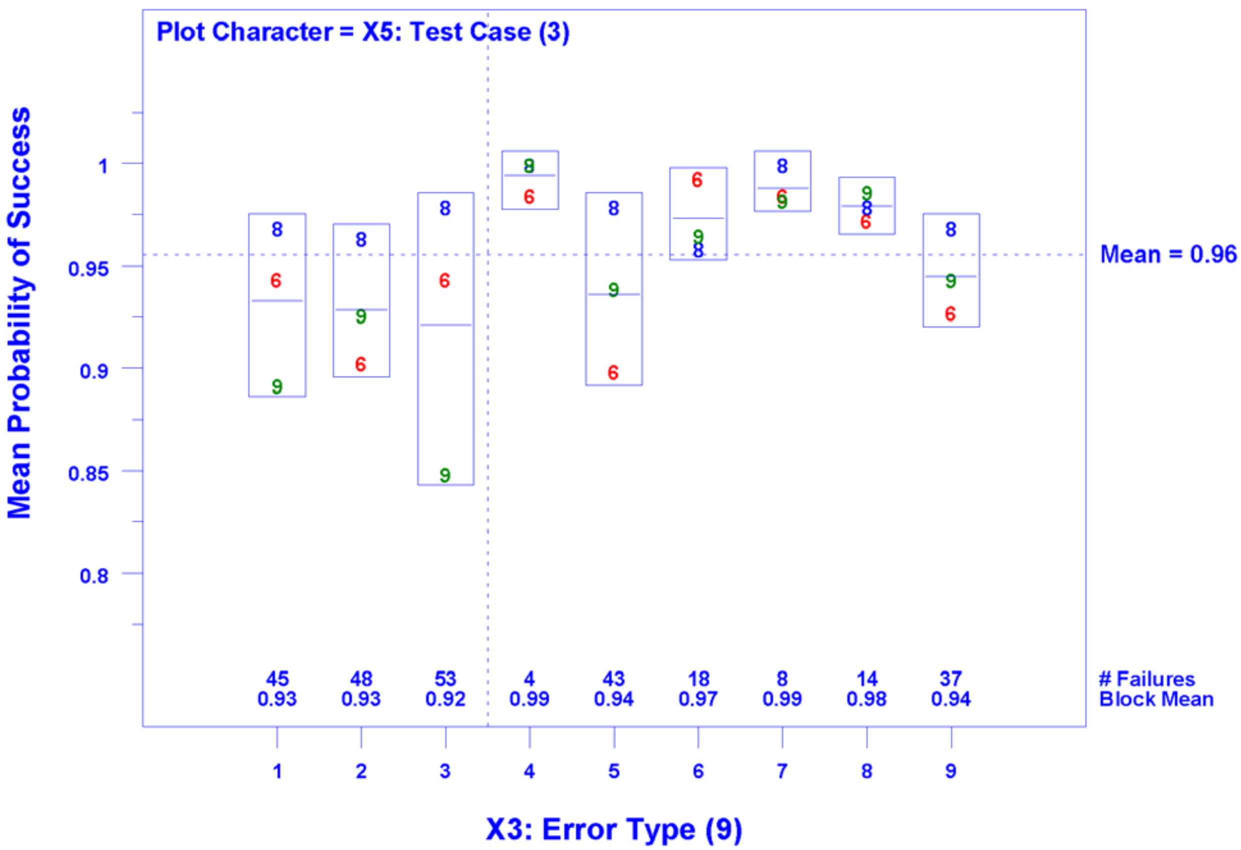

Figure 67: FTC mean block plot for test case (X5) and error type (X3)

Some observations from the block plot are:

- FTC 8 performed the best for all error types except two of the graphic annotation error types (blocks 6 and 8).
- FTC 6 is the worst for five of the nine error types.
- FTC 9 performed worse than the block mean for all three semantic annotations error types (blocks 1-3).
- Error types 4, 7, and 8 all perform well for all test cases with minimal variations (small block height).
- Error type 3 has the widest variation of performance with the tallest block and lowest block mean and worst performance for FTC 9 for any error type.

6 Conclusions

This guide provides supplemental information about the test cases and verification results from the NIST MBE PMI Validation and Conformance Testing Project [1]. The original test case drawings and verification results [4, 6] only show a limited view of the complex information related to the PMI annotations in the test cases and the verification test results.

The PMI annotations in the test cases were developed to measure conformance of CAD software to ASME standards for GD&T [2, 3]. The PMI annotations were not necessarily common constructs for dimensional and geometric tolerances. As shown by Table 1 and Figure 12, some geometric tolerances are used much more frequently than others. This should be expected for position and surface profiles; however, some tolerances might be considered to be underrepresented such as angularity, circular runout, coaxiality, cylindricity, line profile, straightness, symmetry, and total runout. If the underrepresented tolerances are more representative of an end-user's commonly used CAD models, then the test cases and verification results might not be a useful gage of the success of the CAD systems to model that type of PMI.

The original test project verification results only provided a high-level success rate of the CAD systems for modeling several broad categories of semantic and graphic PMI. Specific representative errors in those categories were also shown. However, there was no breakdown of the verification results by test case, CAD system, or type of annotation. The absolute numbers of errors per those characteristics and observations based on the numbers are shown in Section 4.1 in the Keshif data exploration environment. None of those observations are apparent from the high-level success rate of the CAD systems described in the original documentation of the verification results. The exploratory data analysis (EDA) in Section 5 was also used to show the relative success rate of the pair-wise comparison of CAD system, test case, annotation type, and error type. Other observations were made about the test results based on the EDA.

Some interesting questions arise based on the new analysis:

1. Should the verification results be weighted based on the consequence of an error?
2. How can the test cases be improved so that the distribution of PMI annotations does not bias the results for or against any particular type of PMI annotation?
3. Can either the Keshif analysis or EDA of the verification results show that the CAD systems improved between the 2012 versions used for the CTC and 2015 versions for the FTC?

Question 1 is important because of how PMI annotations are consumed by downstream applications. In some cases, a person might be reading a 2D drawing or viewing a 3D model and can easily interpret an annotation that might not be shown as expected. An example of this is shown in Figure 40 for the error when a dimension has an extra space. This is considered an error, in the context of the testing project, that the annotation with the extra space does not match the annotation in the test case drawing. However, in real-world usage, this error might not be consequential. Of course, many of the semantic PMI errors could have significant consequences when consumed by automated downstream manufacturing and inspection software. These errors could result in parts being manufactured that do not reflect their design intent. The specific types of verification errors need to be inspected to determine how errors might be weighted.

Question 2 is illustrated by analysis in Section 4.1.1 where the large number of similar datum targets in CTC 2 skews the verification results against any CAD system that has difficulty with those types of datum targets. Since CTC 2 has eight point datum targets, the verification results are skewed against CAD C as shown in Figure 33. The effect of the distribution of PMI annotations in the test cases in skewing the verification results needs to be investigated.

Question 3 might be answered by the mean probability of success for all test cases and CAD systems. For the FTC (2015 CAD systems), it is 0.96 while for the CTC (2012 CAD systems) the value is 0.97. By this measure, the answer to the question would be "no" if only using the mean value.

However, parts of the main effects plots for the CTC (Figure 52) and FTC (Figure 61) can be combined (Figure 68) to consider CAD system (X1) and error type (X3). These are the only two factors that are similar between the CTC and FTC. The figure shows that CAD C is better for the FTC than the CTC. However, as explained in Section 4.1.1, CAD C performed worse than expected for the CTC because of a particular annotation type (datum targets). The FTC performed worse for the three semantic PMI error types (1-3). Clearly there are some types of errors that are more significant than others. However, it is difficult to compare the performance of the CAD systems because of the significant differences between the types and number of the PMI annotations in the CTC and FTC and the types of verification errors found for each set of test cases.

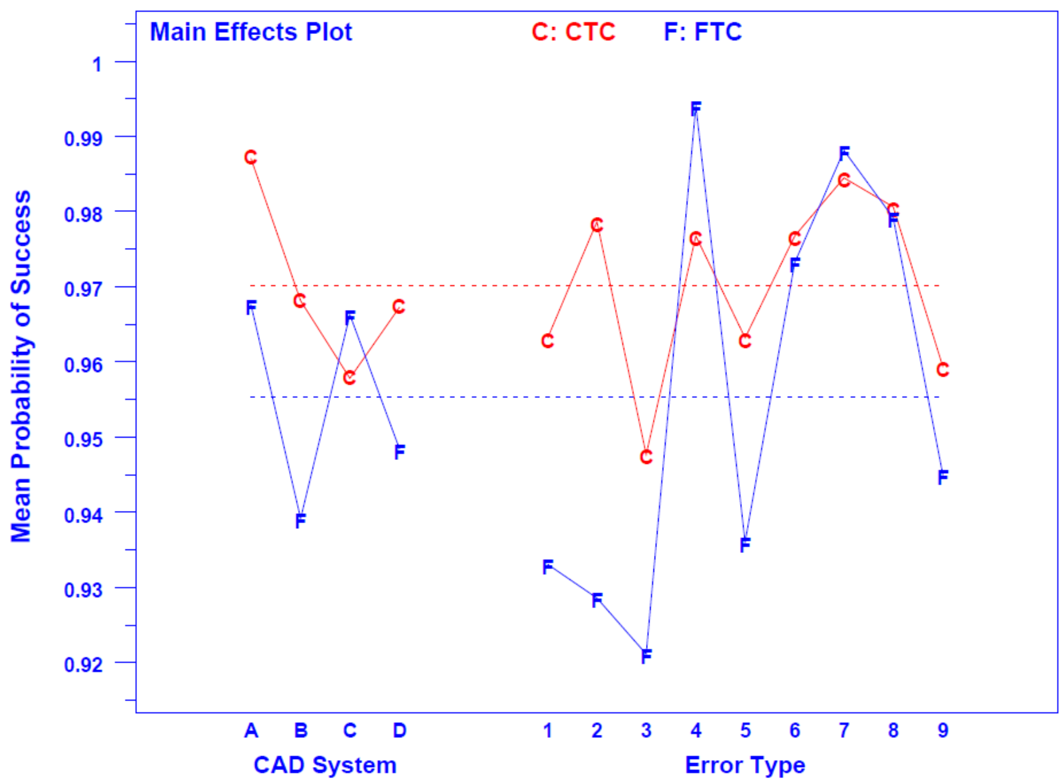

Figure 68: Combined main effects plot for CAD system and error type

Another method to compare the CTC and FTC results is to show how annotation types performed that are common to each set of test cases. Figures 69-72 show that comparison for the four CAD systems for annotation types 1, 2, and 4-9 (dimensions, hole dimensions, datum feature, datum target, position, surface profile, flatness, and perpendicularity). All of the figures show the same trend that the CTC performed better than the FTC. However, for hole dimensions (error type 2), the FTC always performed better than the CTC. This might be due to improvements to the CAD systems or that there were characteristics of the holes that were harder to model in the CTC. Figure 71 also shows that the FTC performed better than the CTC for datum targets (error type 5). However, Section 4.1.1 explains that CAD C performed worse than expected for the CTC datum targets. While there is no definitive answer to question 3, the exploratory data analysis shows several visualizations that might be useful to answer that type of question in future testing.

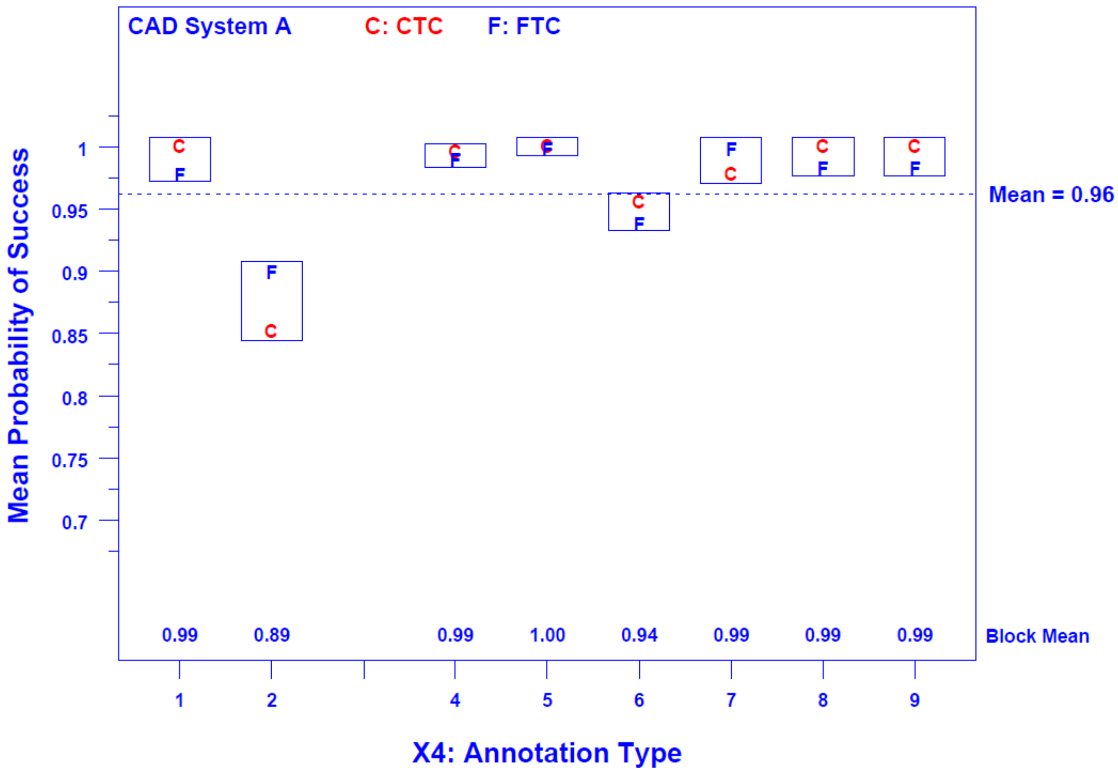

Figure 69: CTC – FTC comparison for select annotation types, CAD system A

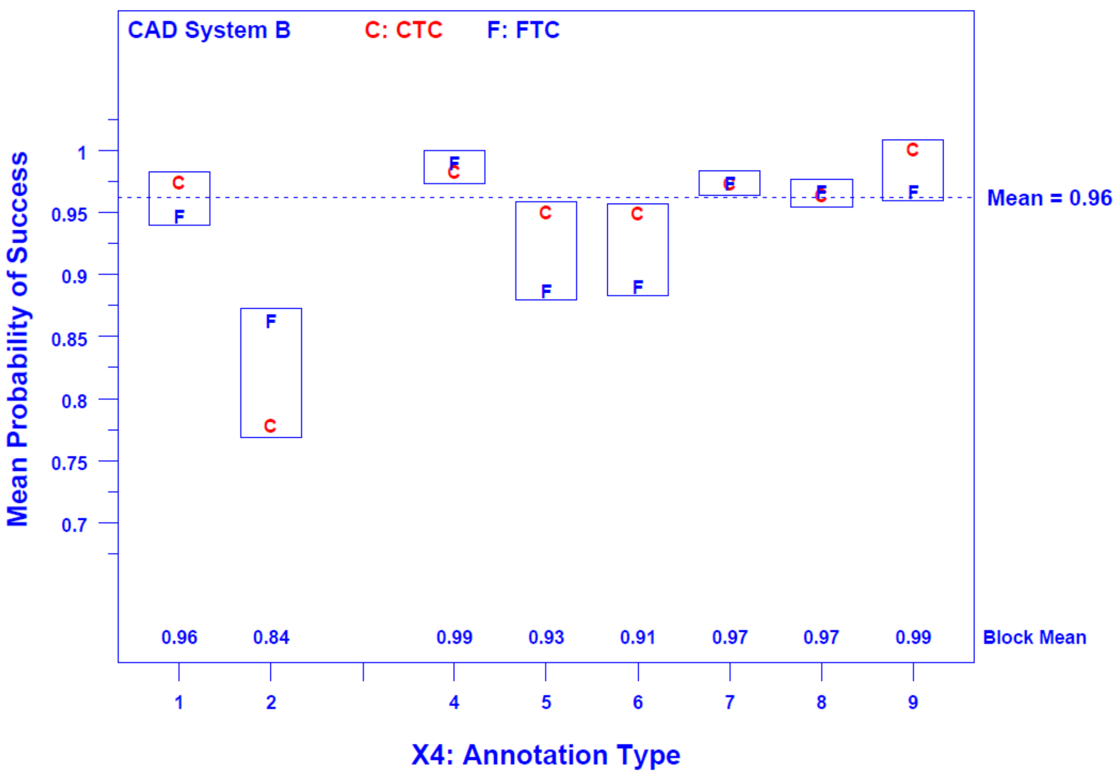

Figure 70: CTC – FTC comparison for select annotation types, CAD system B

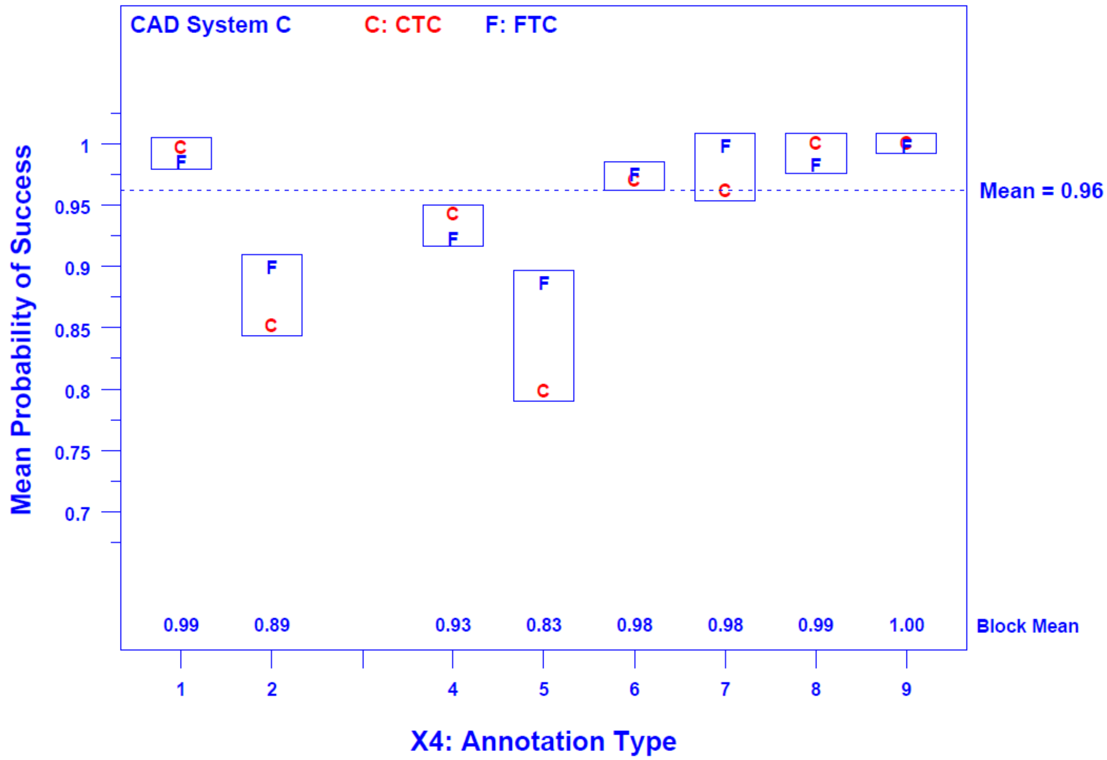

Figure 71: CTC – FTC comparison for select annotation types, CAD system C

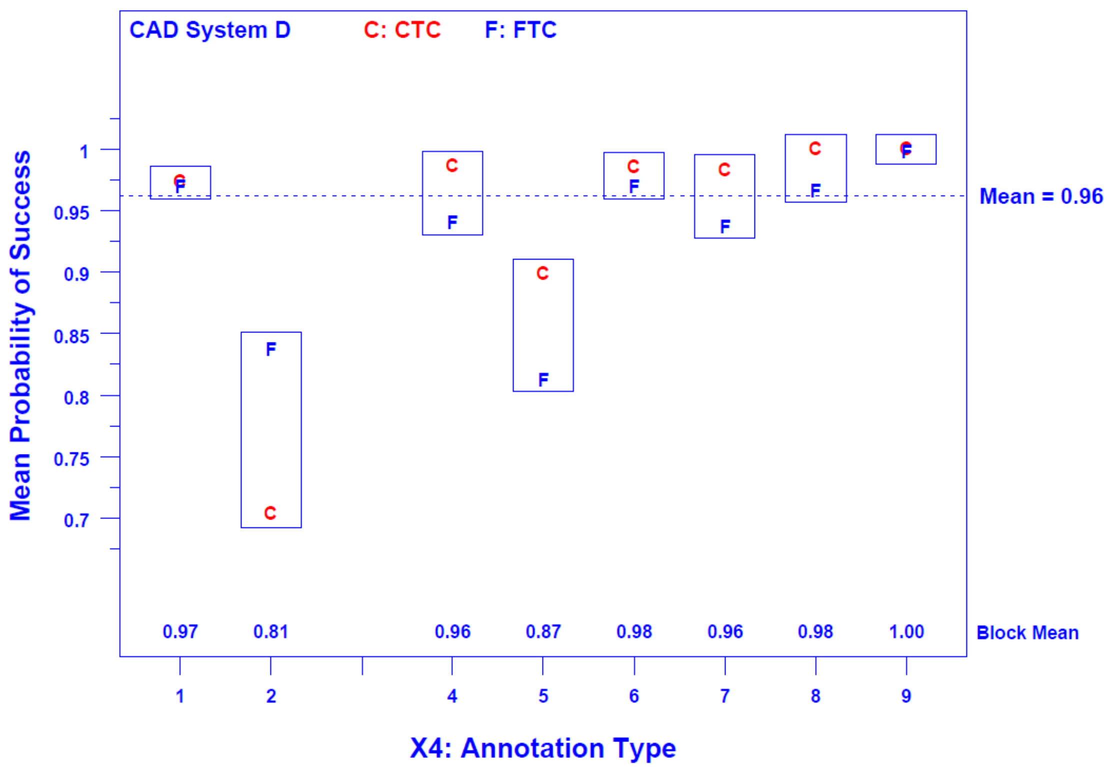

Figure 72: CTC – FTC comparison for select annotation types, CAD system D

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