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Sensitivity analysis of relative worth in empirical and simulation-based QFD matrices

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SENSITIVITY ANALYSIS OF RELATIVE WORTH IN EMPIRICAL AND

SIMULATION-BASED QFD MATRICES

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ABSTRACT

Quality Function Deployment (QFD) is one of the most popular design tools used in product development. One of the objectives of QFD is to map customer requirements to product requirements and calculate their relative worth. A product requirement with a large relative worth indicates that it is an important product requirement in satisfying customer requirements. QFD applications use various rating scales in quantifying the degree of mapping from customer requirements to product requirements and various worth calculation methods to calculate the relative worth. The purpose of this paper is to study the sensitivity of relative worth when different rating scales or worth calculation methods are used. We identified two representative rating scales and two worth calculation methods in QFD matrices published in conference and journal papers (empirical QFD matrices), and used these rating scales and worth calculation methods to study sensitivity of relative worth. Sensitivities of relative worth in empirical QFD matrices and in simulation-generated QFD matrices are compared for validations.

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TABLE OF CONTENTS

ABSTRACT iii

ACKNOWLEDGMENTS iii

LIST OF ILLUSTRATIONS vii

LIST OF TABLES viii

SECTION

1. INTRODUCTION 1

    1.1. QUALITY FUNCTION DEPLOYMENT 1

        1.1.1. Literature Reviews on QFD. 1

        1.1.2. The QFD Matrix. 2

        1.1.3. Degree of Mapping in QFD Matrix.. 3

        1.1.4. Worth Calculation Methods.. 4

2. METHODOLOGY 6

    2.1. DESCRIPTIVE ANALYSIS 6

    2.2. SENSITIVITY ANALYSIS 6

    2.3. CONDITIONS ANALYZED 8

    2.4. SIMULATION ANALYSIS 9

    2.5. EMPIRICAL ANALYSIS 9

3. ANALYSIS RESULTS 10

    3.1. DESCRIPTIVE ANALYSIS RESULTS 10

        3.1.1. Size of QFD Matrices. 10

        3.1.2. Rating Scales. 11

        3.1.3. Proportion of categorical scale 13

        3.1.4. Calculation Schemes. 14

        3.1.5. Summary of descriptive analysis. 14

    3.2. SIMULATION RESULTS 14

        3.2.1. Proportion of change in square matrix.. 15

        3.2.2. Proportion of change with row 17

        3.2.3. Proportion of change with column. 18

    3.3. EMPIRICAL RESULTS 20

3.3.1. Histogram of Data.. 21
3.3.2. Proportion of Changes in Relative Worth. 22
3.4. COMPARISON OF SIMULATION AND EMPIRICAL RESULTS. 23
4. CONCLUSIONS AND FUTURE WORK 28
APPENDICES
A. CUMULATIVE FREQUENCY OF DIFFERENCES 39
B. COMPARISON OF EMPIRICAL AND SIMULATION MATRICES 42
BIBLIOGRAPHY 51
VITA 53

LIST OF ILLUSTRATIONS

Figure 1.1. QFD I matrix 2
Figure 1.2. Example of QFD I for a Can Opener... 5
Figure 2.1. Cumulative distribution of differences... 7
Figure 2.2. Comparison of cumulative distributions. 8
Figure 3.1. Dimension of QFD Matrices. 10
Figure 3.2. Comparison of Rating Scales. 11
Figure 3.3. Types of Linear Scales. 12
Figure 3.4. Types of Exponential Scales. 12
Figure 3.5. Relative frequency of categories. 13
Figure 3.6. Worth Calculation Schemes. 14
Figure 3.7. Proportion of differences larger than or equal to +0.1. 15
Figure 3.8. Proportion of differences smaller than or equal to -0.1................................. 16
Figure 3.9. Proportion of differences larger than or equal to +0.1 17
Figure 3.10. Proportion of differences smaller than or equal to -0.1............................... 18
Figure 3.11. Proportion of differences larger than or equal to +0.1 19
Figure 3.12. Proportion of differences smaller than or equal to -0.1............................... 20
Figure 3.13. Histogram of the QFD matrices segmented by the number of column........ 21
Figure 3.14. Proportion of differences larger than or equal to +0.1 22
Figure 3.15. Proportion of differences smaller than or equal to -0.1............................... 23
Figure 3.16. Proportional Changes Larger Than or Equal to +0.1 for EA-LA................. 24
Figure 3.17. Proportional Changes Less Than or Equal to -0.1 for EA-LA..................... 25
Figure 3.18. Proportional Changes Larger Than or Equal to +0.1 for EA–EW. 26
Figure 3.19. Proportional Changes Less Than or Equal to -0.1 for EA–EW. 26

LIST OF TABLES

Table 1.1. Degree of mapping 4
Table 1.2. Relative worth comparison 5
Table 2.1. Conditions 8
Table 2.2. Sizes of simulation-generated QFD matrices 9

1. INTRODUCTION

1.1. QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD)[1-4] is considered one of the most popular tools used in product development process. It relates customer requirements to system requirements. Using QFD matrices, engineers can specify which system requirements and components are more important in satisfying customer requirements. QFD is used as one of the core tools in concurrent engineering. King[1] introduced 30 QFD matrices used for different purposes including value engineering, reliability engineering, and Failure Modes and Effects Analysis (FMEA). Akao[2] presented more than 10 QFD matrices in four different categories: quality, technology, cost, and reliability deployment The benefits of QFD in system development include cost reduction[3], fewer design changes after the start of production[3], and improved communication among engineers[5]. QFD matrices consist of a variety of matrices used for mapping different inputs to outputs.

1.1.1. Literature Reviews on QFD. As Quality Function Deployment method is very popular among engineers, numerous amounts of studies are made based on it. The most discussed ones are made by Hazelrigg[6], Scott and Antonsson[7], and Olewnik and Lewis[8]. Hazelrigg claims that the group decision making process used in QFD is invalid, with the help of Arrows Impossibility Theorem. On the other hand, Scott and Antonsson discuss that Arrow's Impossibility Theorem does not apply to design decision making, because it is multi-criteria decision making rather than group decision making. Olewnik and Lewis shows that one choice of quantitative scale over another has no effect on the final outcome in terms of rank and relative worth by doing simulation of rating scales in a single QFD matrix and using the average value of relative worth's calculated for different conditions. In this study, 227 QFD matrices are used to find the effect of rating scales and worth calculations schemes on changes in relative worth.

1.1.2. The QFD Matrix. Figure 1.1 illustrates one of the most popular QFD matrix, known as QFD I or "House of Quality" that maps customer requirements to system requirements, and QFD II matrices that maps system requirements to part requirements (QFD II-R) or to parts (QFD-S).

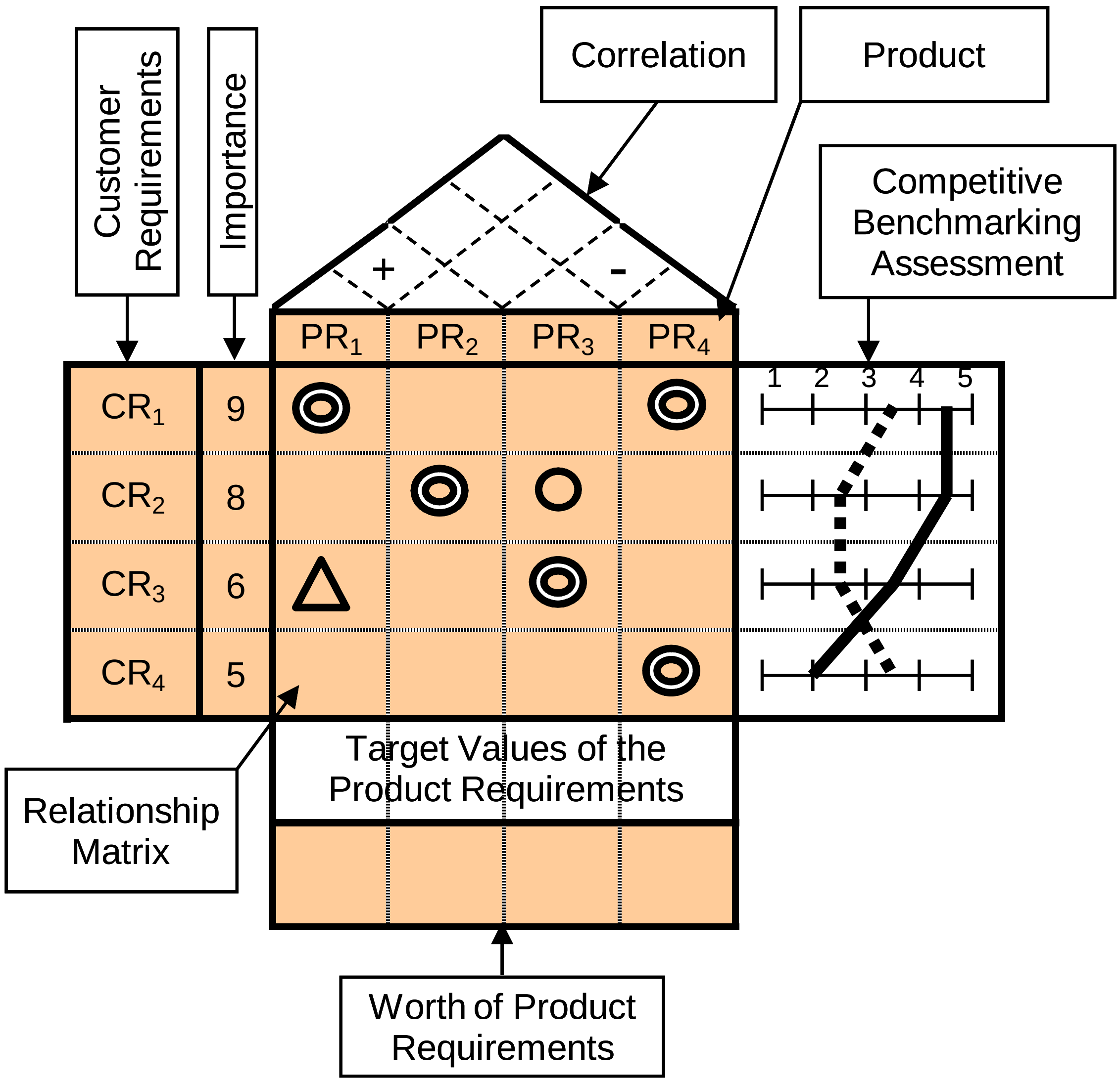


Figure 1.1. QFD I matrix

A typical QFD matrix, also known as "House of Quality" or QFD I, that consists of eight components:

- Customer requirement
- Importance of customer requirement
- System requirements
- Relationship matrix
- Worth of system requirements
- Target values of system requirements
- Correlation matrix

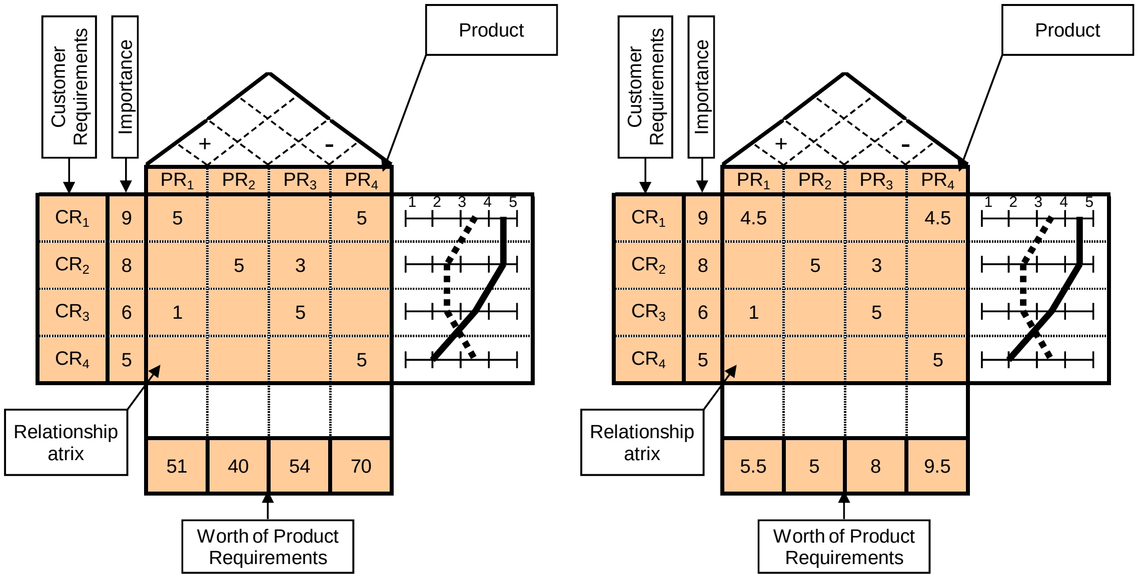
In a QFD I matrix, engineers identify a set of customer requirements (CRs) and its importance using marketing surveys. Then engineers establish product requirements (PRs) needed to satisfy customer requirements. The relationship matrix summarizes the degree of mapping from customer requirements to product requirements. Target values of product requirements are the specific value that a product needs to achieve for each product requirement. The correlation matrix illustrates how changing a target value of one product requirement influences target values of other product requirements. Finally, competitive assessment compares a product with competitors' products by how well products satisfy each customer requirement.

1.1.3. Degree of Mapping in QFD Matrix. In a QFD relationship matrix, the degrees of mapping from customer requirements to product requirements are first assessed using symbols representing categorical scales, such as None-Small-Medium-Large. Then the categorical scales are converted to rating scales to calculate the relative worth of customer requirements. Examples of rating scales are 1-2-3 [11, 13], 1-3-5 [12] for linear scale and 1-2-4[10] for exponential scale. Table 1.1 illustrates examples of conversion from a categorical scale to a rating scale. When a linear 1-3-5 scale is used, None is converted to 0 or blank, Small to 1, Medium to 3, and Large to 5. Similarly, when a linear 1-3-5 scale is used, None is converted to 0 or blank, Small to 1, Medium to 3, and Large to 9.

Table 1.1. Degree of mapping

Categorical scale		Rating scale	
	Symbol	Linear	Exponential
Large	◎	5	9
Medium	○	3	3
Small	△	1	1
None	Blank	0 or blank	0 or blank

1.1.4. Worth Calculation Methods. Once categorical scales are converted to rating scales, the worth of product requirements is calculated from the importance of customer requirements and rating scales, and the calculated worth is normalized to obtain the relative worth. Examples of worth calculation methods are the weighted sum (WS) method [11, 12] and the allocated sum (AS) method [13, 10]. Figure 1.2 illustrates the WS method and the AS method when linear 1-3-5 rating scale is used. In the WS method, the worth of product requirements is the weighted sum of ratings in each column of QFD relationship matrix where importance of customer requirements are the weights. For example, in Fig. 1.2 (a), the worth of product requirement PR1 in Fig. 2 is 51 in the WS method because 9x5+6x1=51. In the AS method, the importance of customer requirements is allocated to each product requirement in each row of the relationship matrix according to the ratio of the degree of mapping in the row, and then the allocated importance is added in each column to find the worth of each product requirement. In Fig. 1.2 (b), the importance of customer requirement CR1, 9, is allocated to PR1, and PR4 proportional to the degree of mapping 5:5. The importance of CR1 allocated to PR1 is 4.5 because 9x(5/(5+5))=4.5. The worth of PR1 in Fig. 2 is 5.5 in the AS method because 4.5+1=5.5.



(a) WS method (b) AS method

Figure 1.2. Example of QFD I for a Can Opener

Finally, the relative worth is calculated by normalizing the worth of product requirements as summarized in Table 1.2.

Table 1.2. Relative worth comparison

	PR_1	PR_2	PR_3	PR_4
WS	0.24	0.19	0.25	0.33
AS	0.20	0.18	0.29	0.34
AS-WS	-0.04	-0.01	0.04	0.01

The relative worth of product requirements (relative worth hereafter) differs when different rating scales and worth calculation methods are used. For example, the last row of Table 1.2 (AS-WS) illustrates the differences in relative worth (differences hereafter) when worth calculation method is changed from WS to AS methods while fixing the rating scale to the linear 1-3-5 scale. In this paper, these differences are used to measure the sensitivity of relative worth due to changes in rating scales or worth calculation methods.

2. METHODOLOGY

2.1. DESCRIPTIVE ANALYSIS

The descriptive characteristics of QFD matrices studied are their *sizes, rating scales,* and *worth calculation schemes* used in relationship matrices. A total of 239 QFD matrices published in journal and conference papers (empirical QFD matrices hereafter) are used. All QFD matrices are analyzed descriptively; however, only complete QFD matrices that list the importance of inputs and that have a complete relationship matrix using 3 point rating scale are studied for sensitivity analysis.

The size is the dimensions (number of rows and columns) of the relationship matrices, i.e., the number of inputs and the number of outputs. The rating scale is the type of rating scale used for quantifying the degrees of mapping in the relationship matrices. The types of scales include linear and exponential rating scales. Worth calculation schemes are classified into WS and AS as described in Section 1.1.4.

2.2. SENSITIVITY ANALYSIS

To study how relative worth differs when various rating scales or worth calculation methods are used, the empirical QFD matrices from conference and journal papers are collected. Then identified the most popular linear and the most popular exponential rating scales used for converting categorical scales to rating scales, and the most popular worth calculation methods. The relative frequency of each category in categorical scales (e.g., None, Small, Medium, and Large) is calculated from empirical QFD matrices in order to generate QFD matrices by simulation and to compare the sensitivity of relative worth in the empirical and simulation-generated QFD matrices.

The sensitivity of relative worth is defined in this paper by the proportion of differences that results in larger than or equal to +0.1 or smaller than or equal to -0.1. Figure 2.1 graphically illustrates this proportion using cumulative frequency of differences. In Fig. 2.1, “a” and “b” are the proportion of differences that results in differences smaller than or equal to -0.1 and larger than or equal to +0.1 respectively.

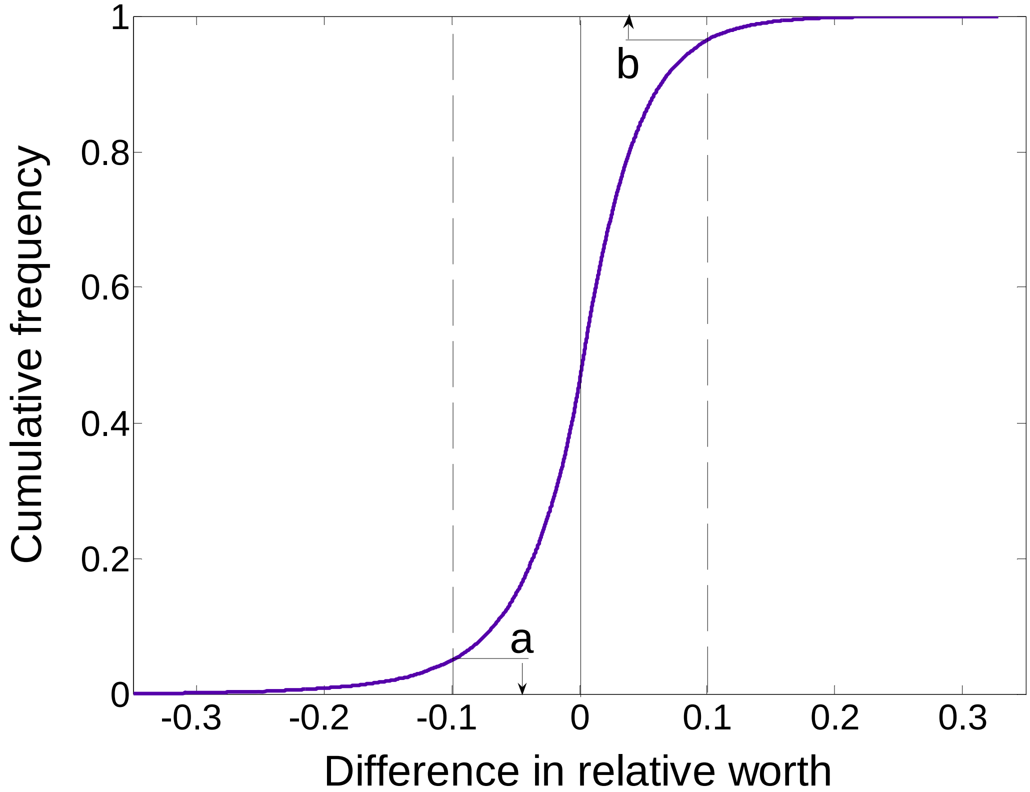


Figure 2.1. Cumulative distribution of differences.

As Fig. 2.2 shows, a and b are smaller if the curve is steeper and the differences are concentrated near zero. Thus a steeper curve indicates that a QFD matrix is less sensitive to changes in rating scales or worth calculation methods.

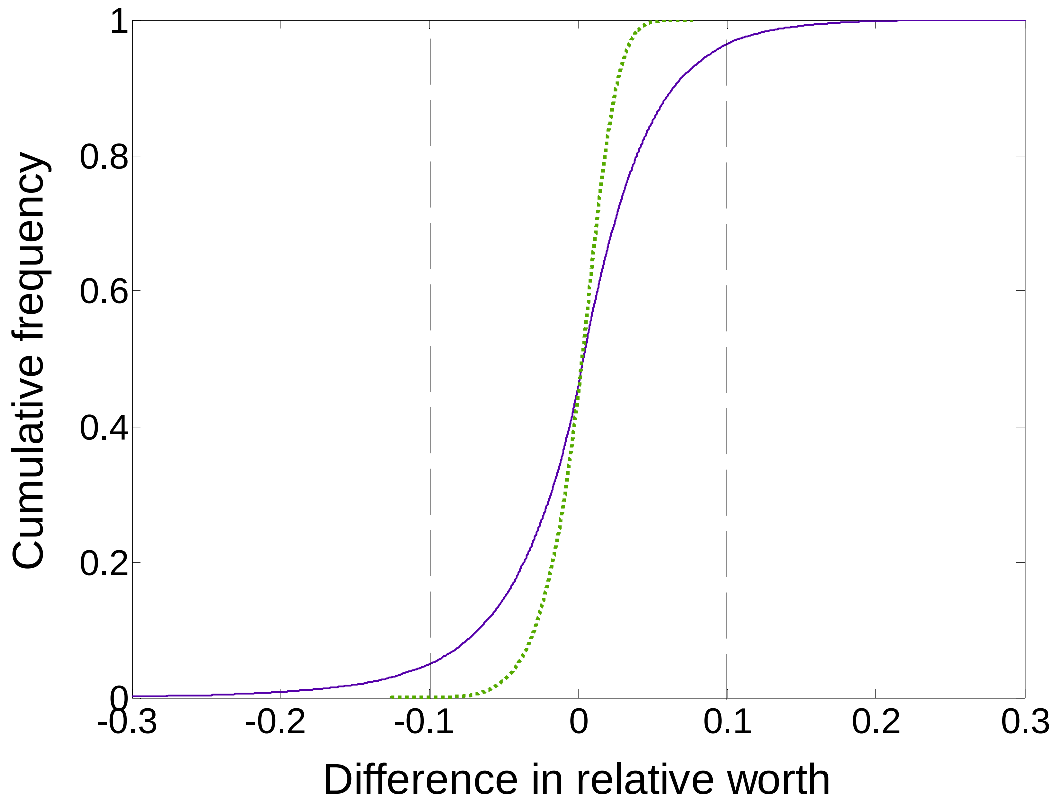


Figure 2.2. Comparison of cumulative distributions.

2.3. CONDITIONS ANALYZED

The four conditions in Table 2.1 shows the change in rating scale from the linear 1-3-5 (L) to the exponential 1-3-9 (E) while fixing the worth calculation method (WS or AS), and changing the WS method (W) to the AS method (A) while fixing the rating scale (L or E).

Table 2.1. Conditions

Condition	Rating scale	Worth calculation
EW–LW	Change L to E	Fix W
EA–LA	Change L to E	Fix A
LA–LW	Fix L	Change W to A
EA–EW	Fix E	Change W to A

2.4. SIMULATION ANALYSIS

In the simulation analysis, 10,000 QFD matrices for each QFD matrix size and calculated the relative worth of product requirements. The importance of customer requirements is randomly generated based on a 10-point rating scale, and the entries of QFD relationship matrices are randomly generated using a categorical None-Small-Medium-Large scale. The matrices which have no entry entirely for a row or a column are excluded from the analysis. The categorical scales are converted to the linear 1-3-5 or the exponential 1-3-9 rating scales to calculate the worth and the normalized worth of product requirements.

In order to study the effects of the size, the numbers of rows, and the number of columns to the sensitivity of relative worth, 10,000 QFD matrices using simulation for each of the sizes in Table 2.2 are generated.

Table 2.2. Sizes of simulation-generated QFD matrices

Conditions	Sizes
Change both row and column	2x2, 3x3, up to 10x10
Change row	2x10, 4x10, up to 10x10
Change column	10x2, 10x4, up to 10x10

2.5. EMPIRICAL ANALYSIS

In the empirical analysis, a total of 227 QFD matrices which use three-point rating scale are used. The relative worth of requirements are calculated and compared for the conditions explained in section 2.3. The result of simulation analysis shows that, changing the number of columns have more significant influence than changing the number of rows. Therefore, the QFD matrices are segmented according to the number of columns.

3. ANALYSIS RESULTS

3.1. DESCRIPTIVE ANALYSIS RESULTS

3.1.1. Size of QFD Matrices. A total of 239 QFD matrices from published conference and journal papers, which are complete in the sense that they have all the information necessary to calculate worth of product requirements, i.e., lists of customer requirements and product requirements, importance of customer requirements, and all the entries in the relationship matrix are used in this study. The sizes of these 239 complete QFD matrices are summarized in Fig. 3.1

Number of rows / Number of columns	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	Total number
1																																																													0
2					3																																																								3
3			2	2	17	1			1																																																				23
4				1	16	5		1	1		2																																																		26
5				1	9	1	2	1	1	1	1	1															1																																		19
6						2	2	3	1	1	1		2	2	1	1	2								2																																				20
7				1	2	2	3	8	3	2					1	1																																													23
8					1	2	4	3	1	3	1	1							1		1	2										1																													21
9							1		3	1	1	1				2		1														1																													11
10							2	4	2	4	3	1				1				2		1																																							20
11					1	1			1	1	1																											1																							6
12					2				1	1	1	1		1	2				2		1						1						1																												14
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47																																																													0
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50																																																													0
Total number	0	0	2	6	52	14	14	22	17	16	12	7	5	5	14	7	6	2	8	4	3	4	1	1	3	1	3	0	1	1	0	2	1	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	239

Figure 3.1. Dimension of QFD Matrices.

The minimum number of rows is three and the minimum number of columns is three (3 by 3 matrix). The maximum number of rows is 45 (45 by 14 matrix), and the maximum number of columns is 59 (13 by 59 and 34 by 59 matrix).

3.1.2. Rating Scales. Figure 3.2 compares the relative frequency of linear and exponential rating scales used in the empirical QFD matrices. Exponential scales are used in 87% of the empirical QFD matrices, and linear scales are used in the remaining matrices.

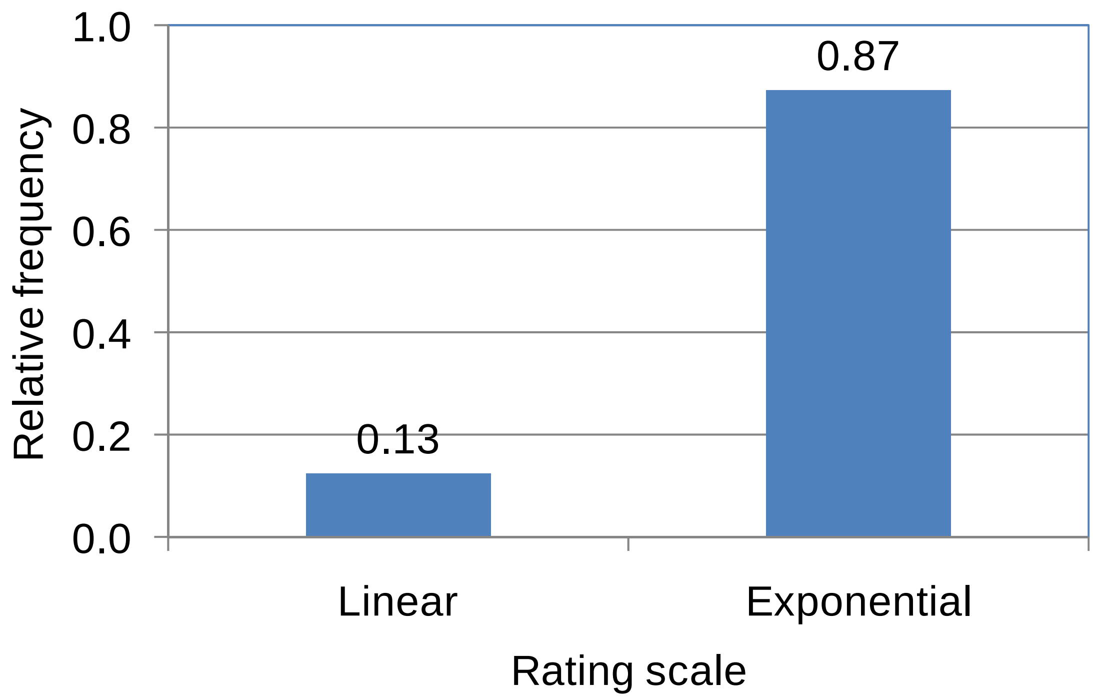

Figure 3.2. Comparison of Rating Scales.

Figures 3.3 and 3.4 summarize the breakdown of linear and exponential rating scales used in empirical QFD matrices. Among linear rating scales, 1-3-5 is the most popular scale that appears in 56% of the empirical QFD matrices that use linear rating scales. Among exponential rating scales, 1-3-9 is the most popular scale that appears in 99% of the empirical QFD matrices that use exponential rating scales. Three-point rating scales are the most popular scales used both in linear and exponential rating scales.

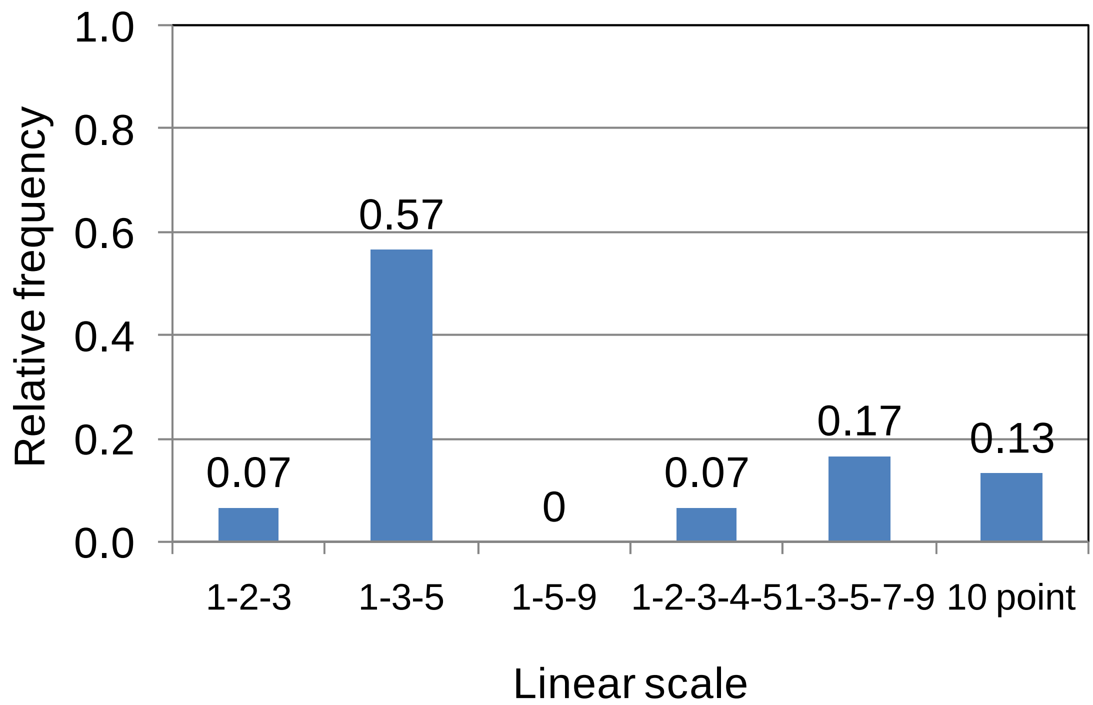

Figure 3.3. Types of Linear Scales.

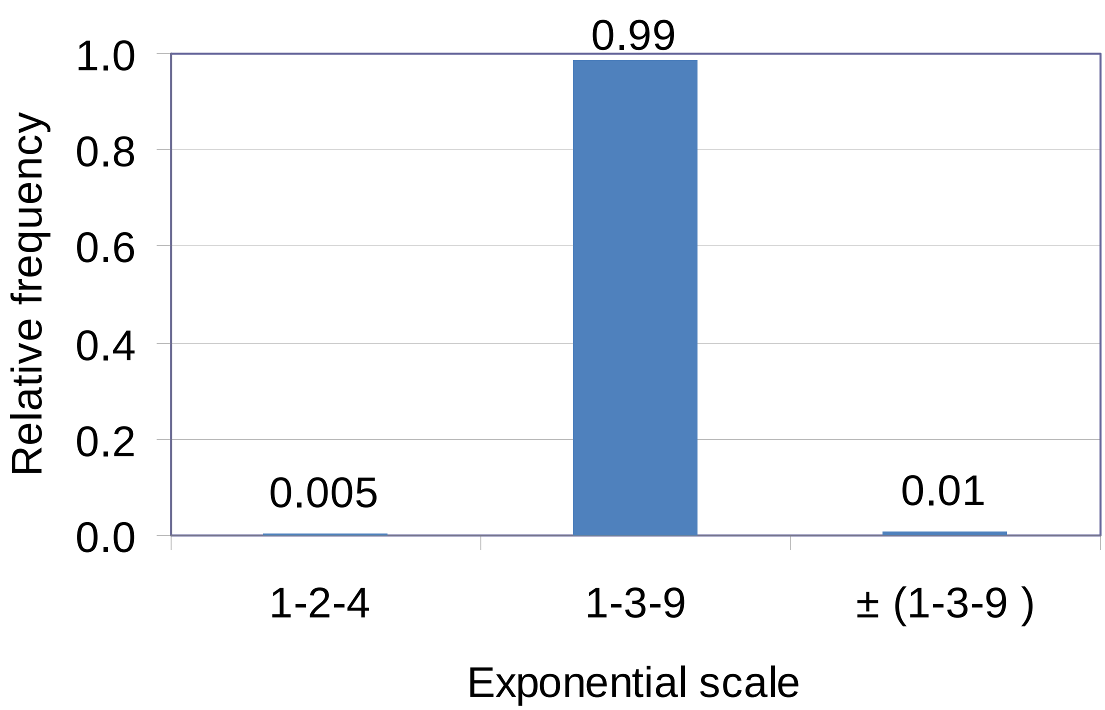

Figure 3.4. Types of Exponential Scales.

Therefore, the further analysis is based on how the relative worth changes when switching from linear 1-3-5 scale to exponential 1-3-9 scale. Five matrices which utilize 5-point, 10-point, and negative rating scales are excluded from the analysis.

3.1.3. Proportion of categorical scale. Because three-point scales are the most popular scales to convert categorical scales to rating scales, the relative frequencies of categories (None, Small, Medium, and Large) in the empirical QFD matrices are calculated. These relative frequencies are used when generating QFD matrices by simulation. Figure 3.5 summarizes the relative frequencies of these categorical scales.

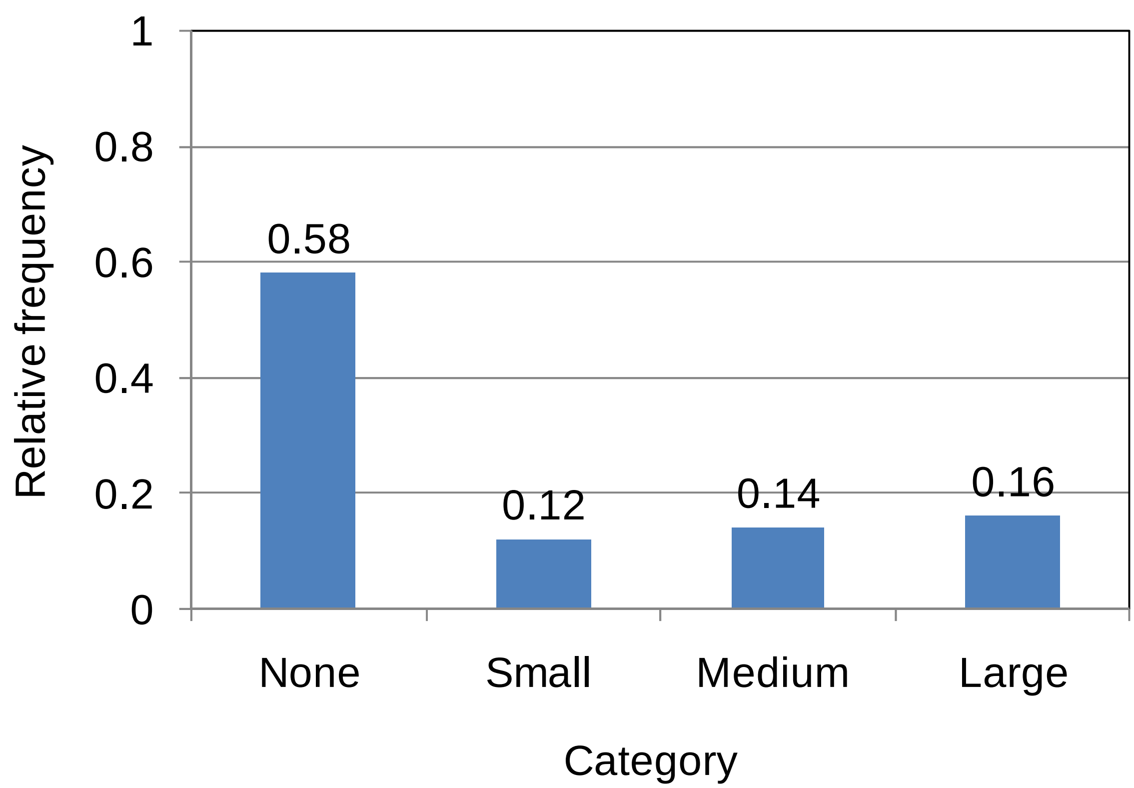

Figure 3.5. Relative frequency of categories.

3.1.4. Calculation Schemes. Figure 3.6 summarizes worth calculation methods observed in the empirical QFD data. 93% of the QFD matrices use the WS method, and the remaining QFD matrices use the AS method. No other worth calculation method is used.

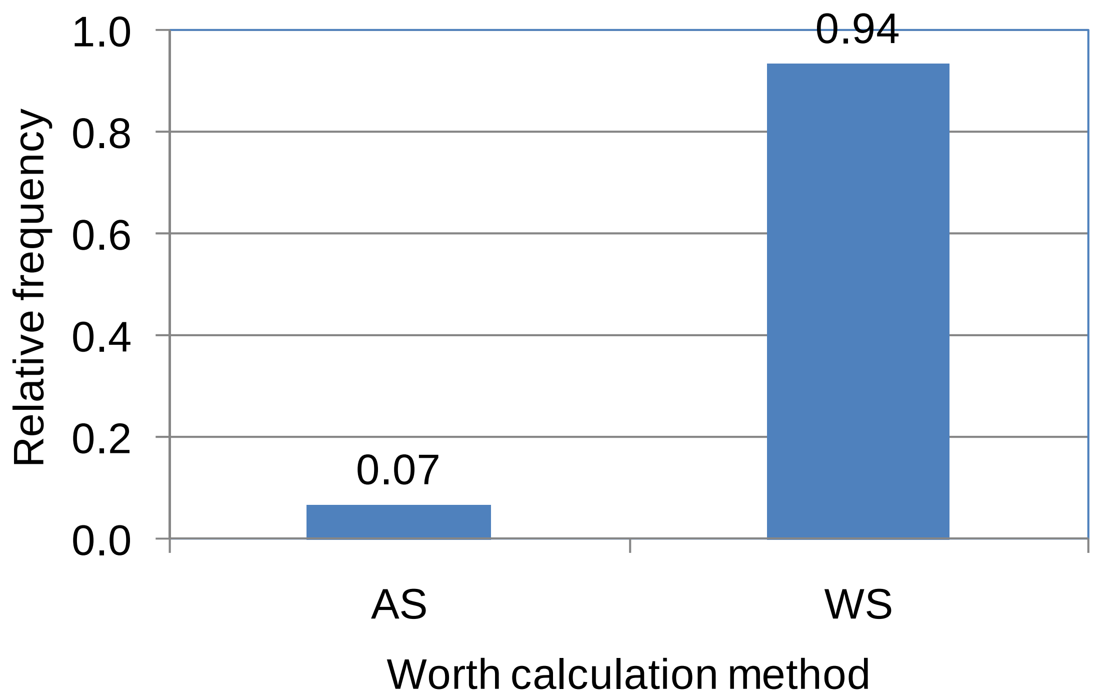

Figure 3.6. Worth Calculation Schemes.

3.1.5. Summary of descriptive analysis. In the descriptive analysis, we observed that 1-3-5 scale is the most popular linear rating scale and 1-3-9 is the most popular exponential rating scale. Only WS and AS are the worth calculation methods used in empirical QFD matrices. Based on these observations, in the sensitivity analysis, we focused on how the relative worth differs when switching from linear 1-3-5 scale to exponential 1-3-9 scale, and from the WS method to the AS method.

3.2. SIMULATION RESULTS

In this section, all the simulation analysis results are compared. Proportion of change in relative worth with changing the dimension is studied. Namely, changing rows and columns simultaneously (square matrix), fixing row or column and changing the other dimension and vice versa.

3.2.1. Proportion of change in square matrix. Figure 3.7 compares the proportion of differences larger than or equal to 0.1 (the proportion corresponding to b in Fig. 2.1) and Fig. 3.8 compares the proportion of differences less than or equal to -0.1 (the proportion corresponding to a in Fig. 2.1) for various sizes of QFD matrices (2x2, 3x3, up to 10x10).

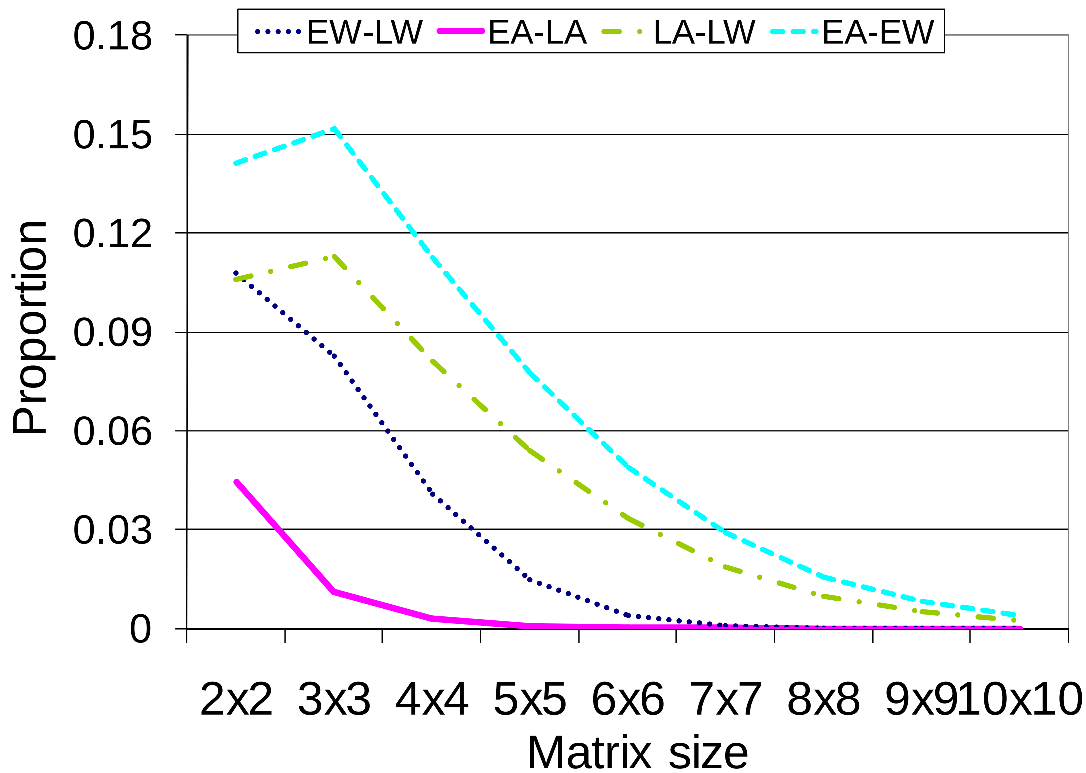

Figure 3.7. Proportion of differences larger than or equal to +0.1.

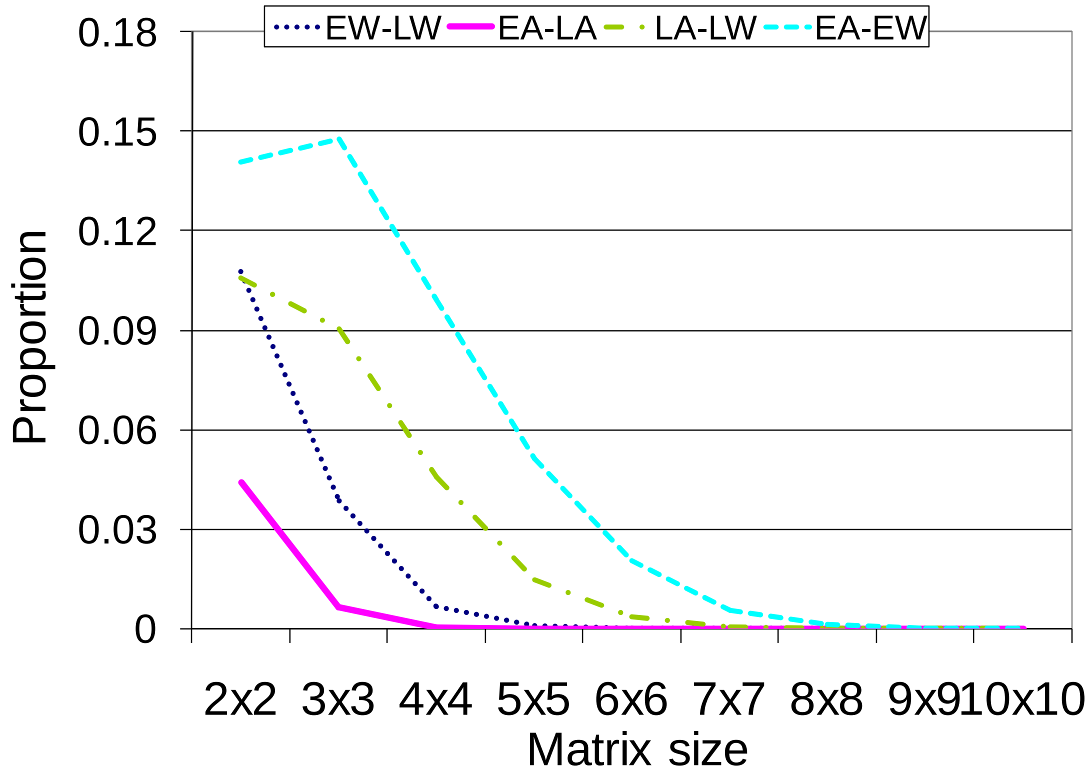

Figure 3.8. Proportion of differences smaller than or equal to -0.1

Figure 3.7 and 3.8 illustrates that the proportion of observing large differences (≥0.1 or ≤0.1) approach zero as the size of the matrix increases. This shows that, large-sized QFD matrices are less sensitive than small-sized QFD matrices. Also, for each size of QFD matrix, changing the rating scales while keeping the worth calculation method fixed (EW-LW and EA-LA) is less sensitive compared to changing the worth calculation methods while keeping the rating scale fixed (LW-LA and EW-EA). Furthermore, we can see that, by changing rating scales (from linear to exponential rating scale) while keeping the worth calculation method fixed to AS method (EA–LA) is the least sensitive condition and changing the worth calculation method (WS to AS) while keeping the rating scale fixed to the exponential scale (EA–EW) is the most sensitive condition. The cumulative frequencies of the differences are illustrated in Fig. A1 of Appendix A.

To find which of the number of rows or the number of columns most influenced differences, we change either the number of rows or columns while keeping the number of the other fixed at 10.

3.2.2. Proportion of Change with Row. The number of columns is fixed at 10 and the number of rows is varied from 2, 3, and up to 10. The proportions of differences of requirements larger than or equal to +0.1 and smaller than or equal to -0.1 are shown in Figs. 3.9 and 3.10 respectively.

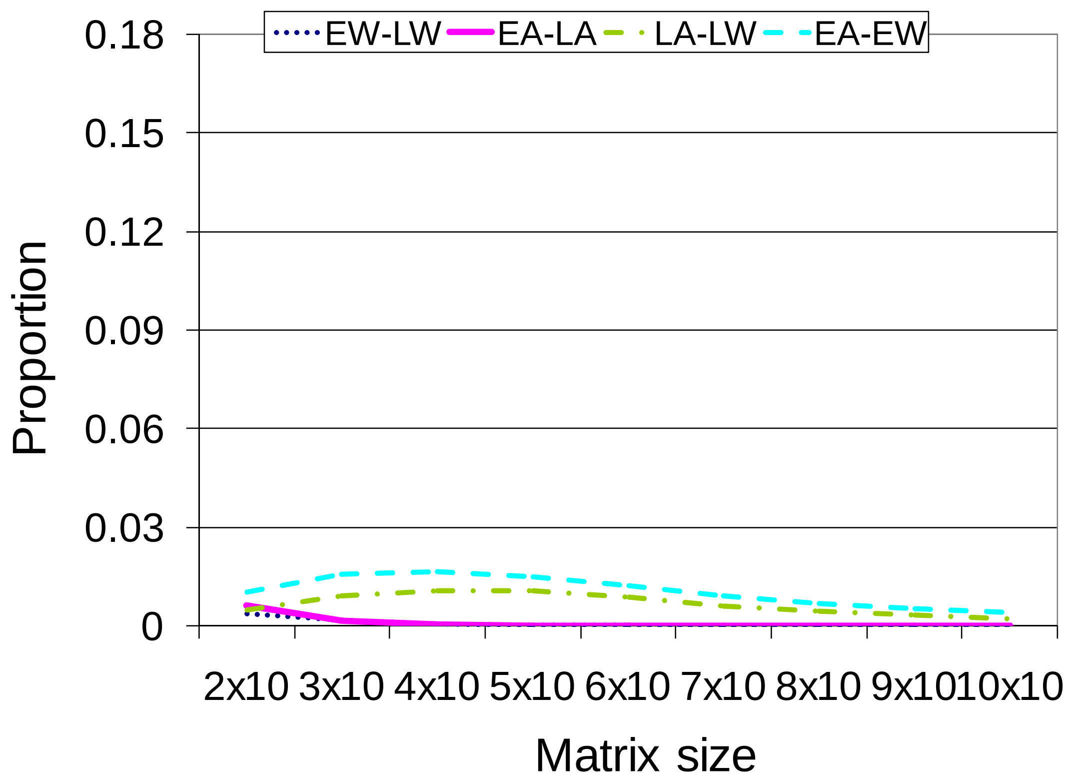

Figure 3.9. Proportion of differences larger than or equal to +0.1

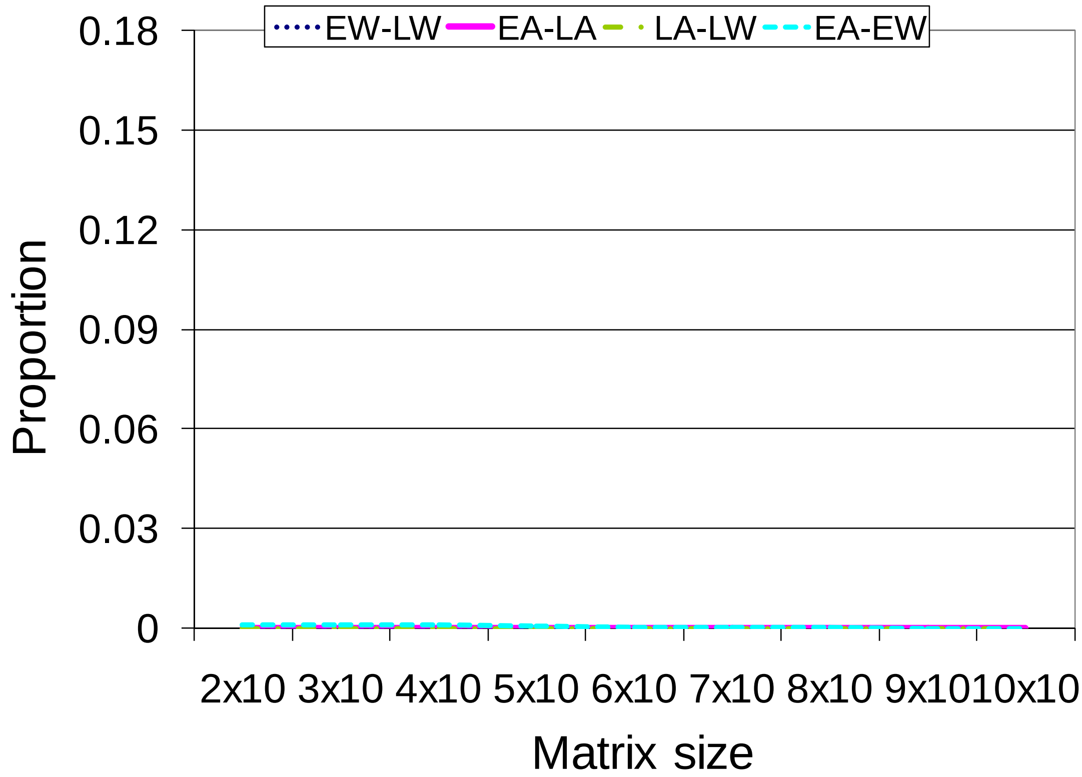

Figure 3.10. Proportion of differences smaller than or equal to -0.1

In the case of changing the number of rows while fixing the number of columns at 10, the proportion of observing large differences is very small (<0.02). Thus we can conclude that changing the number of rows does not have a significant effect on the differences. The cumulative frequencies of the differences are illustrated in Fig. A2 of Appendix A.

3.2.3. Proportion of Change with Column. For this section the number of rows is fixed at 10 and the number of columns is varied from 2, 3, and up to 10. The proportions of differences of requirements larger than or equal to +0.1 and smaller than or equal to -0.1 are shown in Figs. 3.11 and 3.12 respectively.

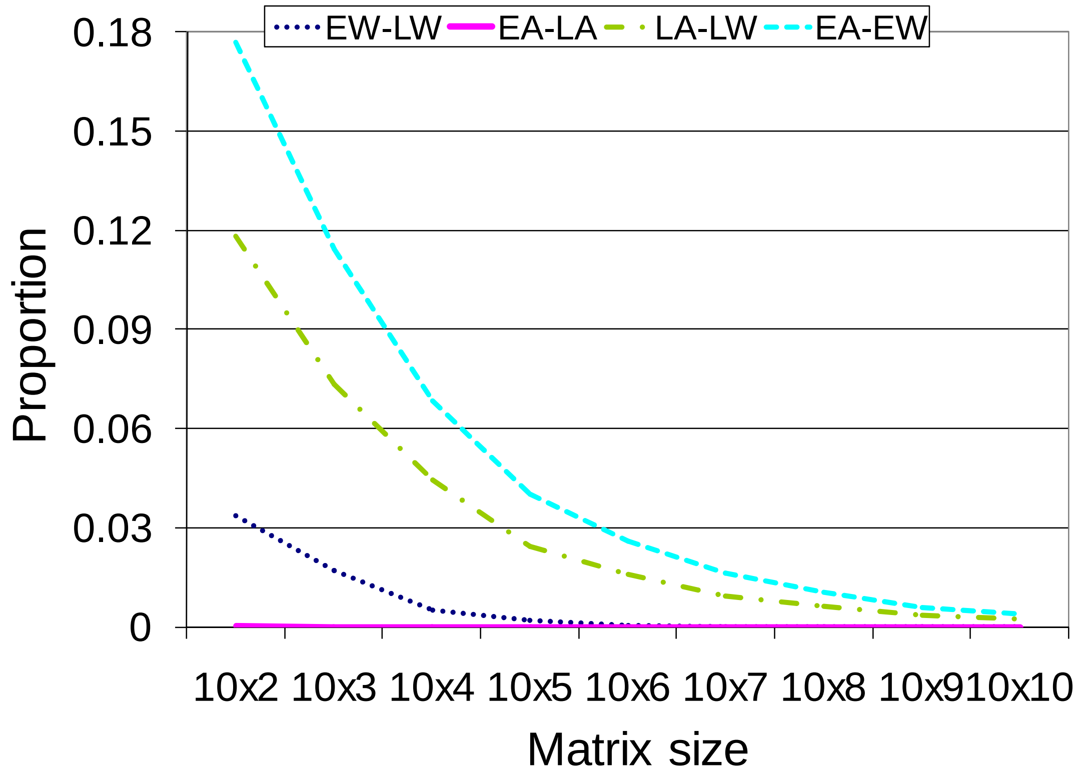

Figure 3.11. Proportion of differences larger than or equal to +0.1

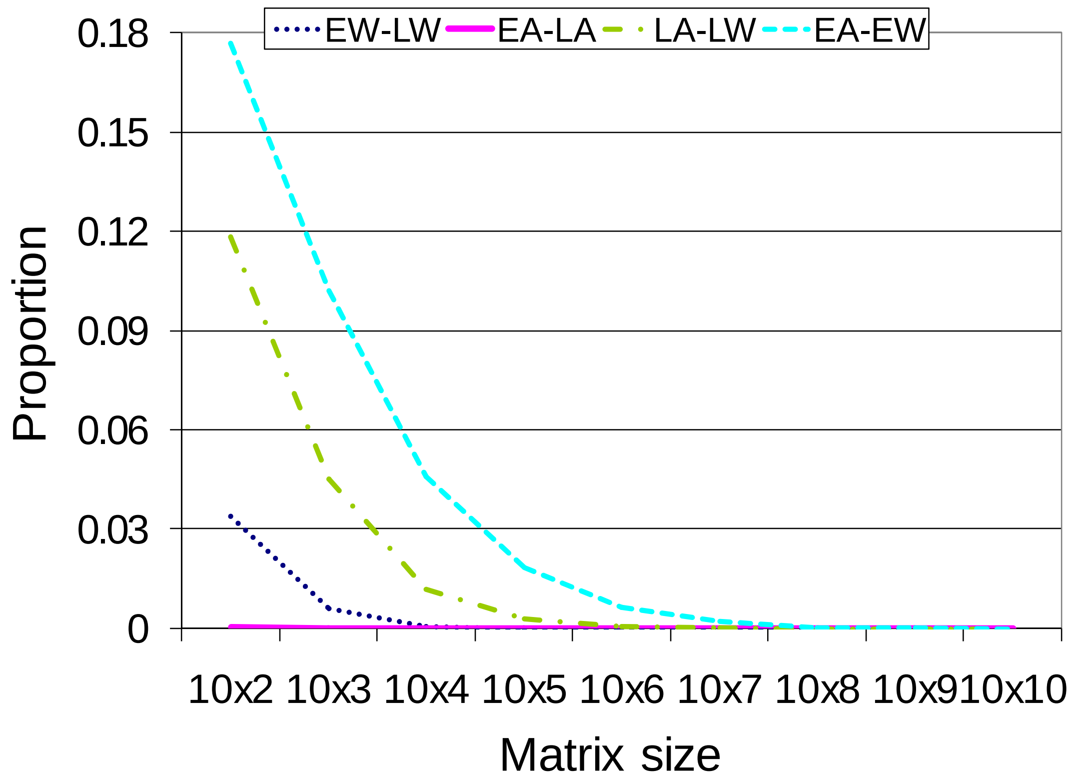

Figure 3.12. Proportion of differences smaller than or equal to -0.1

From Figs. 3.11 and 3.12, the change in the number of columns has a significant effect on the differences as opposed to the change in the number of rows in Figs. 3.8 and 3.9. This effect is particularly significant when the number of columns is relatively small (≤6).

Similar to Figs. 3.7 and 3.8 in which the size of square matrices are varied, QFD matrices become less sensitive as the number of column increases. Similarly, the least sensitive condition (EA–LA) and the most sensitive condition (EA–EW) are the same as those in Figs. 3.7 and 3.8. The cumulative frequencies of the differences are illustrated in Fig. A3 of Appendix A.

3.3. EMPIRICAL RESULTS

3.3.1. Histogram of Data. In the empirical analysis, 227 empirical QFD matrices that use three-point rating scales are selected for sensitivity analysis. From the study of simulation-generated QFD matrices shows that the number of column is influential on the differences, the QFD matrices are segmented by the number of column to have sufficient number of QFD matrices in each condition and then performed the sensitivity analysis on each segment of QFD matrices. Figure 3.13 summarizes the number of QFD matrices segmented by the number of columns: 2-6, 7-10, 11-14, 15-18, and larger than or equal to 19.

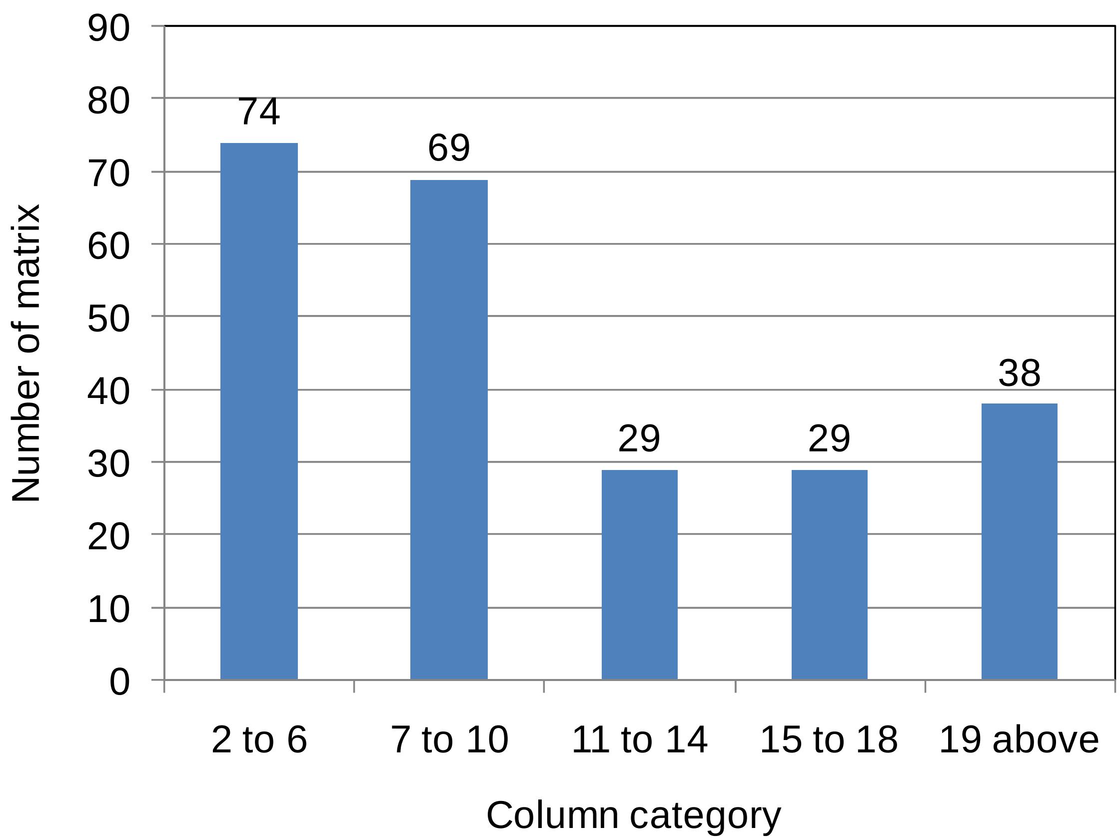

Figure 3.13. Histogram of the QFD matrices segmented by the number of column

3.3.2. Proportion of Changes in Relative Worth. Proportions of observing extreme differences larger than or equal to +0.1 and smaller than or equal to -0.1 are shown in Figs. 3.14 and 3.15 respectively.

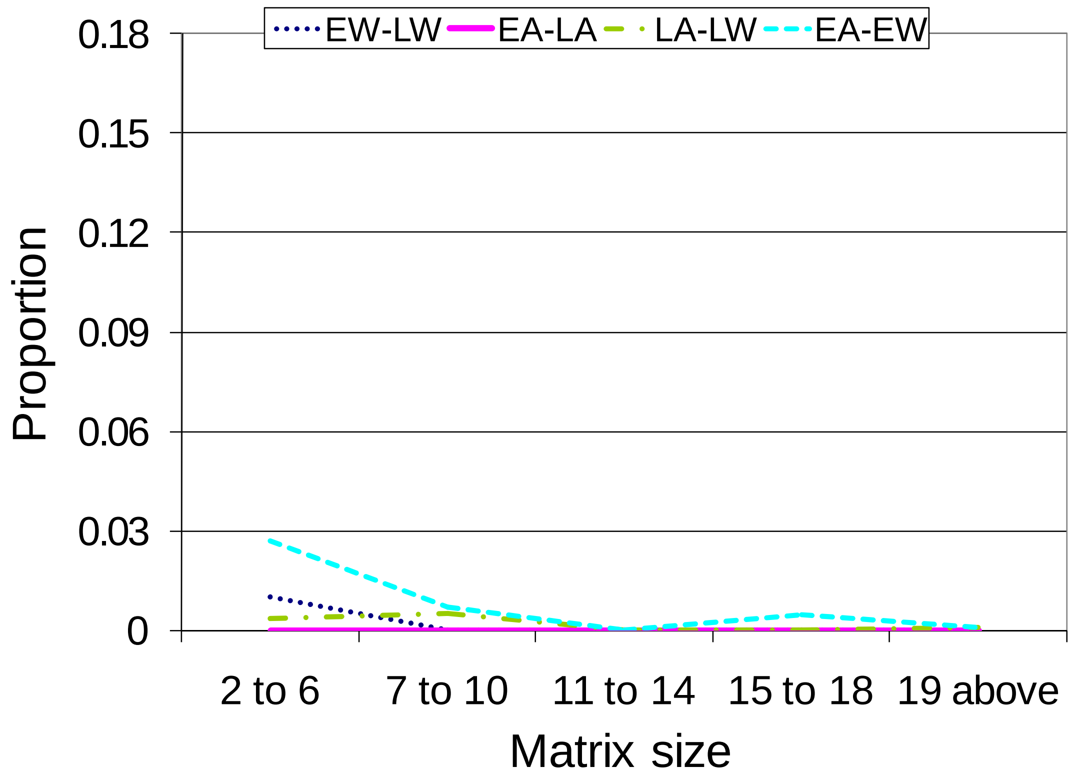

Figure 3.14. Proportion of differences larger than or equal to +0.1

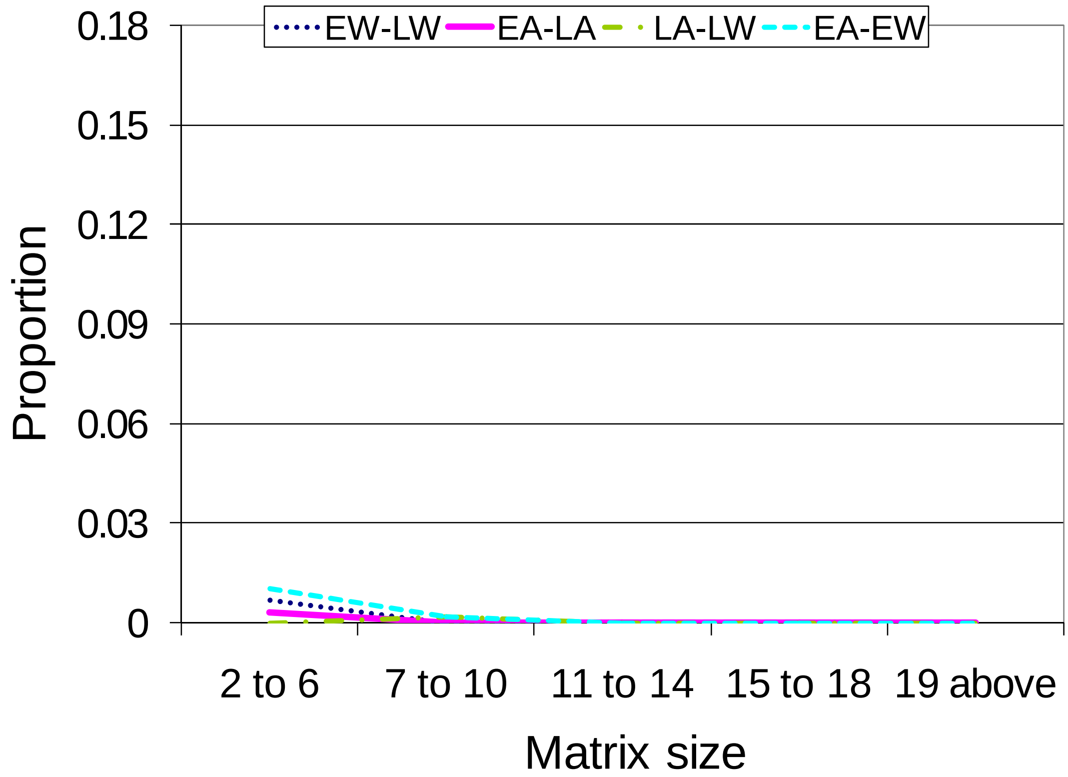

Figure 3.15. Proportion of differences smaller than or equal to -0.1

From Fig's 3.14 and 3.15, it can be seen that, changing the rating scale from linear to exponential while fixing the worth calculation method to the AS method (LA–EA) is the least sensitive condition. On the other hand, changing AS to the WS method by fixing the exponential scale (EW–EA) is the most sensitive condition. Also, the sensitivity decreases as the number of columns increases. This is consistent with the results of the simulation-generated QFD matrices.

3.4. COMPARISON OF SIMULATION AND EMPIRICAL RESULTS.

This section compared the results of the sensitivity analysis using simulation-generated and empirical QFD matrices. Because QFD matrices are segmented by the number of columns, the differences of the empirical QFD matrices with those of the least sensitive (the maximum number of column) and the most sensitive simulation-generated QFD matrices are compared. For example, to compare the sensitivity analysis of empirical QFD matrices with the number of columns between 2 and 6, comparison of empirical results with simulation results for 2x2 and 6x6 is done. Because the sensitivity decreases as the size of QFD matrix decreases (e.g., Figs. 3.7 and 3.8), simulation results of 2x2 is tabulated as upper bound and 6x6 as lower bound. Figures 3.16 and 3.17 compares the proportion of differences larger than or equal to +0.1 and smaller than or equal to -0.1 for the least sensitive condition (EA-LA), and Figs. 3.18 and 3.19 shows the same comparison for the most sensitive condition (EA-EW). The comparison of cumulative frequencies of empirical results and simulation results is compared for the segment 2-6 in Fig. B1 and for the segment 7-10 in Fig. B2 in Appendix B.

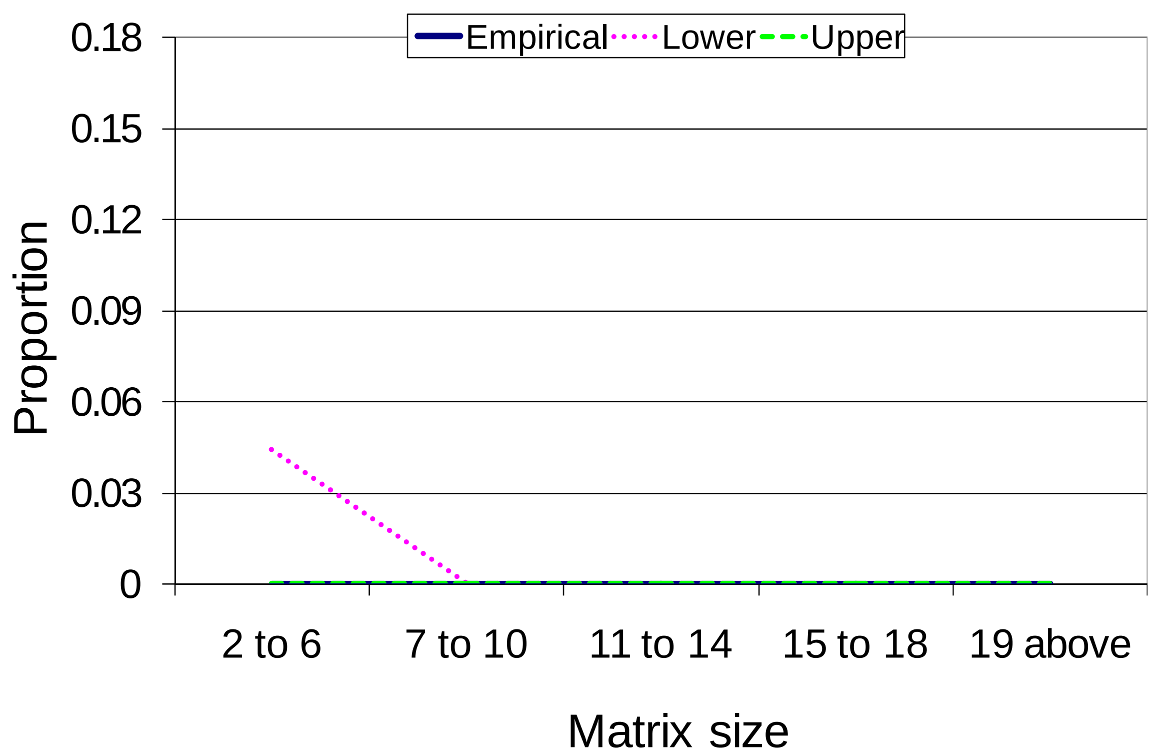

Figure 3.16. Proportional Changes Larger Than or Equal to +0.1 for EA-LA.

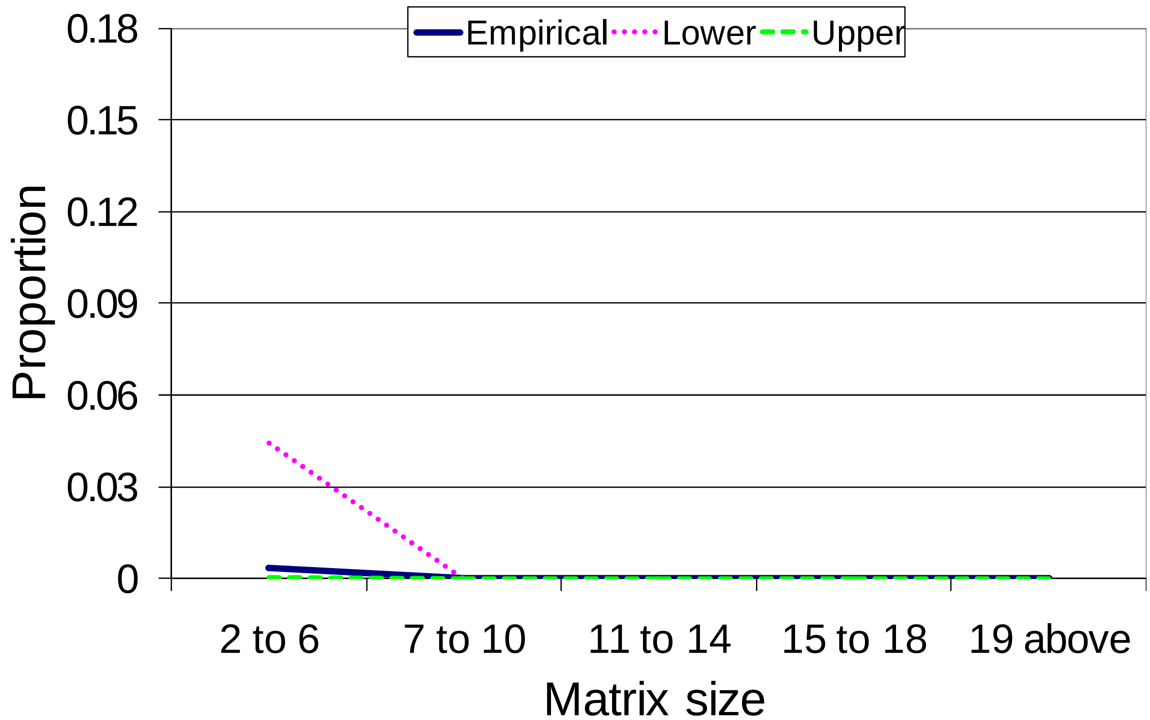

Figure 3.17. Proportional Changes Less Than or Equal to -0.1 for EA-LA.

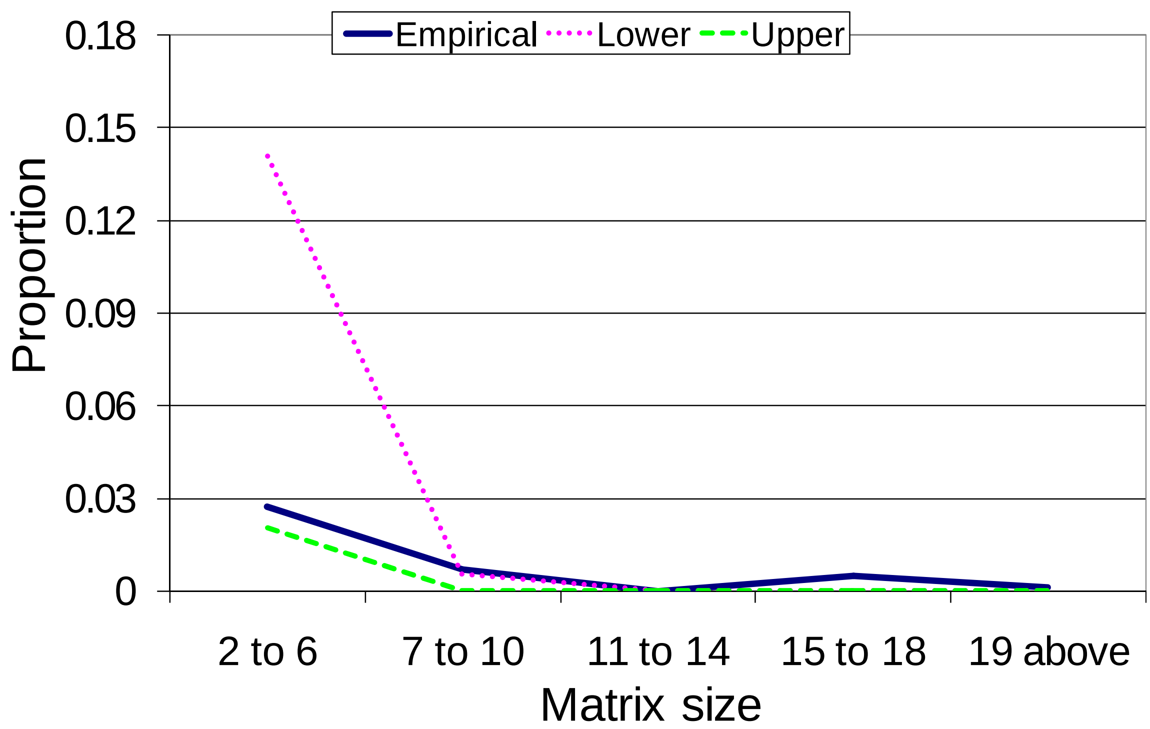

Figure 3.18. Proportional Changes Larger Than or Equal to +0.1 for EA–EW.

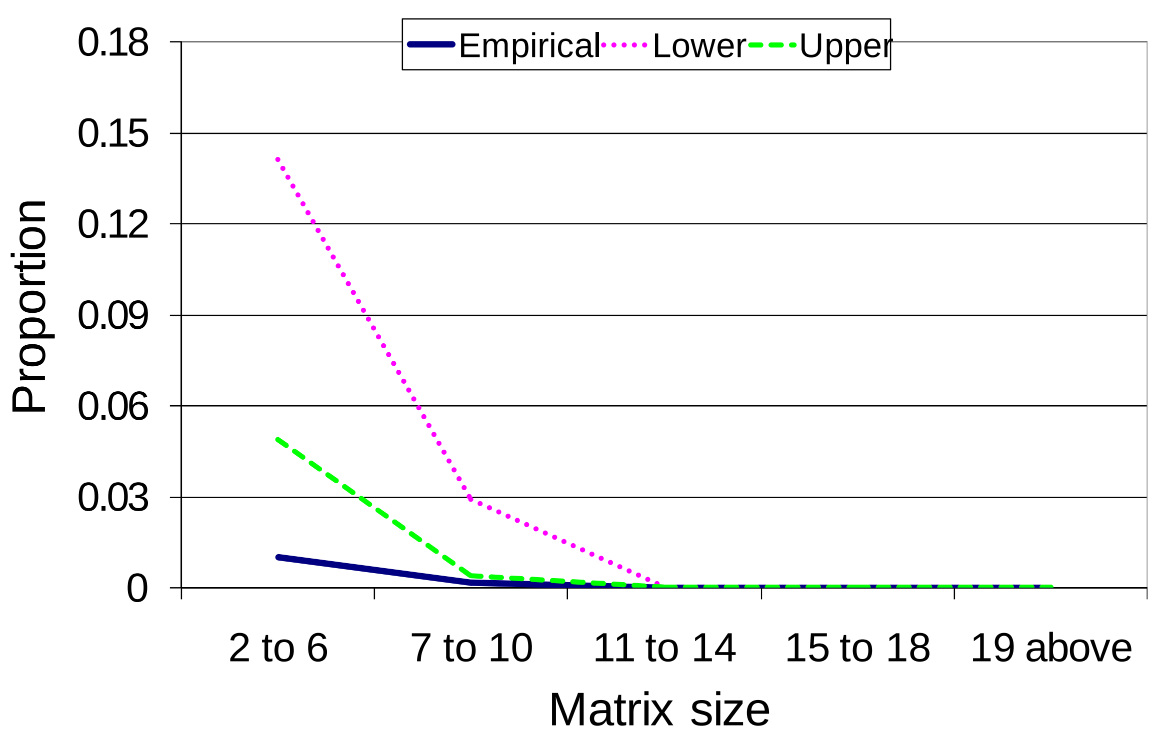

Figure 3.19. Proportional Changes Less Than or Equal to -0.1 for EA–EW.

From Figs. 3.16, 3.17, 3.18, and 3.19, it can be seen that the empirical results lie within the lower and the upper bounds or below the lower bound of the simulation-generated QFD matrices for both, the least sensitive (EA-LA) and the most sensitive condition (EA–EW).

4. CONCLUSIONS AND FUTURE WORK

In this paper, we studied the sensitivity of the relative worth of product requirements in 227 empirical QFD matrices with respect to changes in rating scales (1-3-5 linear and 1-3-9 exponential scales) and worth calculation methods (weighted sum and allocated sum methods). The results of the sensitivity analysis in the empirical QFD matrices are compared with the results of sensitivity analysis in the simulation-generated QFD matrices for validations.

In both empirical and simulation results, it can be seen that, changing from exponential to linear scale while fixing the worth calculation method to AS method (EA–LA) is the least sensitive condition and changing WS to AS method by fixing the exponential scale (EA–EW) is the most sensitive condition. The QFD matrices become less sensitive to changes in rating scales and worth calculation methods as the number of columns increases. The relative worth becomes less insensitive to changes when the number of columns is larger than or equal to 7 in empirical QFD matrices.

Future work includes calculating the minimum and the maximum bounds of the relative worth analytically, and studying the rationale using rating scale (e.g., linear 1-3-5 or exponential 1-3-9) and worth calculation methods (WS and AS).

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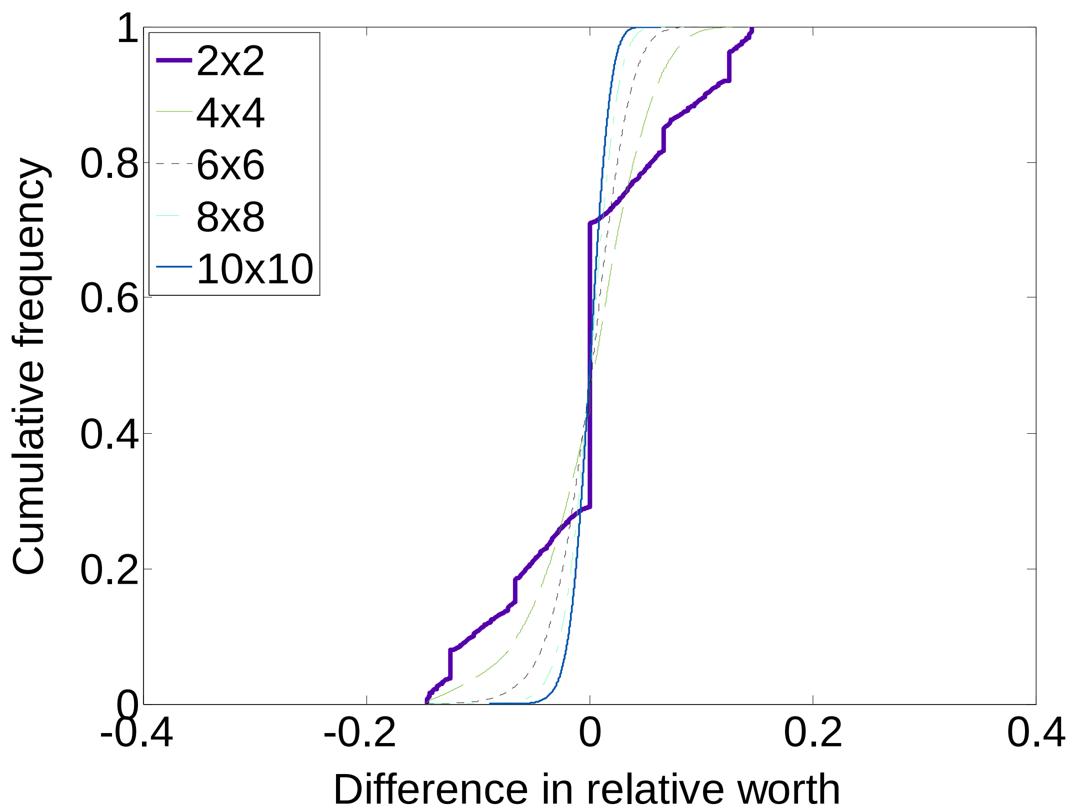
APPENDIX A.

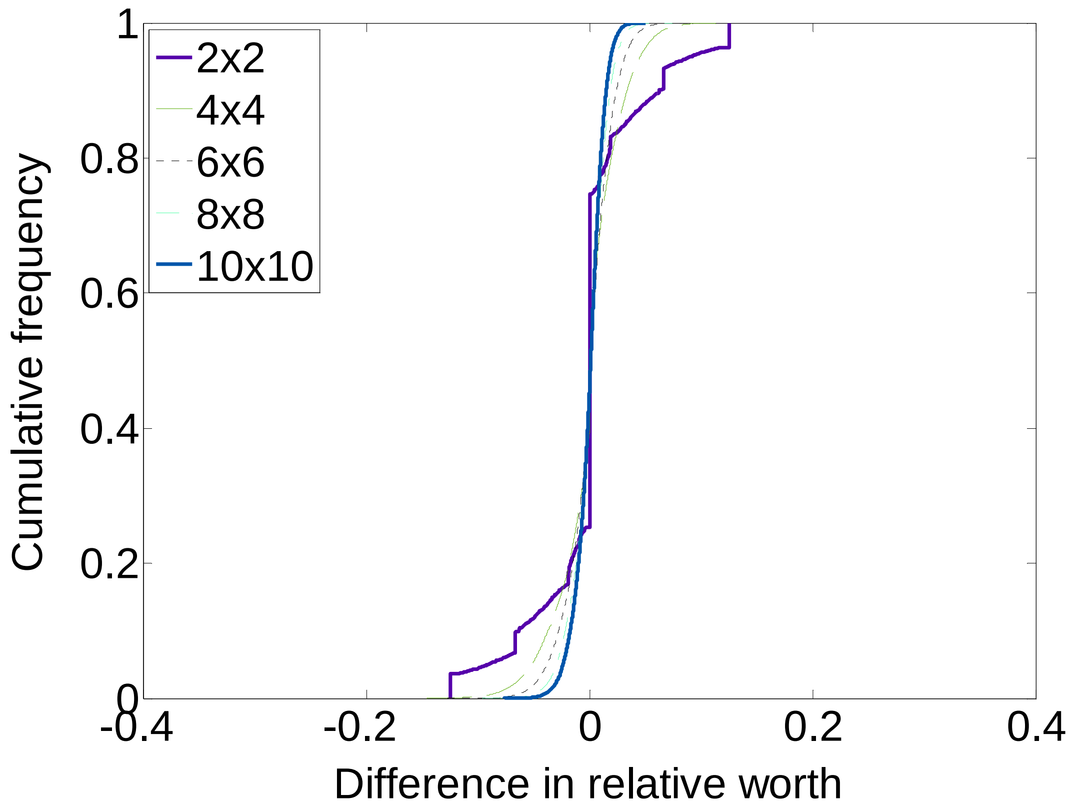
CUMULATIVE FREQUENCY OF DIFFERENCES

A.1 Changing the size of QFD matrix

Figure B1 shows cumulative frequencies of differences in four conditions when changing the size of QFD matrix. In each condition, the relative worth becomes less sensitive to the increase in the size of the matrix, i.e., the cumulative frequency becomes steeper with the increase in the size of QFD matrices.

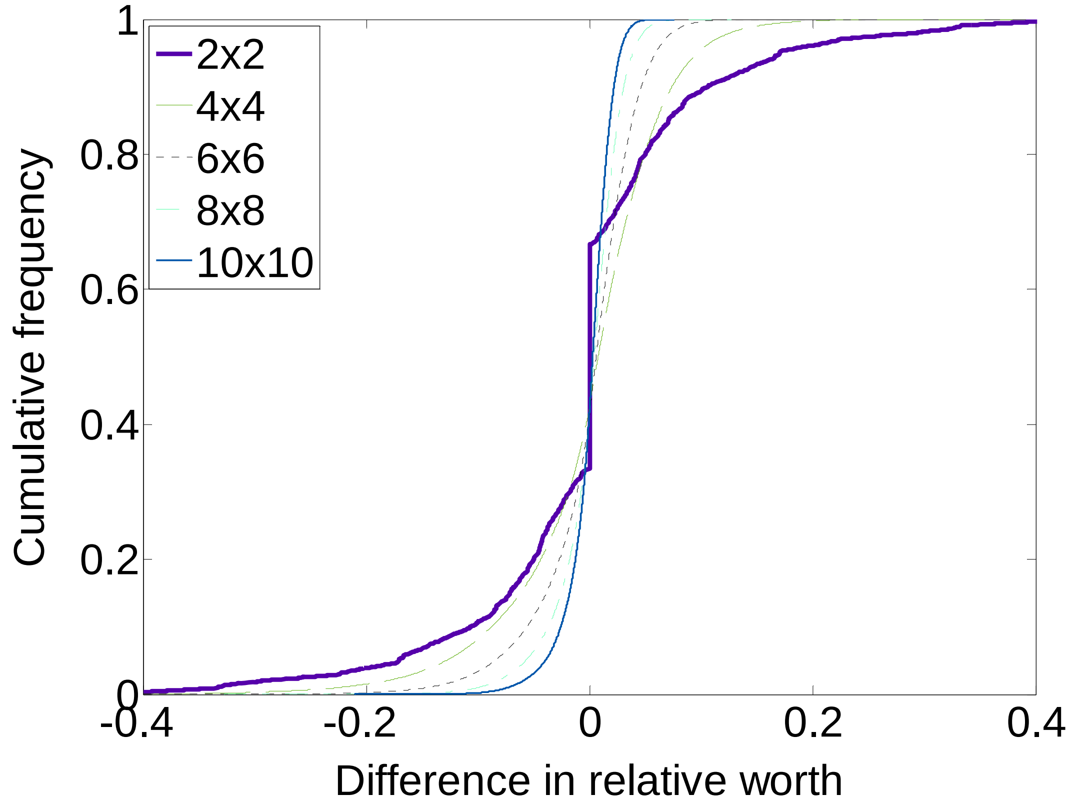


(a) EW-LW



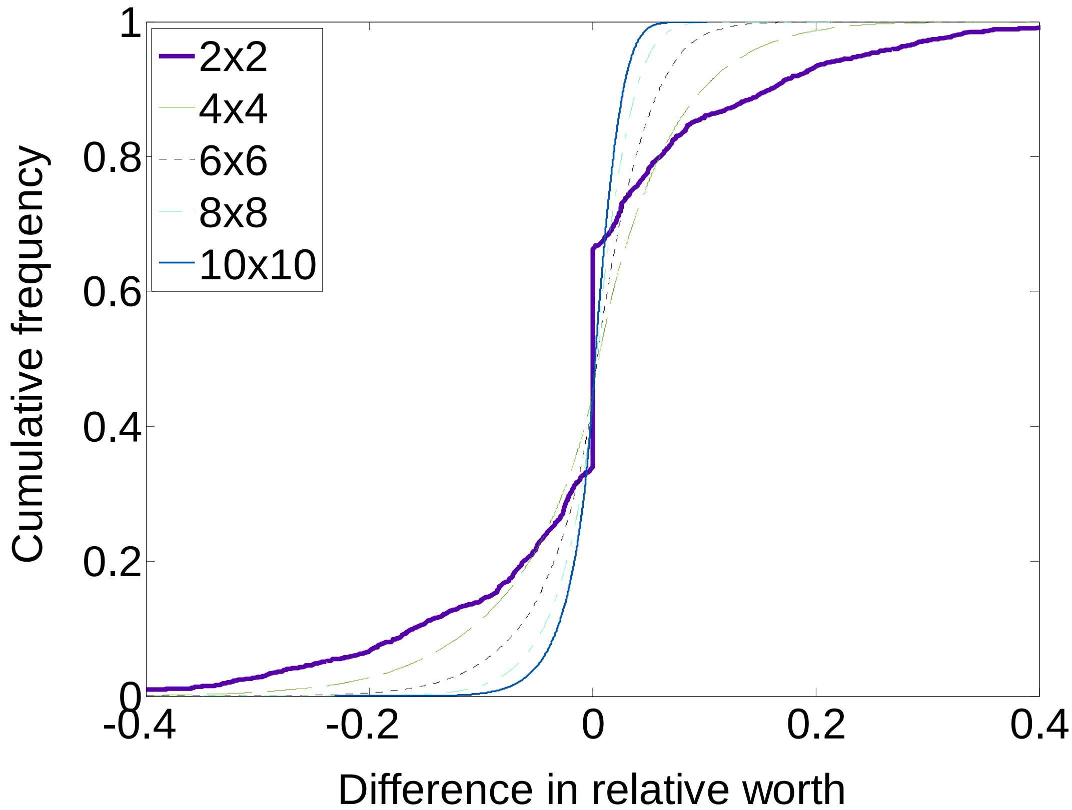
1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
Cumulative frequency
Difference in relative worth
2x2
4x4
6x6
8x8
10x10

(b)EA-LA



1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
Cumulative frequency
Difference in relative worth
2x2
4x4
6x6
8x8
10x10

(c) LA-LW

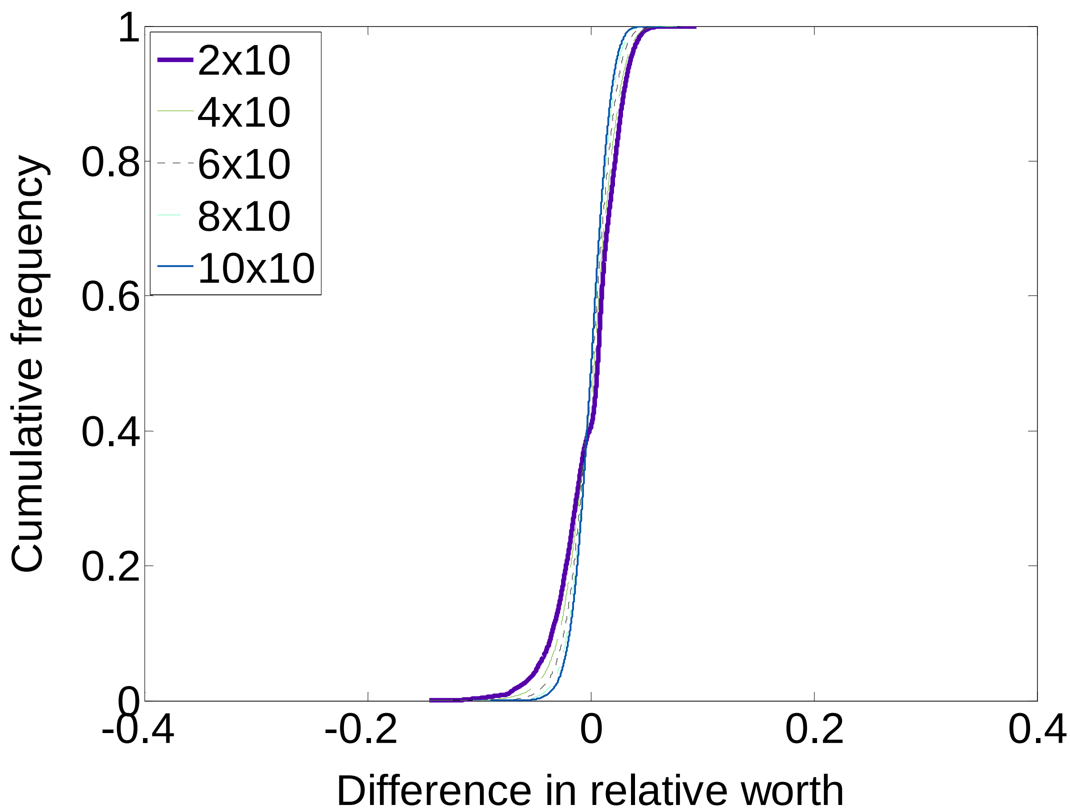


(d) EA-EW

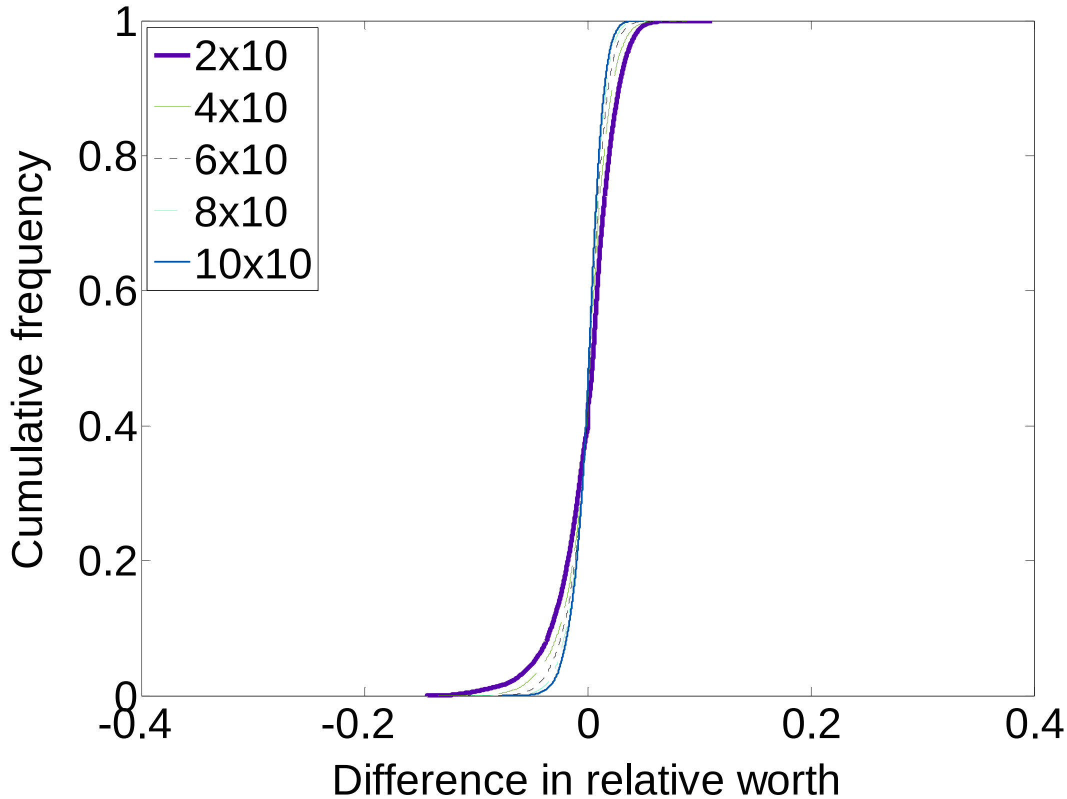
Figure. A1. Effects of the size of QFD matrices

A.2 Changing the number of rows of QFD matrix

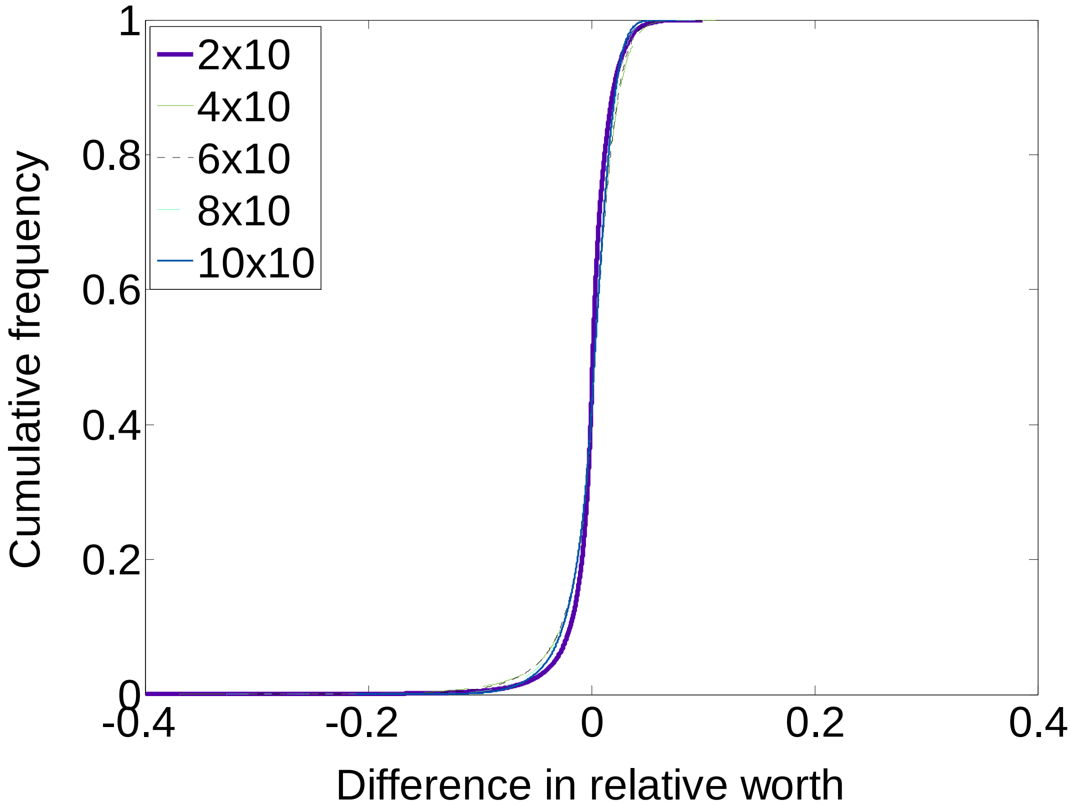
Figure A2 shows cumulative frequencies of differences when changing the number of rows. Figure A2 indicates that cumulative frequency does not change with the number of rows.


2x10
4x10
6x10
8x10
10x10
Cumulative frequency
Difference in relative worth
1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4

(a) EW-LW

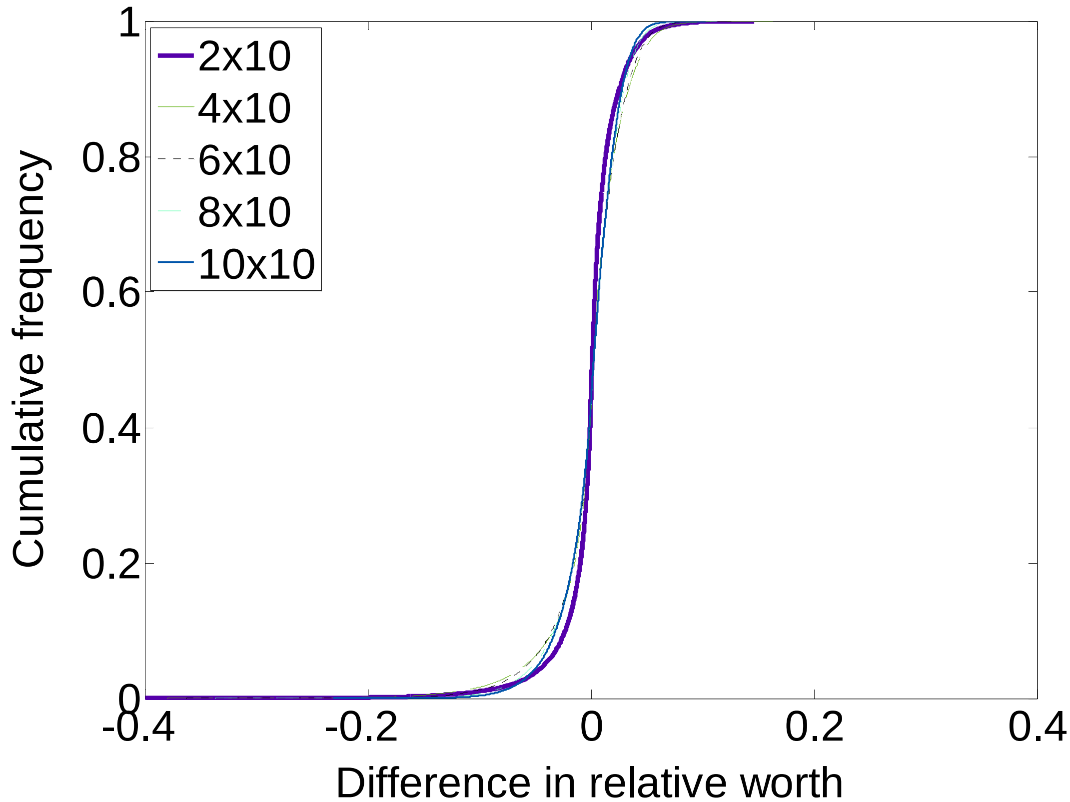

1
0.8
0.6
0.4
0.2
0
Cumulative frequency
2x10
4x10
6x10
8x10
10x10
-0.4
-0.2
0
0.2
0.4
Difference in relative worth

(b) EA-LA



1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
Cumulative frequency
Difference in relative worth
2x10
4x10
6x10
8x10
10x10

(c) LA-LW

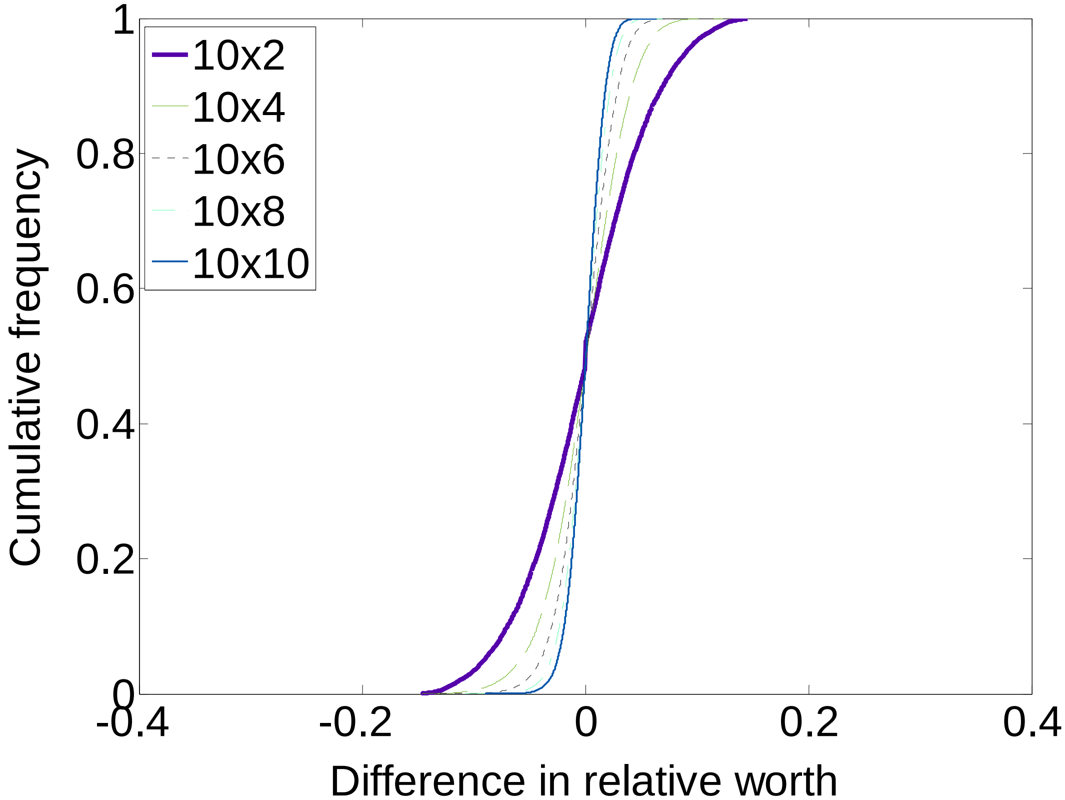


(d) EA-EW

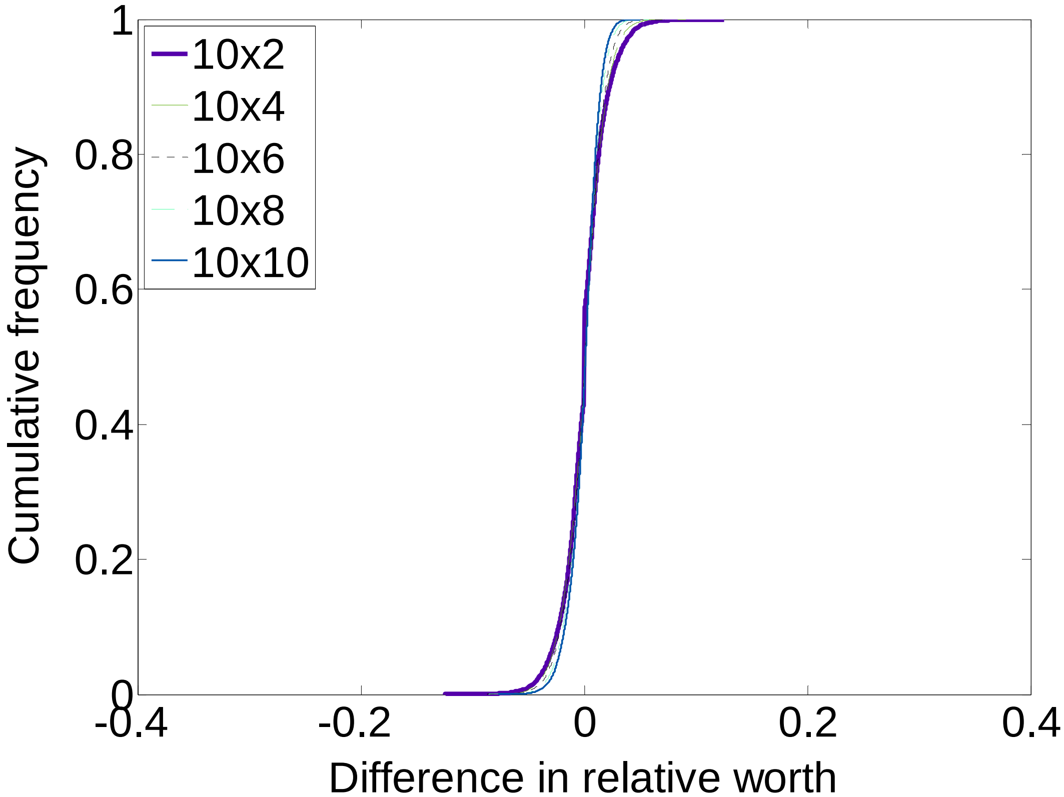
Figure. A2. Effects of the number of rows in QFD matrices

A.3 Changing the number of columns of QFD matrix

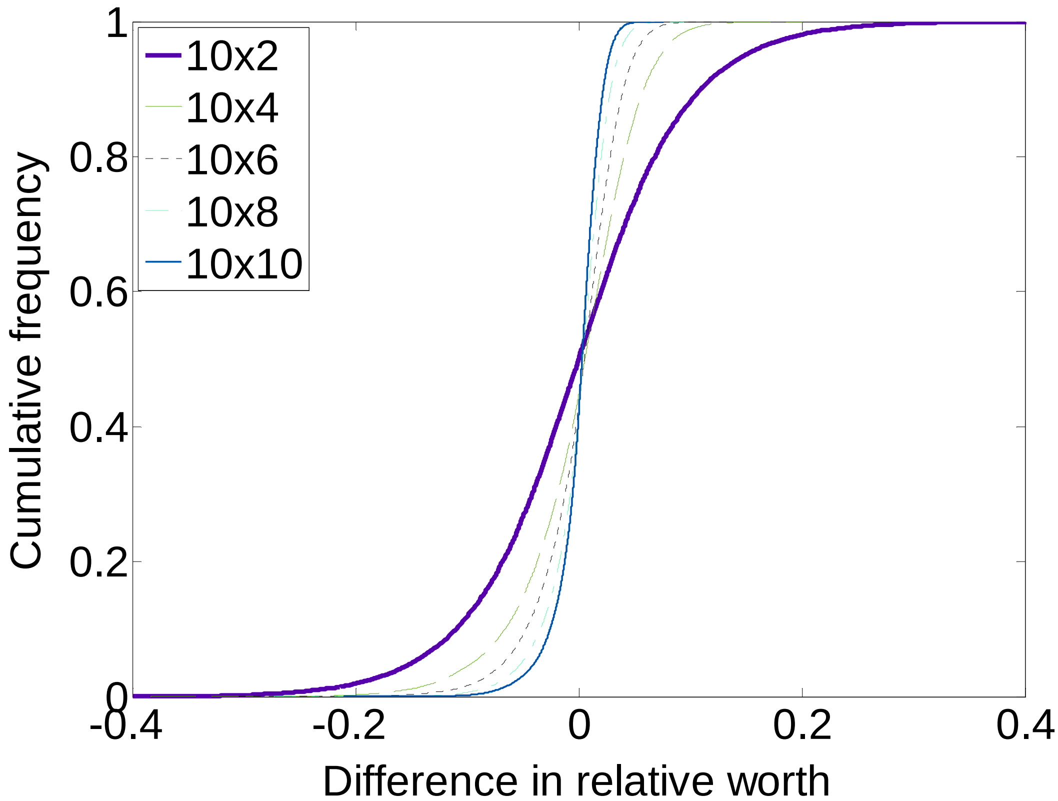
Figure A3 shows cumulative frequencies of differences when changing the number of columns. Figure A3 indicates that cumulative frequency changes significantly with the number of columns.


1
0.8
0.6
0.4
0.2
0
Cumulative frequency
-0.4
-0.2
0
0.2
0.4
Difference in relative worth
10x2
10x4
10x6
10x8
10x10

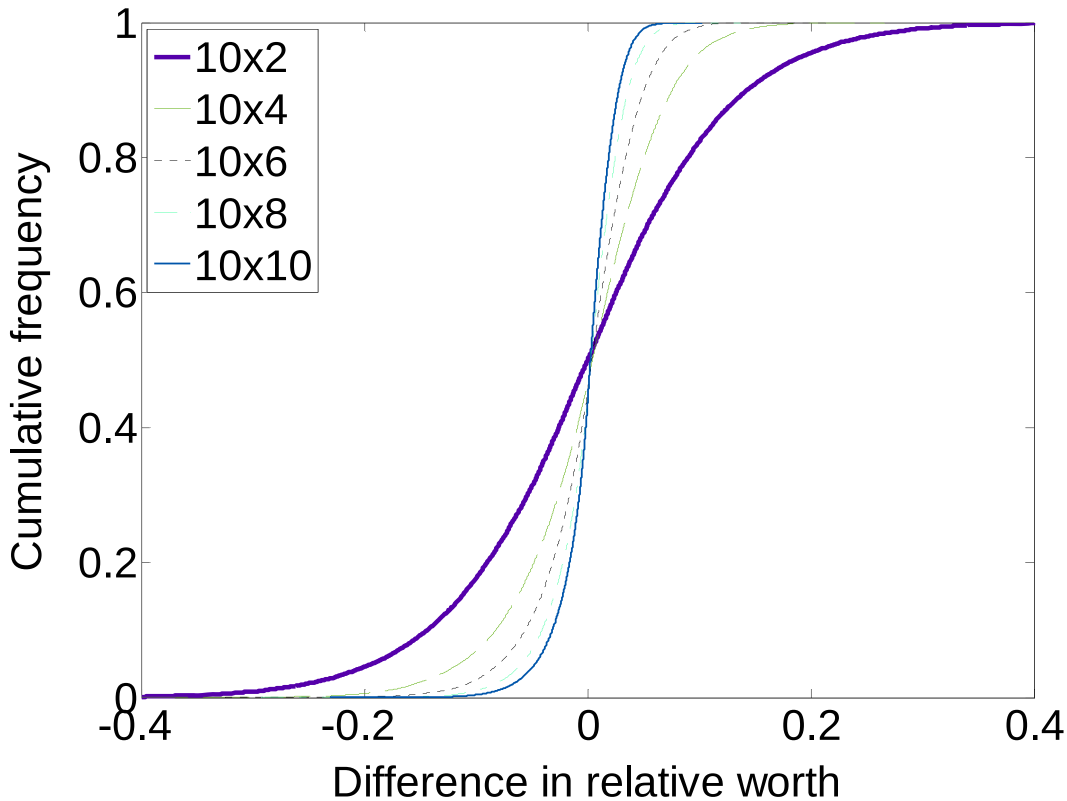
(a) EW-LW


1
0.8
0.6
0.4
0.2
0
Cumulative frequency
10x2
10x4
10x6
10x8
10x10
-0.4
-0.2
0
0.2
0.4
Difference in relative worth

(b) EA-LA


1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
Cumulative frequency
Difference in relative worth
10x2
10x4
10x6
10x8
10x10

(c) LA-LW



(d) EA-EW

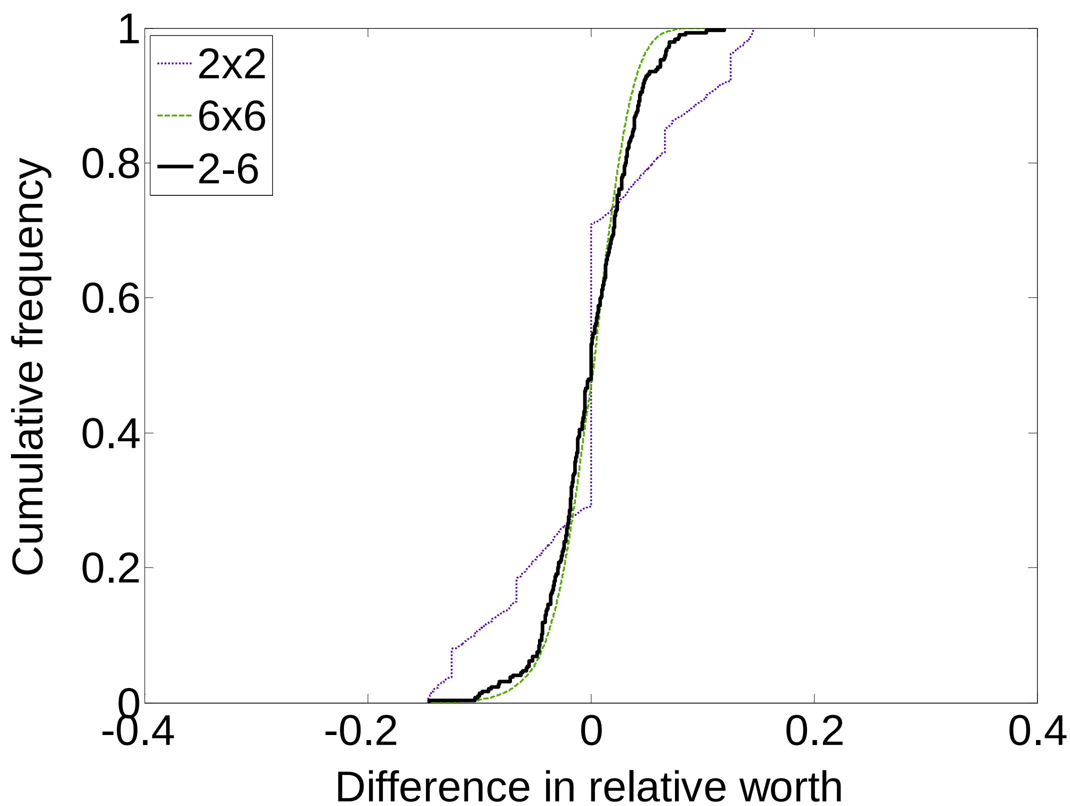
Figure. A3. Effects of the number of columns in QFD matrices

APPENDIX B.

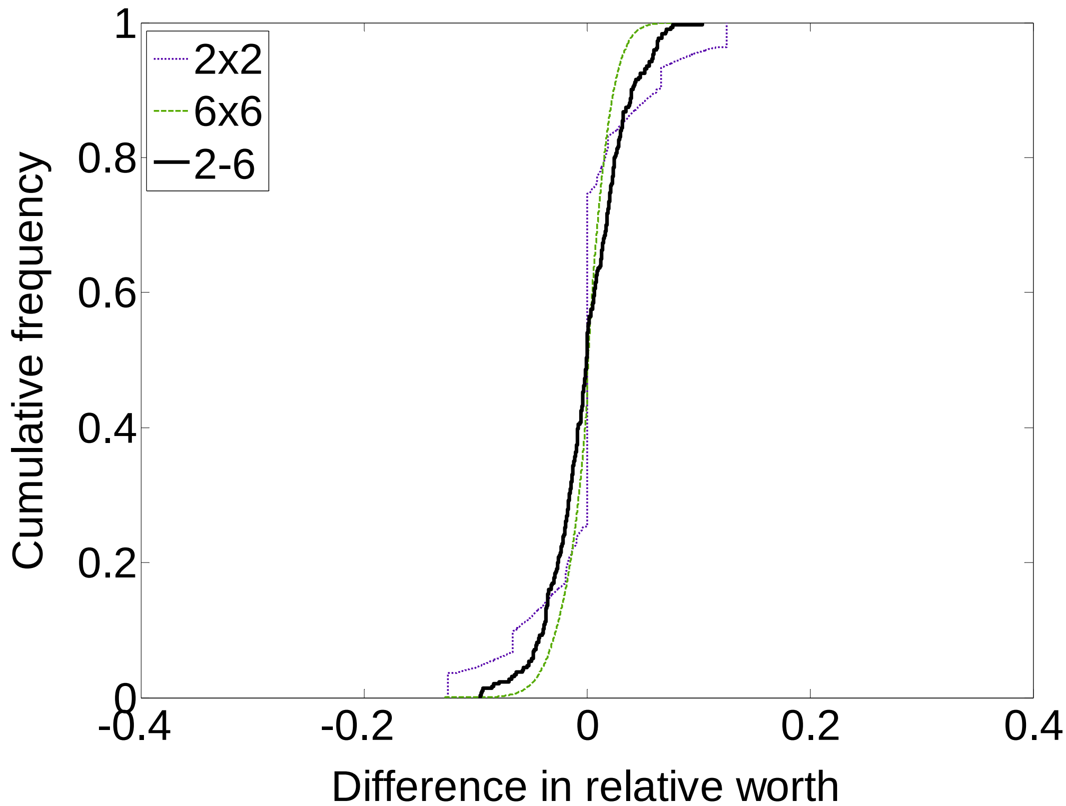
COMPARISON OF EMPIRICAL AND SIMULATION MATRICES

B.1 Comparison of differences in empirical and simulation-generated QFD matrices

Figure B1 compares for each condition, three cumulative frequencies of differences: the empirical QFD matrices segmented by the number of columns between 2 and 6, and 2x2 and 6x6 simulation-generated QFD matrices. In general, the cumulative frequency of the empirical QFD matrices lies between those of simulation-generated QFD matrices, or very close to that of the larger-sized (i.e., 6x6) simulation-generated QFD matrices.

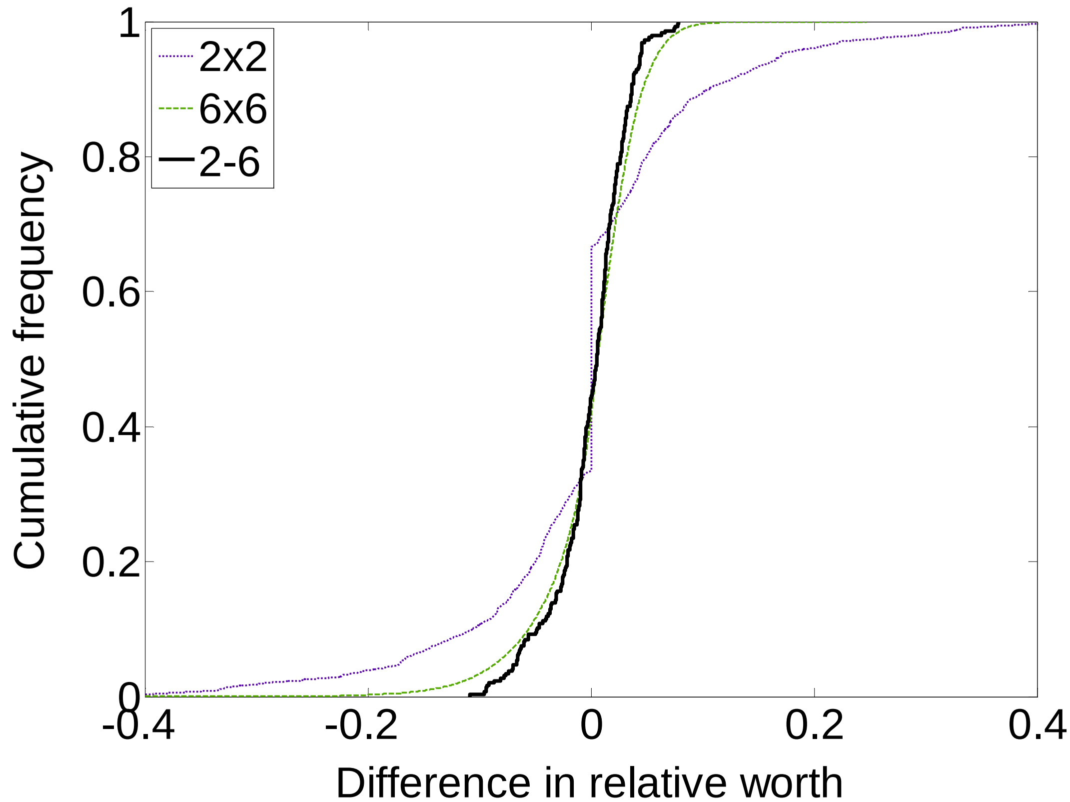


(a) EW-LW

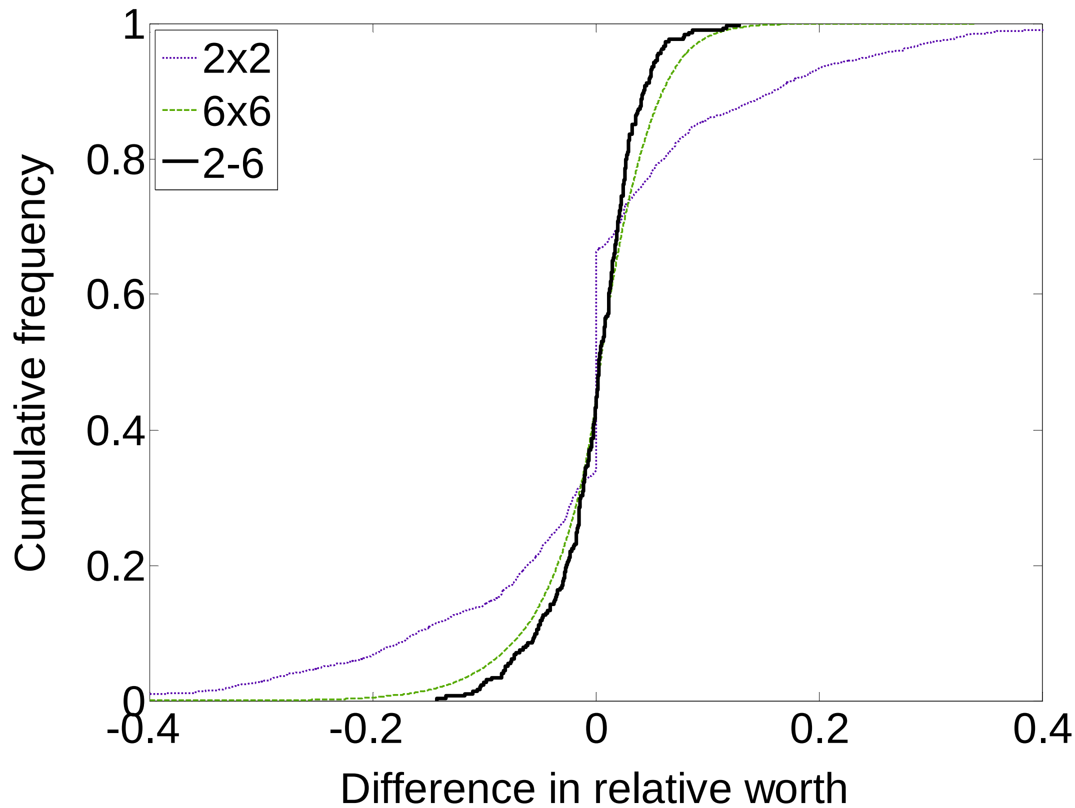


1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
Cumulative frequency
Difference in relative worth
2x2
6x6
2-6

(b) EA-LA


2x2
6x6
2-6
Cumulative frequency
0
0.2
0.4
0.6
0.8
1
-0.4
-0.2
0
0.2
0.4
Difference in relative worth

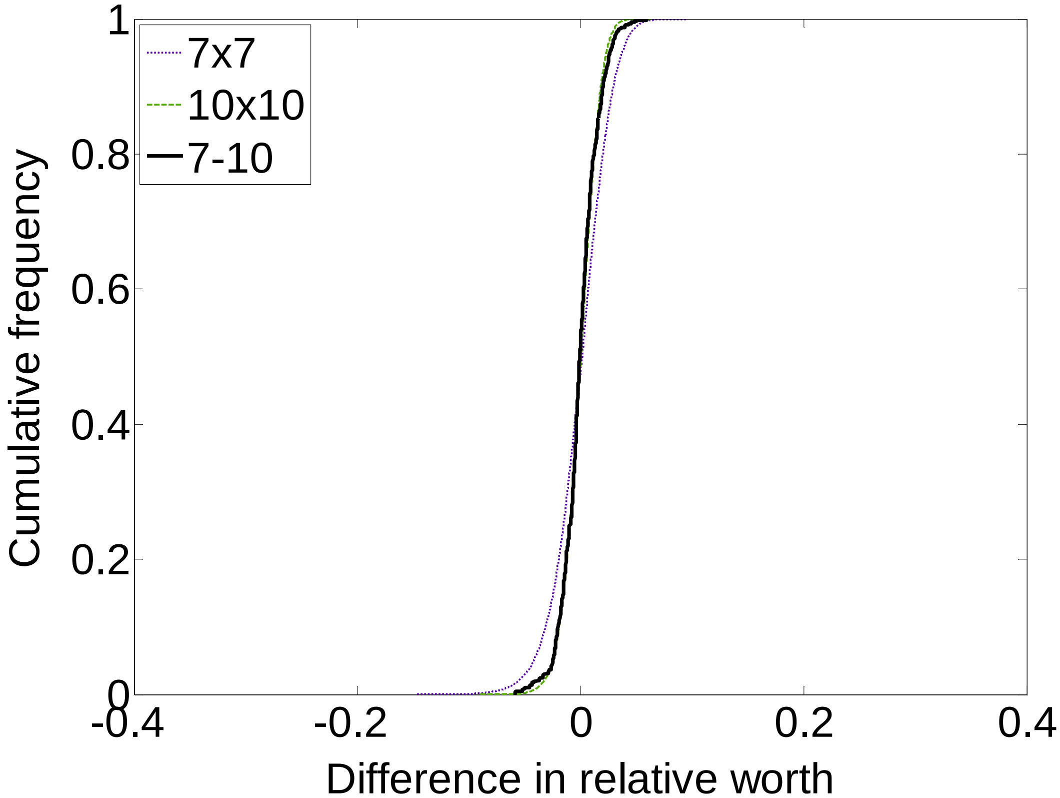
(c) LA-LW



(d) EA-EW

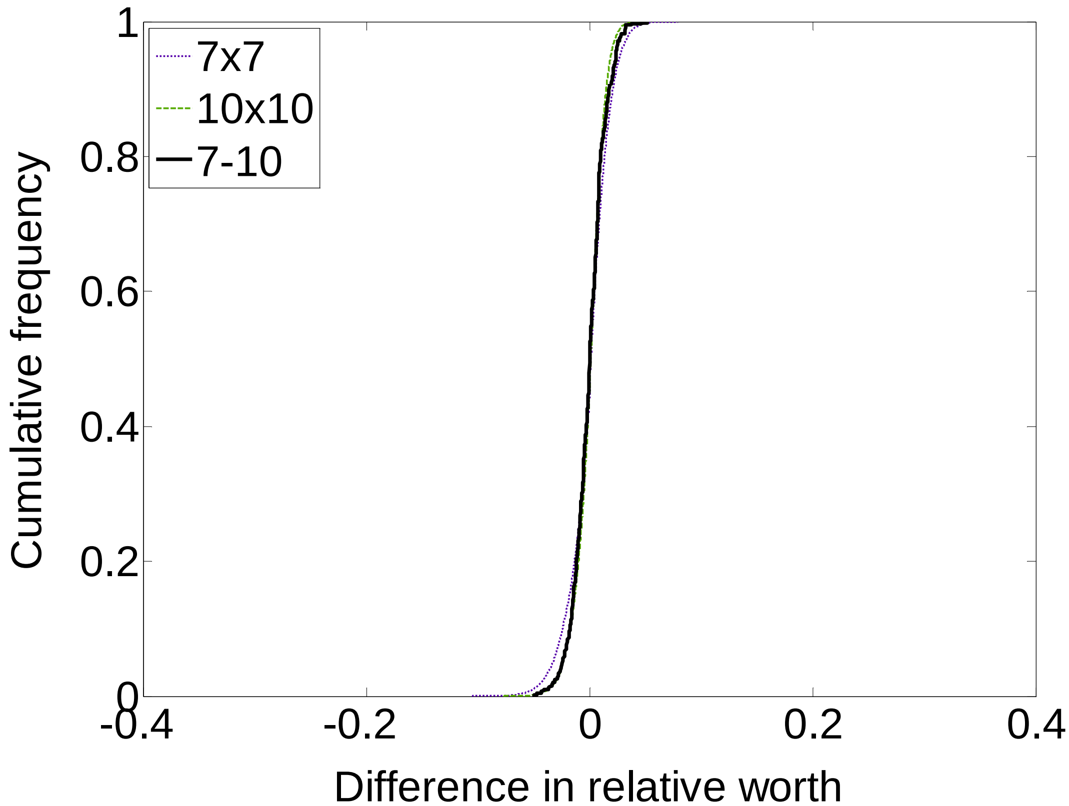
Figure. B1. Comparison of empirical QFD matrices with 2-6 columns and 2x2 and 6x6 simulation-generated QFD matrices

Figure B2 compares for each condition, three cumulative frequencies of differences: the empirical QFD matrices segmented by the number of columns between 7 and 10, and 7x7 and 10x10 simulation-generated QFD matrices. In general, the cumulative frequency of the empirical QFD matrices lies between those of simulation-generated QFD matrices, or very close to that of the larger-sized (i.e., 10x10) simulation-generated QFD matrices.

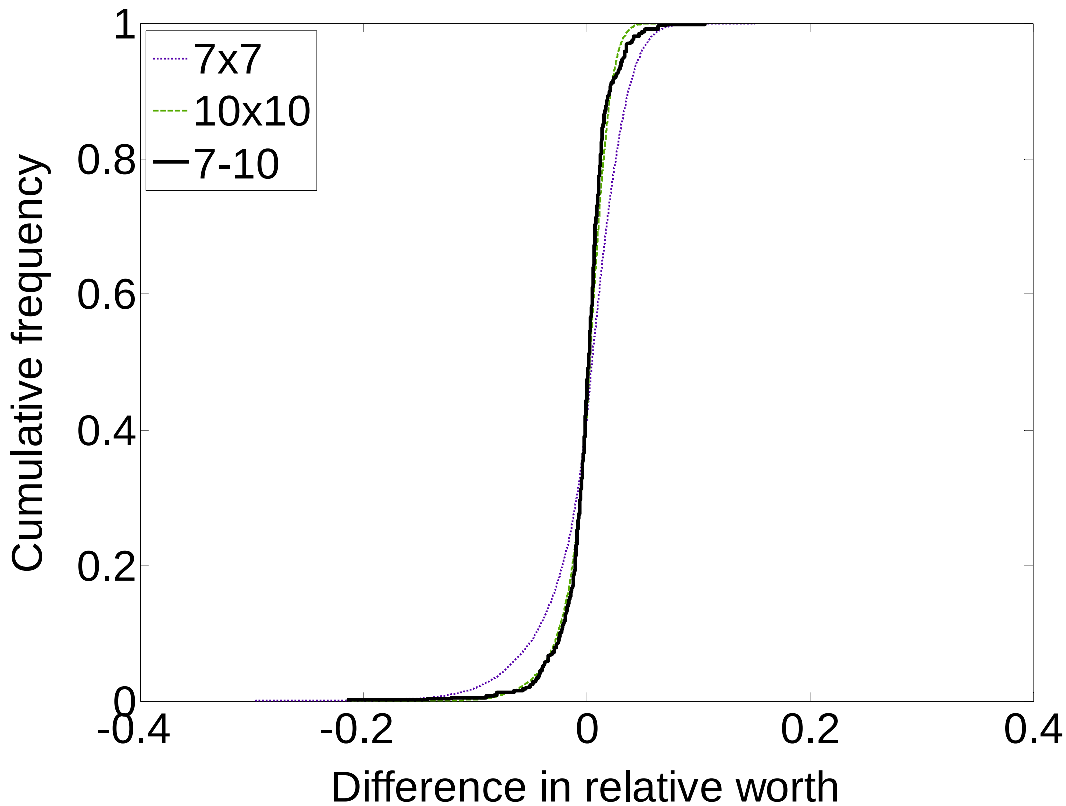


1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
Cumulative frequency
Difference in relative worth
7x7
10x10
7-10

(a) EW-LW

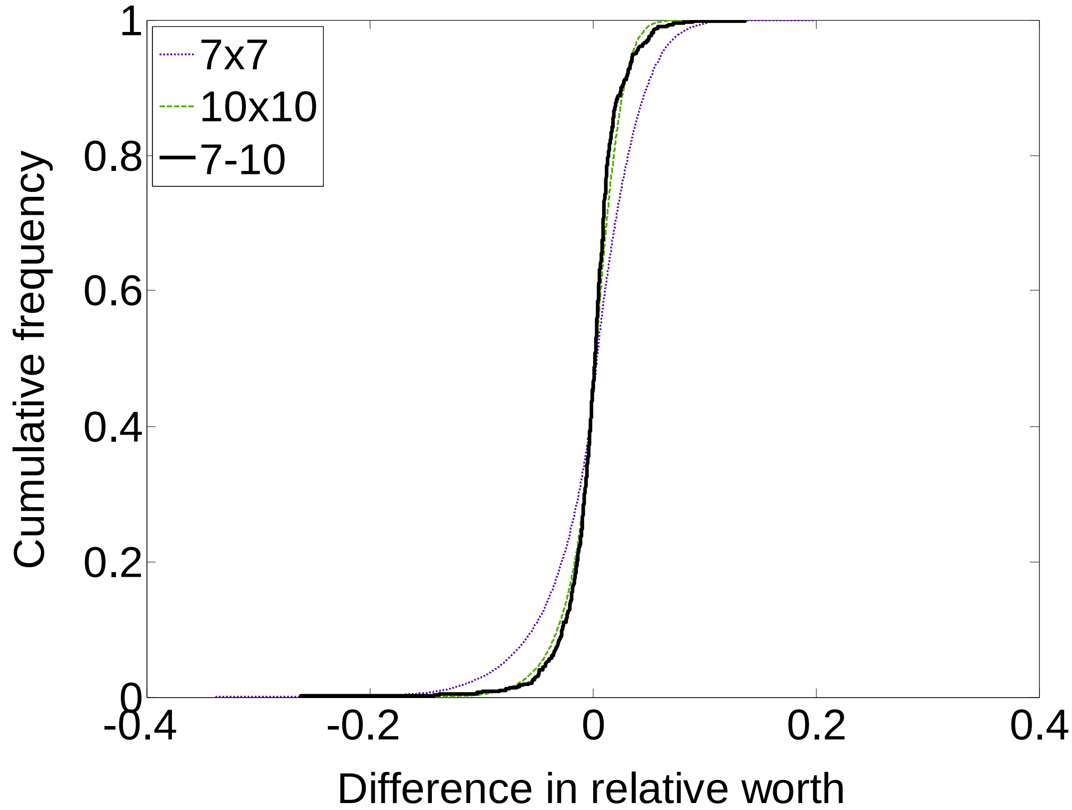

7x7
10x10
7-10
Cumulative frequency
1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
Difference in relative worth

(b) EA-LA



1
0.8
0.6
0.4
0.2
0
Cumulative frequency
7x7
10x10
7-10
-0.4
-0.2
0
0.2
0.4
Difference in relative worth

(c) LA-LW



(d) EA-EW

Figure. B2. Comparison of empirical QFD matrices with 7-10 columns and 7x7 and 10x10 simulation-generated QFD matrices

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