CHAPTER V

RESULTS AND DISCUSSION

The properties obtained from the tests of seven different sets of compounded HDPE are shown and analyzed in this chapter. The numerical results are illustrated in Appendix A.

5.1 Regression Analysis

From the results of all the properties tested on compounded HDPE, empirical models can be derived to reveal the relationship between the physical properties studied and the various amount of the selected additives. Variable codes are used to represent the quantity of the additives applied in the present study. Empirical models in terms of the response surface equations will be derived. For example, the property of Lightness index (L_c) for compounded HDPE with PATHP, DSTDP and OBA upon the first pass is shown in Table 5.1. The data from the Lightness index test can be analyzed by multiple regression analysis to estimate the corresponding regression coefficients of the response surface equation. Related calculations for the multiple regression analysis are depicted in Appendix C. The response surface equation for compounded HDPE with PATHP, DSTDP and OBA on the L_c upon the first pass is shown in Equation (5-1).

Table 5.1 : Lightness index of HDPE compounded with PATHP, DSTDP and OBA after the first pass.

Formulae	Code			Lightness index
	x_1	x_2	x_3	y
C1	-1	-1	-1	82.29
C2	1	-1	-1	68.83
C3	-1	1	-1	84.40
C4	1	1	-1	67.49
C5	-1	-1	1	82.74
C6	1	-1	1	69.86
C7	-1	1	1	86.55
C8	1	1	1	68.36
C9	-1.682	0	0	85.94
C10	1.682	0	0	64.77
C11	0	-1.682	0	75.96
C12	0	1.682	0	78.57
C13	0	0	-1.682	74.86
C14	0	0	1.682	81.57
C15	0	0	0	78.40
C16	0	0	0	78.34
C17	0	0	0	79.80
C18	0	0	0	80.07
C19	0	0	0	78.24
C20	0	0	0	78.83
Total				**1545.87**

$$y = 78.963 - 7.106x_1 + 0.547x_2 + 1.156x_3 - 1.377x_1^2 - 0.702x_2^2 - 0.366x_3^2 - 1.095x_1x_2 - 0.088x_1x_3 + 0.193x_2x_3 \quad \ldots(5\text{-}1)$$

where x_1, x_2 and x_3 are the aforementioned variable codes representing the quantity of PATHP, DSTDP and OBA respectively. The regression coefficient of the response surface equations of other properties for the compounded HDPE can also be derived. Tables 5.2 to 5.8 show the regression coefficients derived form the regression analysis of the various properties investigated on the compounded HDPE and the variable codes of additives quantity. Table 5.9 demonstrates the error between the L_c derived from the actual experiment and that estimated by calculation. The analysis listed in Table 5.9 evidently proves that the response surface equation in the current study has a maximum error about 2.6%.

5.2 Analysis of Variance (ANOVA)

From the regression coefficients estimation of properties of compounded HDPE by regression analysis, one can derive the response surface equations. The appropriateness testing of the response surface equations from the designed experiment will be carried out by variance analysis of the data from all the experiments. An example of the analysis is shown in Tables 5.10 to 5.11, the detailed calculation is shown in Appendix C.

Form the ANOVA table demonstrated in Table 5.10, it was found that the F_0 is 46.30 when compared with the critical F-distribution at the level of significance at 0.025 (or degree of confidence is 97.5%) $F_{0.025,9,10}$ is 3.78. It is apparent that F_0 is greater than $F_{0.025,9,10}$, hence the hypothesis of $H_0 : B_1 = B_2 =$

Equation : $y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2$

Where : y = Property

x_1 = Code of Blended AO = (Amount of Blended AO - 0.05)/0.03

x_2 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_{12}	b_{11}	b_{22}
Melt Flow Rate (g/10min)						
pass 1	0.20738	0.00311	0.00400	-0.00068	-0.0057	-0.00455
pass 3	0.24648	-0.00865	0.00377	-0.00810	-0.01083	-0.00423
pass 5	0.26848	-0.01482	0.00153	-0.00598	-0.00916	-0.00096
Lightness Index						
pass 1	82.074	-3.278	2.647	-0.980	-0.300	-1.660
pass 3	79.306	-2.816	3.120	-1.590	-0.376	-1.549
pass 5	74.686	-3.690	2.287	-2.395	0.551	-2.209
O.I.T. (min)						
pass 1	84.740	12.738	-0.010	17.850	1.486	3.061
pass 3	75.220	12.579	6.026	7.825	2.290	3.165
pass 5	65.260	9.423	-0.612	2.475	7.339	0.589

Table 5.2 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with Blended AO and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of PATHP = (Amount of PATHP - 0.05)/0.03

x_2 = Code of DLTDP = (Amount of DLTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.16989	-0.00878	0.00466	-0.00065	0.00033	-0.00130	-0.00178	0.00934	0.00128	0.00563
pass 3	0.22653	-0.00576	0.00306	0.00078	0.00051	-0.00159	-0.00121	0.00422	-0.00075	0.00360
pass 5	0.24742	-0.01601	0.00437	0.00109	0.00091	-0.00516	-0.00279	0.01381	-0.00088	0.00665
Lightness Index										
pass 1	75.637	-7.873	0.040	2.149	1.421	0.226	0.119	1.506	-1.876	-0.7322
pass 3	72.033	-7.276	-0.095	2.038	0.771	0.056	0.134	1.129	-1.876	-0.382
pass 5	68.791	-6.719	-0.251	2.001	0.318	0.148	-0.088	1.148	-1.325	-0.287
O.I.T. (min)										
pass 1	55.566	10.622	-12.405	3.654	-3.038	1.913	-4.113	4.966	5.514	5.196
pass 3	53.224	14.003	-10.288	-3.465	-3.300	-3.225	-3.950	2.196	10.805	2.744
pass 5	50.973	15.362	-10.982	-1.965	-6.825	-3.475	-3.000	2.978	8.458	5.152

Table 5.3 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with PATHP, DLTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of PATHP = (Amount of PATHP - 0.05)/0.03

x_2 = Code of DSTDP = (Amount of DSDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.17340	-0.00597	-0.00249	0.00063	-0.00739	0.00066	0.00326	0.00611	0.00408	0.00111
pass 3	0.22461	0.00151	-0.00485	0.00493	-0.00209	-0.00579	-0.00286	0.00655	0.00560	0.00323
pass 5	0.26347	-0.01159	-0.00370	0.00118	-0.00116	-0.00476	-0.00071	0.00956	0.00228	0.00276
Lightness Index										
pass 1	78.963	-7.106	0.547	1.156	-1.095	-0.088	0.193	-1.377	-0.702	-0.366
pass 3	75.484	-6.732	0.566	0.596	-0.941	0.429	-0.821	-1.577	-0.673	-0.343
pass 5	73.028	-6.375	0.318	-0.740	-0.766	0.676	-0.971	-2.174	-1.826	-0.697
O.I.T. (min)										
pass 1	68.281	16.176	-9.608	1.166	-6.263	-4.113	10.588	2.890	3.279	1.671
pass 3	54.728	13.812	-15.790	0.960	-3.113	-1.538	-3.138	4.820	5.403	1.708
pass 5	52.480	12.153	-14.245	2.732	-4.413	-3.888	-3.338	3.332	9.449	-0.911

Table 5.4 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with PATHP, DSTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of ODHP = (Amount of ODHP - 0.05)/0.03

x_2 = Code of DLTDP = (Amount of DLTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.19069	0.00066	-0.00076	0.00244	0.00144	0.00094	0.00114	-0.00209	0.00406	-0.01486
pass 3	0.24191	0.00236	-0.00173	0.00038	-0.00098	0.00258	-0.02480	0.00257	0.00503	0.00549
pass 5	0.27725	-0.00434	-0.00116	0.00310	0.00354	-0.00326	-0.02159	0.00499	0.00630	0.00743
Lightness Index										
pass 1	82.806	-3.202	-0.039	1.370	0.839	0.064	-0.241	0.004	0.579	-0.616
pass 3	79.092	-3.183	-0.254	1.803	0.866	0.384	-0.554	0.129	0.557	-0.815
pass 5	76.077	-3.152	-0.019	2.004	0.801	0.056	-0.919	-0.423	0.289	-0.923
O.I.T. (min)										
pass 1	74.923	4.117	-5.384	-3.528	0.463	-0.838	1.188	-6.910	0.462	-4.753
pass 3	65.842	6.548	-5.877	-2.805	1.125	-0.400	0.650	-4.655	-1.332	-4.019
pass 5	58.517	6.924	-9.276	-1.462	2.538	-6.188	0.688	-3.304	3.378	-3.781

Table 5.5 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with ODHP, DLTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of ODHP = (Amount of ODHP - 0.05)/0.03

x_2 = Code of DSTDP = (Amount of DSTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.19618	0.00351	0.00596	-0.00457	-0.0004	-0.00605	-0.00723	-0.00244	-0.00196	0.00349
pass 3	0.25185	-0.00009	-0.00447	0.00700	-0.00058	-0.00355	-0.00355	-0.00321	-0.00689	0.00714
pass 5	0.29211	-0.01998	-0.00076	0.00237	-0.0033	-0.00795	-0.0103	-0.00021	-0.00889	0.00554
Lightness Index										
pass 1	83.505	-2.644	-0.593	1.725	0.409	1.616	0.129	-0.743	0.043	0.035
pass 3	79.550	-2.376	-0.858	1.734	0.651	1.529	0.921	-1.186	-0.670	0.074
pass 5	76.626	-2.173	-0.230	1.772	0.743	1.540	0.698	-3.038	-0.993	0.462
O.I.T. (min)										
pass 1	71.697	4.999	-10.644	4.311	-4.863	-8.713	0.838	-7.138	-4.221	1.259
pass 3	60.548	3.480	-10.657	2.049	-2.150	-5.850	3.025	-4.660	-1.533	-1.639
pass 5	65.542	2.167	-9.682	0.085	-1.338	-4.338	1.338	-7.438	-4.892	-3.036

Table 5.6 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with ODHP, DSTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of DAT = (Amount of DAT - 0.05)/0.03

x_2 = Code of DLTDP = (Amount of DLTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.14816	-0.00887	-0.00206	-0.00236	-0.00455	-0.00503	-0.00823	0.01335	0.00981	0.01030
pass 3	0.18510	-0.00865	-0.00193	-0.00310	-0.00401	-0.00581	-0.00944	0.01198	0.00666	0.00924
pass 5	0.20018	-0.01229	-0.00370	-0.00222	-0.00735	-0.00668	-0.00870	0.01842	0.00673	0.00890
Lightness Index										
pass 1	70.707	-8.707	0.595	-0.365	-1.376	-0.981	-1.474	1.091	-0.010	-2.352
pass 3	60.826	-9.638	-0.367	-0.499	-2.724	-1.086	-1.489	0.758	1.117	-1.202
pass 5	54.458	-9.216	-0.503	-0.930	-3.646	-1.331	-1.209	1.007	1.771	-0.439
O.I.T. (min)										
pass 1	84.248	14.008	-5.575	3.929	-1.950	-1.350	2.875	-2.133	2.746	2.941
pass 3	77.844	12.009	-8.551	0.823	-5.863	0.913	5.488	-5.450	7.278	3.636
pass 5	77.175	14.574	-6.765	-3.362	-0.700	2.875	7.650	-7.549	6.098	1.414

Table 5.7 : Coefficients receive from the multiple regression analysis for the properties of HDPE compounded with DAT, DLTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of DAT = (Amount of DAT - 0.05)/0.03

x_2 = Code of DSTDP = (Amount of DSTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.16831	-0.00607	0.00238	0.00104	-0.00176	-0.00181	0.00346	0.00105	-0.00234	0.00107
pass 3	0.19543	-0.00408	0.00033	-0.00100	-0.00101	-0.00186	0.00016	0.00119	0.00057	0.00034
pass 5	0.21458	-0.00978	-0.00163	-0.00237	-0.00061	-0.00064	-0.00291	0.00680	-0.00399	-0.00040
Lightness Index										
pass 1	68.724	-8.348	0.704	1.101	1.887	0.606	-0.529	1.887	0.871	-0.358
pass 3	62.410	-10.329	0.306	1.739	0.989	-1.079	-1.309	1.685	0.518	-0.599
pass 5	58.219	-10.548	1.316	0.864	0.321	-0.264	0.261	1.006	0.244	-1.471
O.I.T. (min)										
pass 1	93.638	10.915	-5.746	2.686	0.113	-1.363	-2.663	-10.451	4.645	1.357
pass 3	86.792	13.986	-4.864	1.037	-1.025	0.325	1.550	-4.906	2.766	-1.618
pass 5	80.003	12.923	-7.552	1.046	0.313	1.438	0.588	-3.184	1.465	-2.283

Table 5.8 : Coefficients receive from the multiple regression analysis for the properties of HDPE compounded with DAT, DSTDP and OBA.

Table 5.9 : Experimental and calculated error for the L_c of HDPE compounded with PATHP, DSTDP and OBA after the first pass.

FORMULAE	Lightness corrected		Error	% Error
	Experimental (y_i)	Calculation ($\hat{y}_i$)	$e_i = (y_i - \hat{y}_i)$	
C1	82.29	80.96	1.33	1.610
C2	68.83	69.12	-0.29	-0.420
C3	84.4	83.86	0.54	0.635
C4	67.49	67.64	-0.15	-0.219
C5	82.74	83.07	-0.33	-0.395
C6	69.86	70.87	-1.01	-1.447
C7	86.55	86.74	-0.19	-0.214
C8	68.36	70.16	-1.80	-2.633
C9	85.94	87.05	-1.11	-1.292
C10	64.77	63.15	1.62	2.504
C11	75.96	76.09	-0.13	-0.171
C12	78.57	77.93	0.64	0.815
C13	74.86	76.02	-1.16	-1.543
C14	81.57	79.90	1.67	2.043
C15	78.4	78.96	-0.56	-0.716
C16	78.34	78.96	-0.62	-0.793
C17	79.8	78.96	0.84	1.051
C18	80.07	78.96	1.11	1.384
C19	78.24	78.96	-0.72	-0.922
C20	78.83	78.96	-0.13	-0.167

Table 5.10 : ANOVA table for the multiple regression analysis of the interactions of PATHP, DSTDP and OBA on the Lightness corrected after the first pass.

Source of Variation	Sum of Square	Degree of freedom	Mean Square	F_0
Regression	754.303	9	83.811	46.30
- First order terms	711.907	3	237.302	131.10
- Second order terms	42.397	6	7.066	3.90
Error	18.101	10	1.810	
- Lack of fit	14.931	5	2.986	4.71
- Pure error	3.170	5	0.634	
Total	772.404	19	R^2 = 0.9766	

Table 5.11 : Statistic-t_0 test of coefficients testing for interactions of PATHP, DSTDP and OBA on Lightness corrected after the first pass at the level of significant of 0.025.

Regression Coefficients		t_0	Hypothesis test ($t_{0.025/2,10}$ = 2.228)
b_0	78.963	143.92	Significance
b_1	-7.106	-19.52	Significance
b_2	0.547	1.50	Not Significance
b_3	1.156	3.17	Significance
b_{11}	-1.377	-3.89	Significance
b_{22}	-0.702	-1.98	Not Significance
b_{33}	-0.366	-1.03	Not Significance
b_{12}	-1.095	-2.30	Significance
b_{13}	-0.088	-0.18	Not Significance
b_{23}	0.193	0.40	Not Significance

... $=B_k = 0$ is rejected. This shows that of the three kinds of additives, PATHP (x_1), DSTDP (x_2) and OBA (x_3), one of them is influential on L_c property of compounded HDPE.

From F_0 of error; F_0 equals to 4.71 as compared with the critical of F-distribution at the level of significance at 0.025. $F_{0.025,5,5}$ equals to 7.15. It is apparent that F_0 is less than $F_{0.025,5,5}$, hence the hypothesis of H_0 : The model adequately fits the data is acceptable, proving that the coefficients from regression analysis in the second order polynomial equation can be used in estimating the L_c.

For the L_c from ANOVA table, the coefficient of determination, R^2, equals to 0.9766. The fact that R^2 is approaching 1 is a clear indication that varying amount of the studied additives is related to L_c. On the other hand, the overall variance of the L_c caused by the variation of the additive quantity of primary antioxidant, secondary antioxidant and optical brightener equals to 97.66%.

Table 5.11 shows the statistical t_0 of the regression coefficients of the multiple regression equations for L_c. The calculation is shown in details in Appendix C. When compared the statistical t_0 of each regression coefficient and the critical t-distribution at the level of significance at 0.025, which was calculated from Table D.1 in Appendix D, the $t_{0.025/2,10}$ is 2.228. It is apparent that the statistical t_0 of the regression coefficient testing is greater than that at $t_{0.025/2,10}$. This implies that the regression coefficients from the test is significant to the response surface equation. However, if the statistical t_0 of any regression coefficients is less than that at $t_{0.025/2,10}$, it implies that particular regression coefficient is not significant to the response surface equation. It can be deleted from the response surface equation as shown in Table 5.11. Therefore, the response surface equation of L_c from Equation (5-1) can be rewritten as follows :-

$$y = 78.963 - 7.106x_1 + 1.156x_3 - 1.095x_1x_2 - 1.377x_1^2 \quad \ldots(5\text{-}2)$$

Likewise, Appendix B shows the analysis of variance of the multiple regression and the statistical t_0 test for the significance of other regression coefficients for response surface equations for compounded HDPE. From the regression coefficient test with statistical t_0, the response surface equation can be derived to show the relationship between the properties of compounded HDPE and the variable code of additives quantity as shown in Tables 5.12 to 5.18.

Moreover, with the same method, regression coefficients of the response surface equations can be calculated for estimating the properties of compounded HDPE showing the relations of real additives quantity used in each formula of primary antioxidant, secondary antioxidant and optical brightener as shown in Tables 5.19 to 5.25.

Equation : $y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2$

Where : y = Property

x_1 = Code of Blended AO = (Amount of Blended antioxidant - 0.05)/0.03

x_2 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_{12}	b_{11}	b_{22}
Melt Flow Rate (g/10min)						
pass 1	0.20738	0.00311	0.00400		-0.0057	-0.00455
pass 3	0.24648	-0.00865	0.00377	-0.00810	-0.01083	-0.00423
pass 5	0.26848	-0.01482		-0.00598	-0.00916	
Lightness Index						
pass 1	82.074	-3.278	2.647		-0.300	-1.660
pass 3	79.306	-2.816	3.120			
pass 5	74.686	-3.690	2.287			
O.I.T. (min)						
pass 1	84.740	12.738		17.850		
pass 3	75.220	12.579	6.026	7.825		
pass 5	65.260	9.423	.		7.339	

Table 5.12 : Coefficients deriving from the multiple regression analysis for properties of HDPE compounded with Blended AO and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of PATHP = (Amount of PATHP - 0.05)/0.03

x_2 = Code of DLTDP = (Amount of DLTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.16989	-0.00878	0.00466					0.00934		0.00563
pass 3	0.22653	-0.00576	0.00306					0.00422		0.00360
pass 5	0.24742	-0.01601						0.01381		0.00665
Lightness Index										
pass 1	75.637	-7.873		2.149				1.506	-1.876	
pass 3	72.033	-7.276		2.038				1.129	-1.876	
pass 5	68.791	-6.719		2.001					-1.325	
O.I.T. (min)										
pass 1	55.566	10.622	-12.405					4.966	5.514	5.196
pass 3	53.224	14.00	-10.288					2.196	10.805	2.744
pass 5	50.973	15.36	-10.982		-6.825				8.458	5.152

Table 5.13 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with PATHP, DLTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of PATHP = (Amount of PATHP - 0.05)/0.03

x_2 = Code of DSTDP = (Amount of DSTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.17340	-0.00597			-0.00739			0.00611	0.00408	
pass 3	0.22461		-0.00485	0.00493		-0.00579		0.00655	0.00560	
pass 5	0.26347	-0.01159						0.00956		
Lightness Index										
pass 1	78.963	-7.106		1.156	-1.095			-1.377		
pass 3	75.484	-6.732						-1.577		
pass 5	73.028	-6.375						-2.174	-1.826	
O.I.T. (min)										
pass 1	68.281	16.176	-9.608		-6.263		10.588		3.279	
pass 3	54.728	13.812	-15.79					4.82	5.403	
pass 5	52.48	12.153	-14.245						9.449	

Table 5.14 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with PATHP, DSTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of ODHP = (Amount of ODHP - 0.05)/0.03

x_2 = Code of DLTDP = (Amount of DLTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.19069						-0.01486			
pass 3	0.24191						-0.02480		0.00503	0.00549
pass 5	0.27725						-0.02159		0.00630	0.00743
Lightness Index										
pass 1	82.806	-3.202		1.370						
pass 3	79.092	-3.183		1.803						-0.815
pass 5	76.077	-3.152		2.004						
O.I.T. (min)										
pass 1	74.923	4.117	-5.384	-3.528				-6.910		-4.753
pass 3	65.842	6.548	-5.877					-4.655		-4.019
pass 5	58.517	6.924	-9.276			-6.188				

Table 5.15 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with ODHP, DLTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of ODHP = (Amount of ODHP - 0.05)/0.03

x_2 = Code of DSTDP = (Amount of DSTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.19618		0.00596	-0.00457		-0.00605	-0.00723			0.00349
pass 3	0.25185			0.00700		-0.00355			-0.00689	0.00714
pass 5	0.29211	-0.01998							-0.00889	
Lightness Index										
pass 1	83.505	-2.644		1.725		1.616				
pass 3	79.550	-2.376		1.734		1.529		-1.186		0.074
pass 5	76.626	-2.173		1.772		1.540		-3.038		
O.I.T. (min)										
pass 1	71.697	4.999	-10.644	4.311	-4.863	-8.713		-7.138	-4.221	
pass 3	60.548	3.480	-10.657			-5.850		-4.660		
pass 5	65.542		-9.682			-4.338		-7.438	-4.892	

Table 5.16 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with ODHP, DSTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of DAT = (Amount of DAT - 0.05)/0.03

x_2 = Code of DLTDP = (Amount of DLTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.14816	-0.00887						0.01335	0.00981	0.01030
pass 3	0.18510	-0.00865					-0.00944	0.01198	0.00666	0.00924
pass 5	0.20018	-0.01229						0.01842		0.00890
Lightness Index										
pass 1	70.707	-8.707								-2.352
pass 3	60.826	-9.638			-2.724					
pass 5	54.458	-9.216			-3.646					
O.I.T. (min)										
pass 1	84.248	14.008	-5.575	3.929						
pass 3	77.844	12.009	-8.551		-5.863			-5.450	7.278	3.636
pass 5	77.175	14.574	-6.765				7.650	-7.549	6.098	

Table 5.17 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with DAT, DLTDP and OBA.

Equation : $y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2$

Where : y = Property

x_1 = Code of DAT = (Amount of DAT - 0.05)/0.03

x_2 = Code of DSTDP = (Amount of DSTDP - 0.05)/0.03

x_3 = Code of OBA = (Amount of OBA - 0.00075)/0.00025

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.16831	-0.00607					0.00346			
pass 3	0.19543	-0.00408		-0.00100		-0.00186		0.00119		
pass 5	0.21458	-0.00978						0.00680	-0.00399	
Lightness Index										
pass 1	68.724	-8.348						1.887		
pass 3	62.410	-10.329		1.739				1.685		
pass 5	58.219	-10.548								
O.I.T. (min)										
pass 1	93.638	10.915	-5.746					-10.451	4.645	
pass 3	86.792	13.986	-4.864					-4.906		
pass 5	80.003	12.923	-7.552							

Table 5.18 : Coefficients deriving from the multiple regression analysis for the properties of HDPE compounded with DAT, DSTDP and OBA.

Equation : $y = b_0+b_1X_1+b_2X_2+b_{12}X_1X_2+b_{11}X_1^2+b_{22}X_2^2$

Where : y = Property

X_1 = Amount of Blended AO (%)

X_2 = Amount of OBA (%)

b = Regression Coefficients

y	b_0	b_1	b_2	b_{12}	b_{11}	b_{22}
Melt Flow Rate (g/10min)						
pass 1	0.13341	0.73700	125.200		-6.33333	-72800.00
pass 3	0.14093	1.72500	170.600	-1080.00	-12.03333	-67680.00
pass 5	0.23783	1.12178	39.86667	-797.333	-10.17777	
Lightness Index						
pass 1	63.82	-75.93	50428.00		-333.33	26560000
pass 3	74.64	-93.87	12480.00			
pass 5	73.98	-123.00	9148.00			
O.I.T. (min)						
pass 1	152.76	-1360.40	-119000.0	2380000.0		
pass 3	75.30	-363.20	-28062.7	1043333.3		
pass 5	69.94	-501.34			8154.44	

Table 5.19 : Coefficients for the properties of HDPE compounded with actual amount of Blended AO and OBA.

Equation	:	y	=	$b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$
Where	:	y	=	Property
		X_1	=	Amount of PATHP (%)
		X_2	=	Amount of DLTDP (%)
		X_3	=	Amount of OBA (%)
		b	=	Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.21834	-1.33044	0.15533	-0.62556				10.37778		6.25556
pass 3	0.25275	-0.66089	0.10200	-0.40000				4.68889		4.00000
pass 5	0.33094	-2.06811		-0.73889				15.34444		7.38889
Lightness Index										
pass 1	81.28	-429.73	208.44	8597.60				1673.11	-2084.44	
pass 3	75.97	-367.98	208.44	8152.00				1254.44	-2084.44	
pass 5	70.31	-233.97	147.22	8004.00					-1472.22	
O.I.T. (min)										
pass 1	102.09	-197.71	-1026.17	-577.33				5517.78	6162.67	5773.33
pass 3	90.78	222.67	-1543.49	-304.89				2440.00	12005.56	3048.89
pass 5	62.53	891.17	-926.67	-572.44	-7583.33				9397.78	5724.44

Table 5.20 : Coefficients for the properties of HDPE compounded with actual amount of PATHP, DLTDP and OBA.

Equation : $y = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$

Where : y = Property

X_1 = Amount of PATHP (%)

X_2 = Amount of DSTDP (%)

X_3 = Amount of OBA (%)

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.19113	-0.46733	-0.04277		-8.21111			6.78889	4.53333	
pass 3	0.23557	-0.40611	-0.78389	20.04167		-6.43333		7.27778	6.22222	
pass 5	0.30961	-1.45922						10.72889		
Lightness Index										
pass 1	80.47	-23.03	60.83	4624.00	-1216.67			-1530.00		
pass 3	82.32	-49.18						-1752.22		
pass 5	72.54	29.06	202.89					-2415.56	-2028.89	
O.I.T. (min)										
pass 1	78.46	887.15	-924.88	-588.23	-6958.89		11764.44		3643.33	
pass 3	86.42	-75.16	-1126.67					5355.56	6003.33	
pass 5	82.22	405.10	-1524.72						10498.89	

Table 5.21 : Coefficients for the properties of HDPE compounded with actual amount of PATHP, DSTDP and OBA.

Equation	:	y	=	$b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$	
Where	:	y	=	Property	
		X_1	=	Amount of ODHP	(%)
		X_2	=	Amount of DLTDP	(%)
		X_3	=	Amount of OBA	(%)
		b	=	Regression Coefficients	

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.14941		0.82556	0.82556			-16.51111			
pass 3	0.20224		0.81890	0.76779			-27.55556		5.58889	6.10000
pass 5	0.25541		0.49945	0.37390			-23.98889		7.00000	8.25556
Lightness Index										
pass 1	84.03	-106.73		5480.00						
pass 3	76.72	-106.10		7302.56						-905.56
pass 5	75.32	-105.07		8016.00						
O.I.T. (min)										
pass 1	55.219	905.011	-179.467	-13583.89				-7677.778		-5281.111
pass 3	38.588	735.489	-195.900	528.111				-5172.222		-5281.111
pass 5	45.247	547.581	-309.200	343.781		-6875.556				

Table 5.22 : Coefficients for the properties of HDPE compounded with actual amount of ODHP, DLTDP and OBA.

Equation : $y = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$

Where : y = Property

X_1 = Amount of ODHP (%)

X_2 = Amount of DSTDP (%)

X_3 = Amount of OBA (%)

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.17276	0.33611	0.60034	-17.93000		-6.72222	-8.03333			3.87778
pass 3	0.22168	0.19722	0.76556	27.40389		-3.94444			-7.65556	7.93333
pass 5	0.30071	-0.66600	0.98778						-9.87778	
Lightness Index										
pass 1	87.23	-177.91		6810.22		1795.56				
pass 3	79.47	-32.37		6842.83		1698.89		-1317.78		82.22
pass 5	70.77	179.57		7002.44		1711.11		-3375.56		
O.I.T. (min)										
pass 1	-1.10	1713.97	384.37	17728.06	-5403.33	-9681.11		-7931.11	-4690.00	
pass 3	43.31	958.78	-355.23	325.00		-6500.00		-5177.78		
pass 5	35.37	1067.45	220.82	241.00		-4820.00		-8264.44	-5435.56	

Table 5.23 : Coefficients for the properties of HDPE compounded with actual amount of ODHP, DSTDP and OBA.

Equation : $y = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$

Where : y = Property

X_1 = Amount of DAT (%)

X_2 = Amount of DLTDP (%)

X_3 = Amount of OBA (%)

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.25590	-1.77900	-1.09000	-1.14444				14.83333	10.90000	11.44444
pass 3	0.25074	-1.61944	-0.21555	-0.50222			-10.48889	13.31111	7.40000	10.26667
pass 5	0.29656	-2.456333		-0.98889				20.46667		9.88889
Lightness Index										
pass 1	78.68	-290.23		261.33						-2613.33
pass 3	69.32	-169.93	151.33		-3026.67					
pass 5	59.69	-104.64	202.56		-4051.11					
O.I.T. (min)										
pass 1	58.41	466.93	-185.83	15716.00						
pass 3	70.97	1331.58	-767.98	-404.00	-6514.44			-6055.56	8086.67	4040.00
pass 5	81.38	1324.58	-1328.06	-425.00			8500.00	-8387.78	6775.56	

Table 5.24 : Coefficients for the properties of HDPE compounded with actual amount of DAT, DLTDP and OBA.

Equation : $y = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$

Where : y = Property

X_1 = Amount of DAT (%)

X_2 = Amount of DSTDP (%)

X_3 = Amount of OBA (%)

b = Regression Coefficients

y	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
Melt Flow Rate (g/10min)										
pass 1	0.18804	-0.20233	-0.19222	-0.19222			3.84444			
pass 3	0.20337	-0.16489		-3.89667		-2.06667		1.32222		
pass 5	0.23869	-1.08156	0.44333					7.55556	-4.43333	
Lightness Index										
pass 1	87.88	-487.93						2096.67		
pass 3	79.09	-531.52		6956.00				1872.22		
pass 5	75.80	-351.60								
O.I.T. (min)										
pass 1	68.89	1525.06	-707.64					-11612.22	5161.11	
pass 3	57.96	1011.31	-162.13					-5451.11		
pass 5	71.05	430.77	-251.73							

Table 5.25 : Coefficients for the properties of HDPE compounded with actual amount of DAT, DSTDP and OBA.

5.3 Effects of the Quantity of Additives Studied on the Properties of Compounded HDPE

Response surface methodology was used to show the relationship between the properties of compounded HDPE and the amount of additives as shown in Figures 5.1 to 5.57. The effects of the selected additives on the properties of the compounded HDPE are presented and discussed in the following sections.

5.3.1 Color Test

Interaction of blended antioxidant and OBA

Figure 5.1 shows the interaction of the blended antioxidant and the OBA on the Lightness index (L_c) upon the first to the fifth processing pass. When the concentration of the blended antioxidant increased, the level of the L_c, which reflects the whiteness of the compounded HDPE, decreased. At high concentration of the blended antioxidant, the OBA of about 0.0007% in concentration gave the highest L_c and the best whiteness. At low concentration of the blended antioxidant, the L_c is enhanced upon greater concentration of the OBA. The combination of the blended antioxidant and the OBA gave a good color stability for the compounded HDPE.

Interaction of PATHP, DLTDP and OBA

Figures 5.2 to 5.4 show the interaction of PATHP, DLTDP and OBA on the Lightness index (L_c) upon the first to the fifth processing pass. When the concentration of PATHP increased, the L_c was decreased. At the

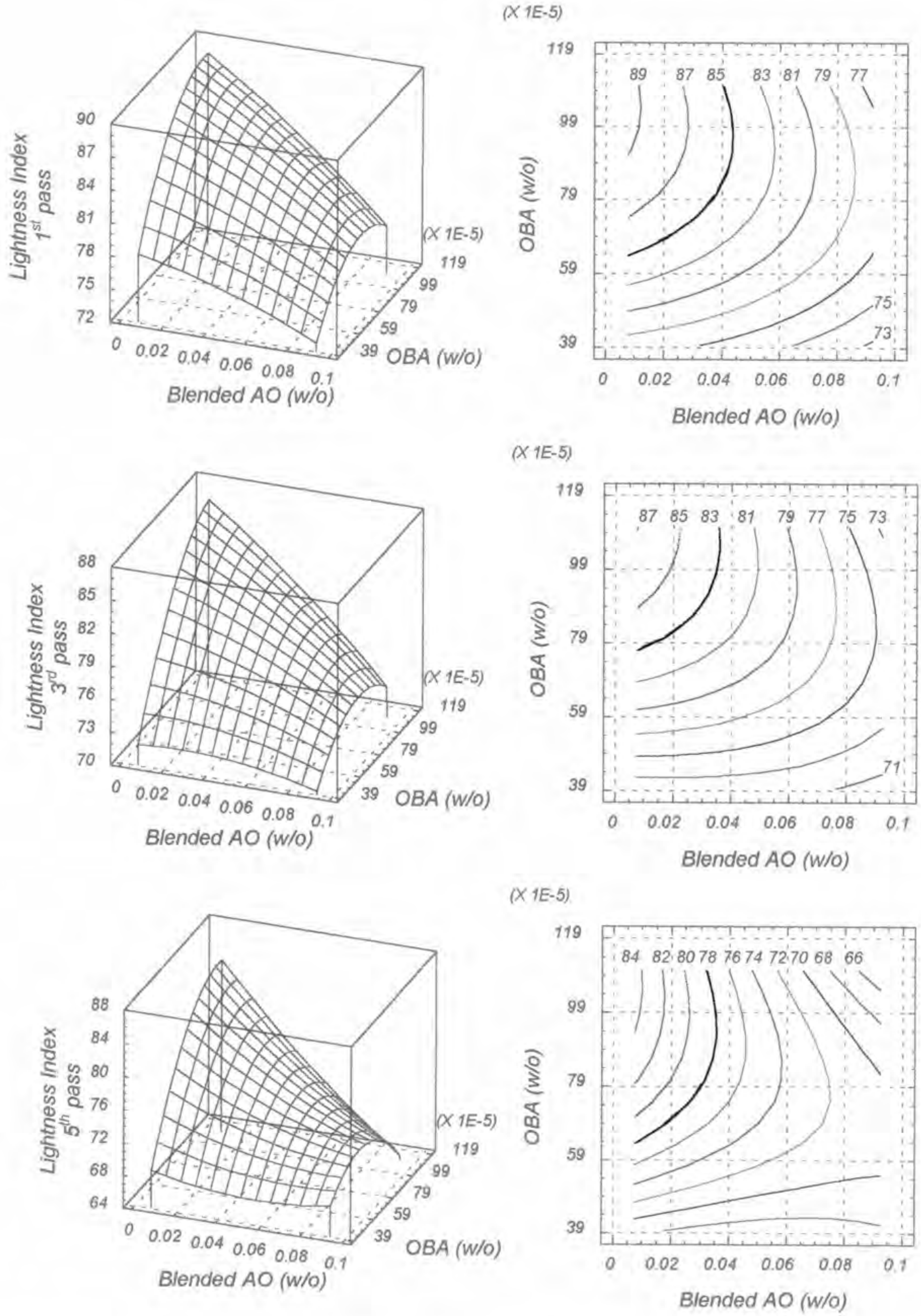

Figure 5.1 : Interaction of Blended AO and OBA on Lightness index (L_c) upon first to fifth pass.

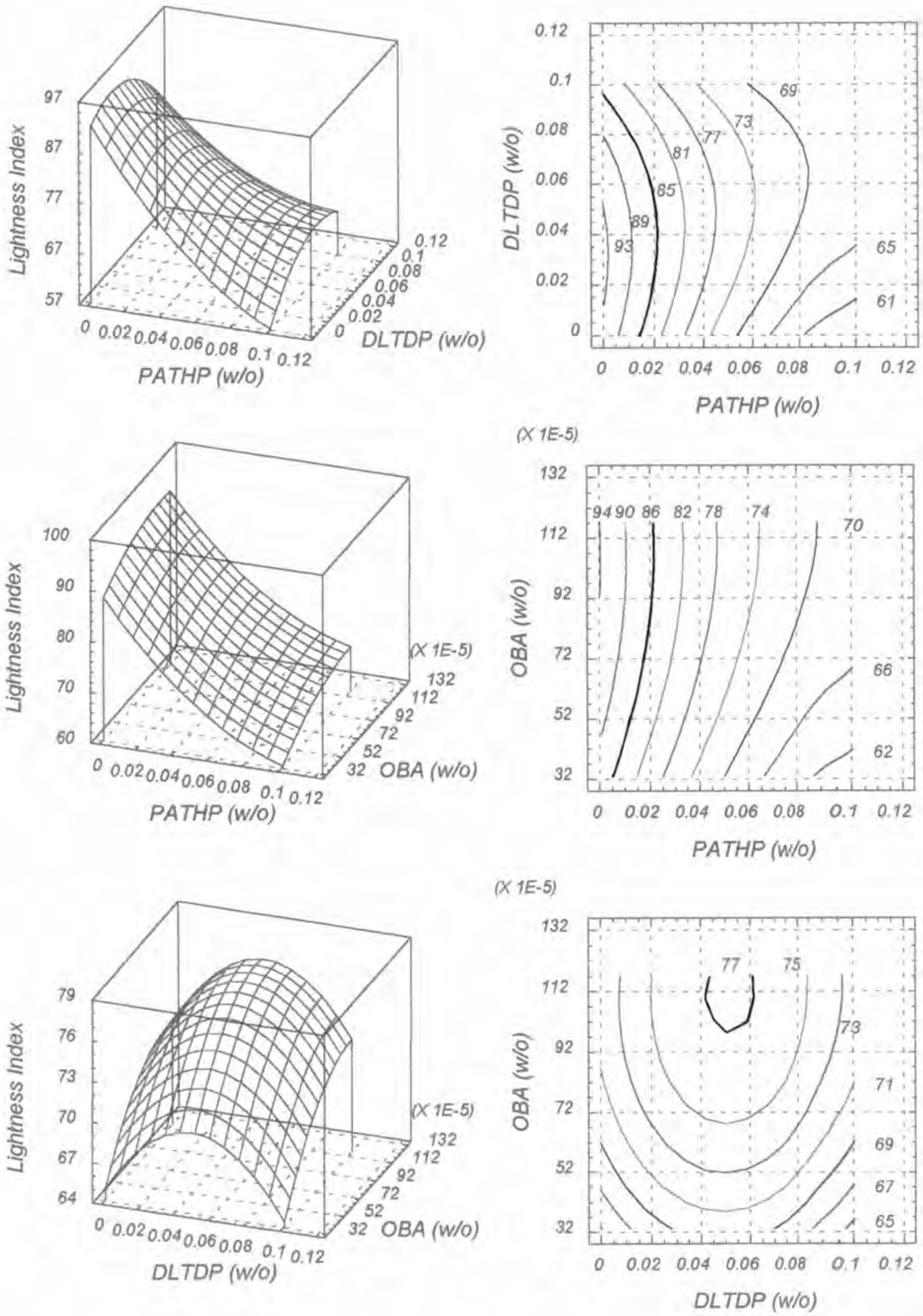

Figure 5.2 : Interaction of PATHP, DLTDP and OBA on Lightness index (L_c) upon first pass.

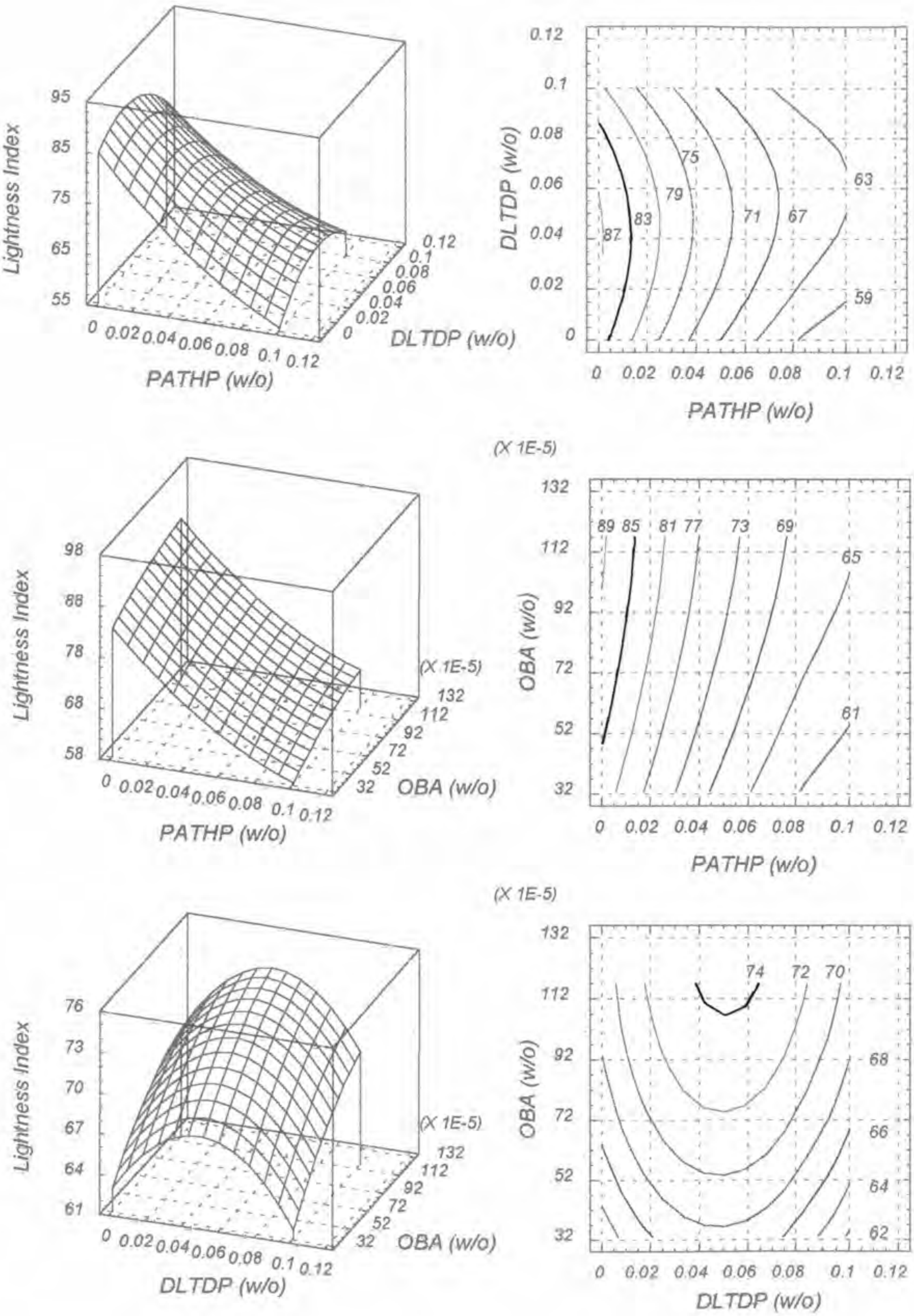

Figure 5.3 : Interaction of PATHP, DLTDP and OBA on Lightness index (L_c) upon third pass.

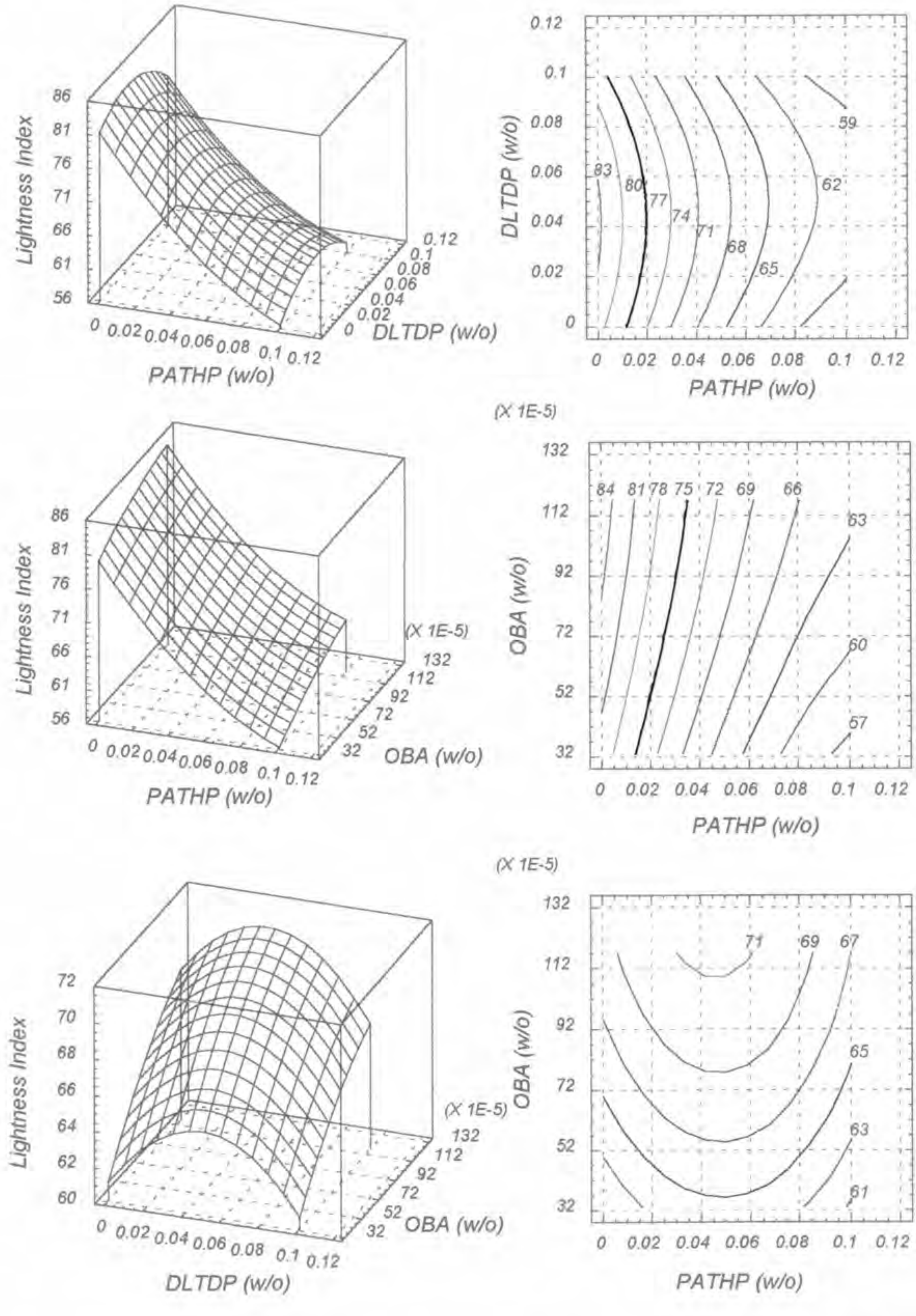

Figure 5.4 : Interaction of PATHP, DLTDP and OBA on Lightness index (L_c) upon fifth pass.

concentration of DLTDP of around 0.05 to 0.06%, the L_c was raised. When the amount of the OBA was increased, the L_c became higher as well.

Interaction of PATHP, DSTDP and OBA

Figures 5.5 to 5.7 show the interaction of PATHP, DSTDP and OBA on the Lightness index (L_c) upon the first to the fifth processing pass. When the amount of PATHP was increased, the L_c was decreased. At a low concentration of PATHP, when the concentration of both DSTDP and the OBA increased, the L_c became greater as well. However, at high concentration of the PATHP, DSTDP and the OBA had only a minute effect on the L_c. At the concentration of DSTDP of around 0.06%, the L_c was at its highest level. The DSTDP and the OBA are evidently capable of improving the color of the compounded HDPE.

Interaction of ODHP, DLTDP and OBA

Figures 5.8 to 5.10 show the interaction of ODHP, DLTDP and OBA on the Lightness index (L_c) upon the first to the fifth processing pass. When the amount of ODHP was increased, the L_c was reduced. At a low concentration of ODHP, the L_c was slightly affected by the DLTDP. When the concentration of the DLTDP and the OBA increased, the L_c was also enhanced.

Interaction of ODHP, DSTDP and OBA

Figures 5.11 to 5.13 show the interaction of ODHP, DSTDP and OBA on the Lightness index (L_c) upon the first to the fifth processing pass. When the concentration of ODHP is raised, the L_c decreased. At the low concentration of the ODHP, the OBA had a slight effect on the L_c. However, when the amount of the ODHP was increased, the OBA helped enhancing the L_c. The

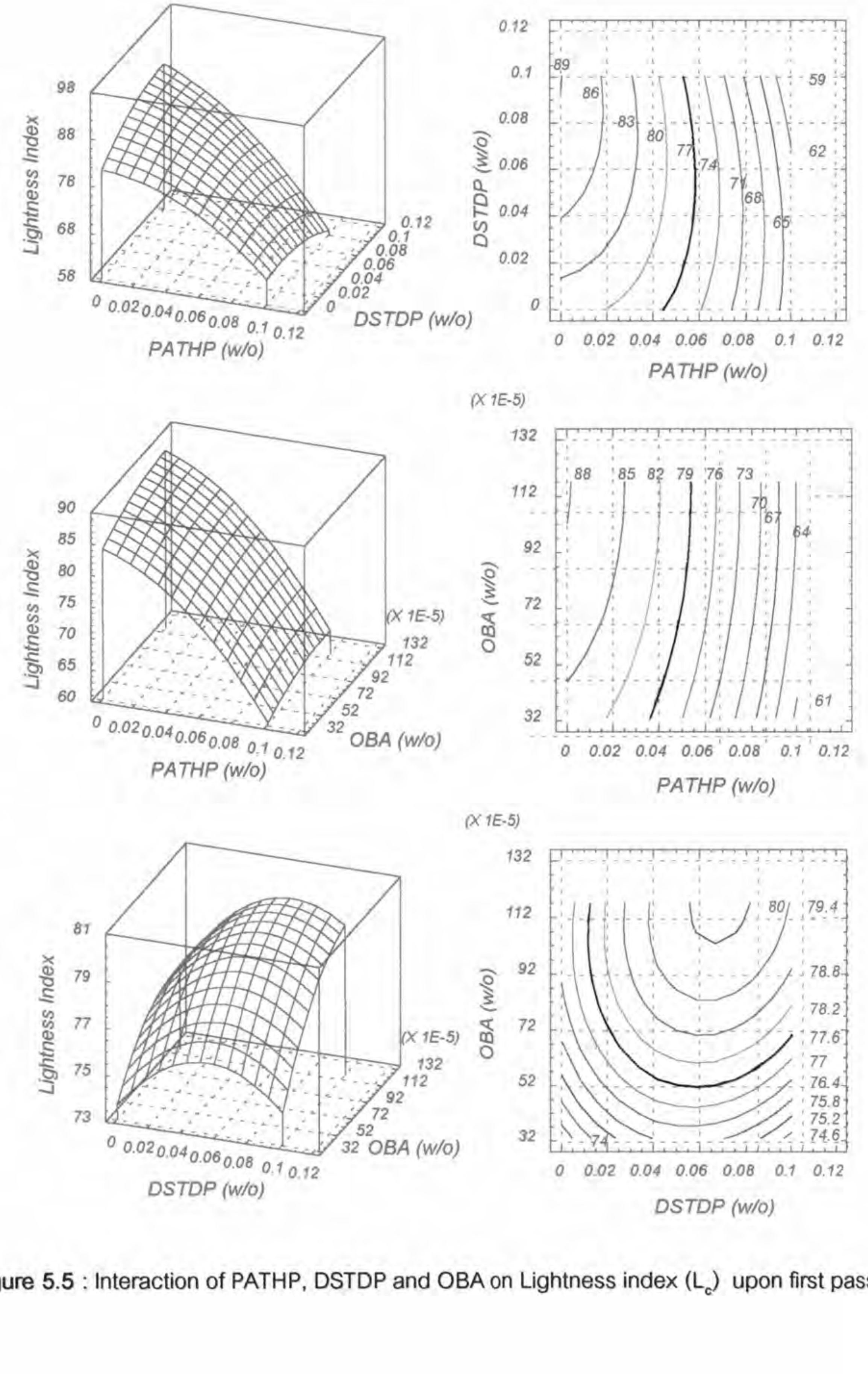

Figure 5.5 : Interaction of PATHP, DSTDP and OBA on Lightness index (L_c) upon first pass.

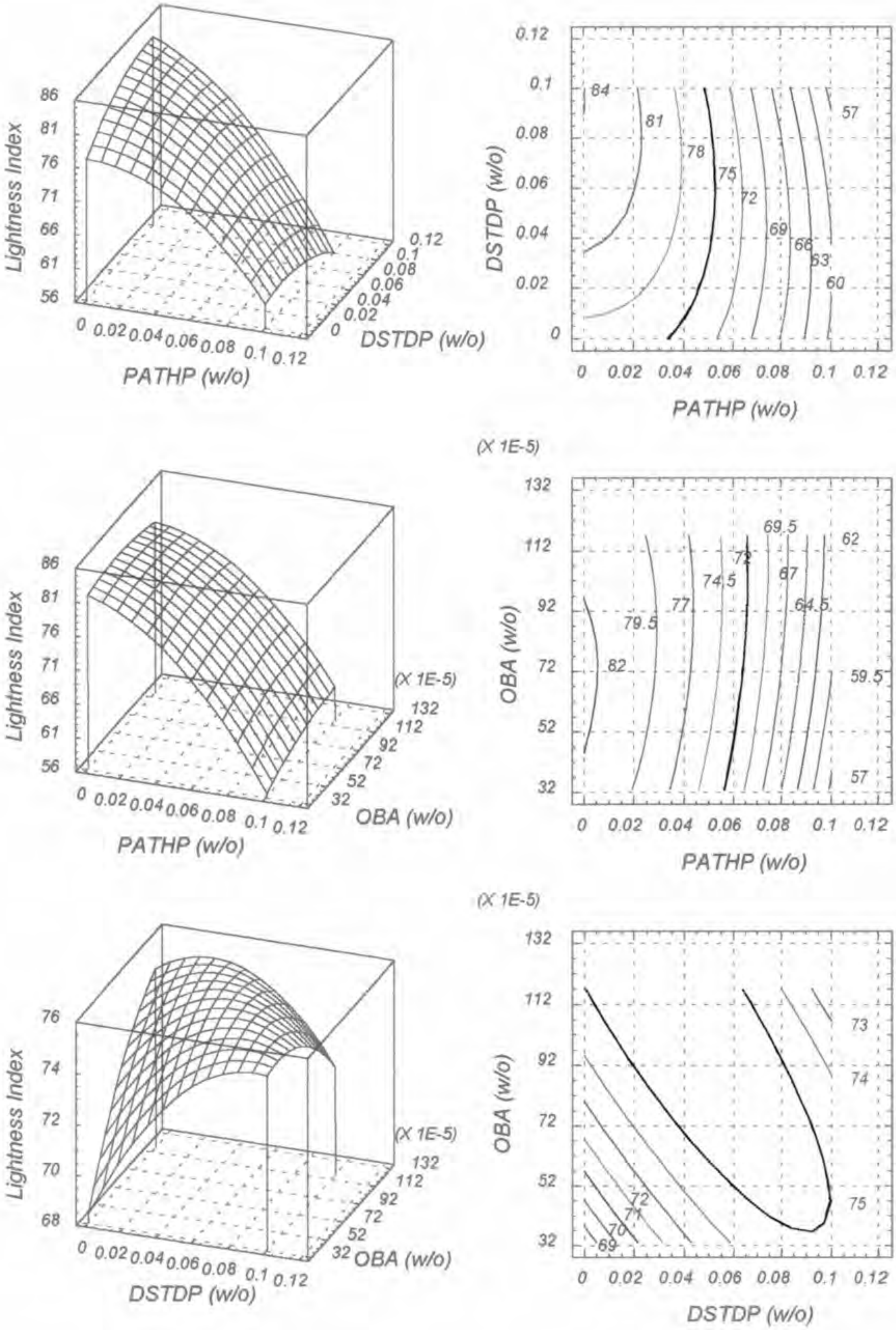

Figure 5.6 : Interaction of PATHP, DSTDP and OBA on Lightness index (L_c) upon third pass.

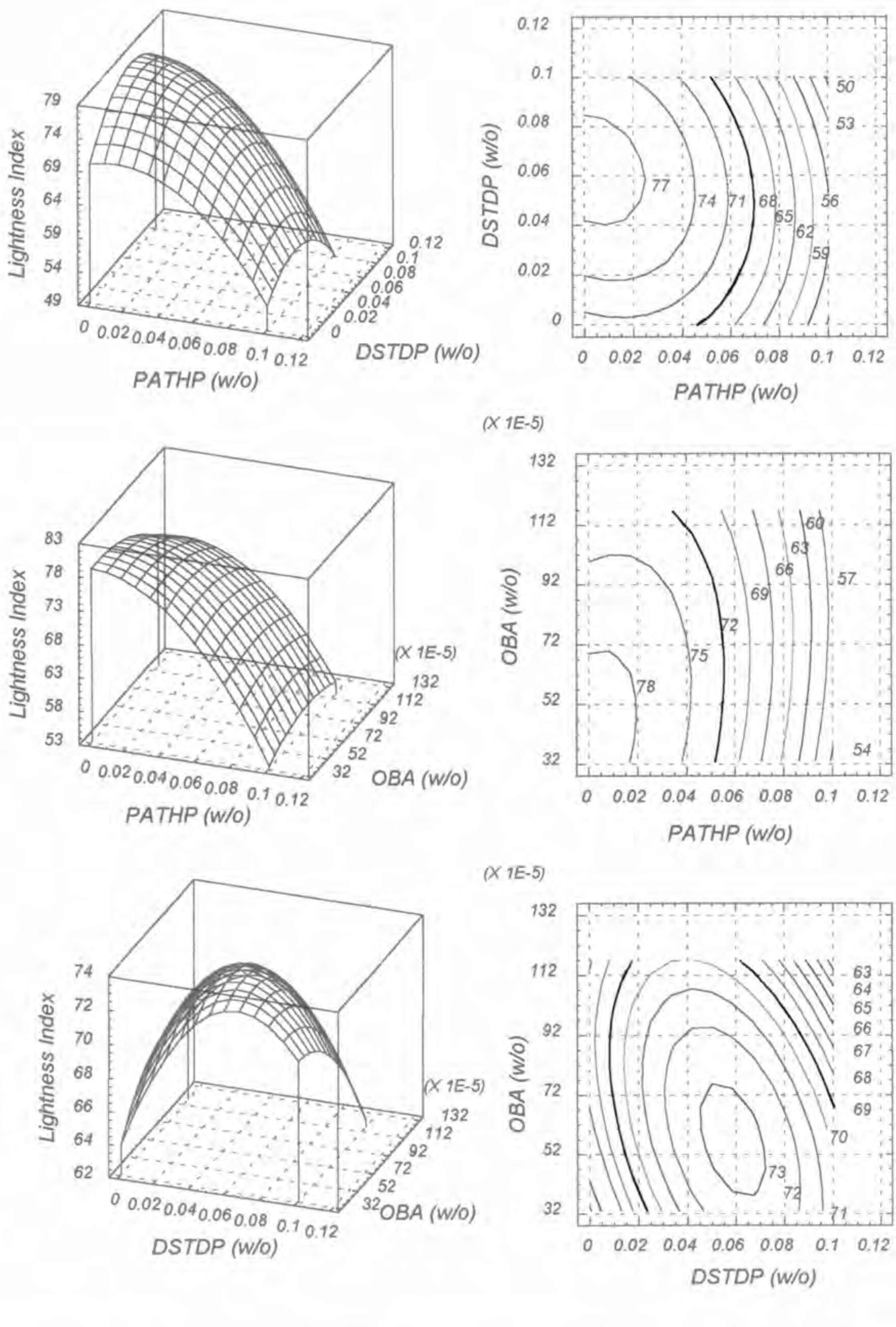

Figure 5.7 : Interaction of PATHP, DSTDP and OBA on Lightness index (L_c) upon fifth pass.

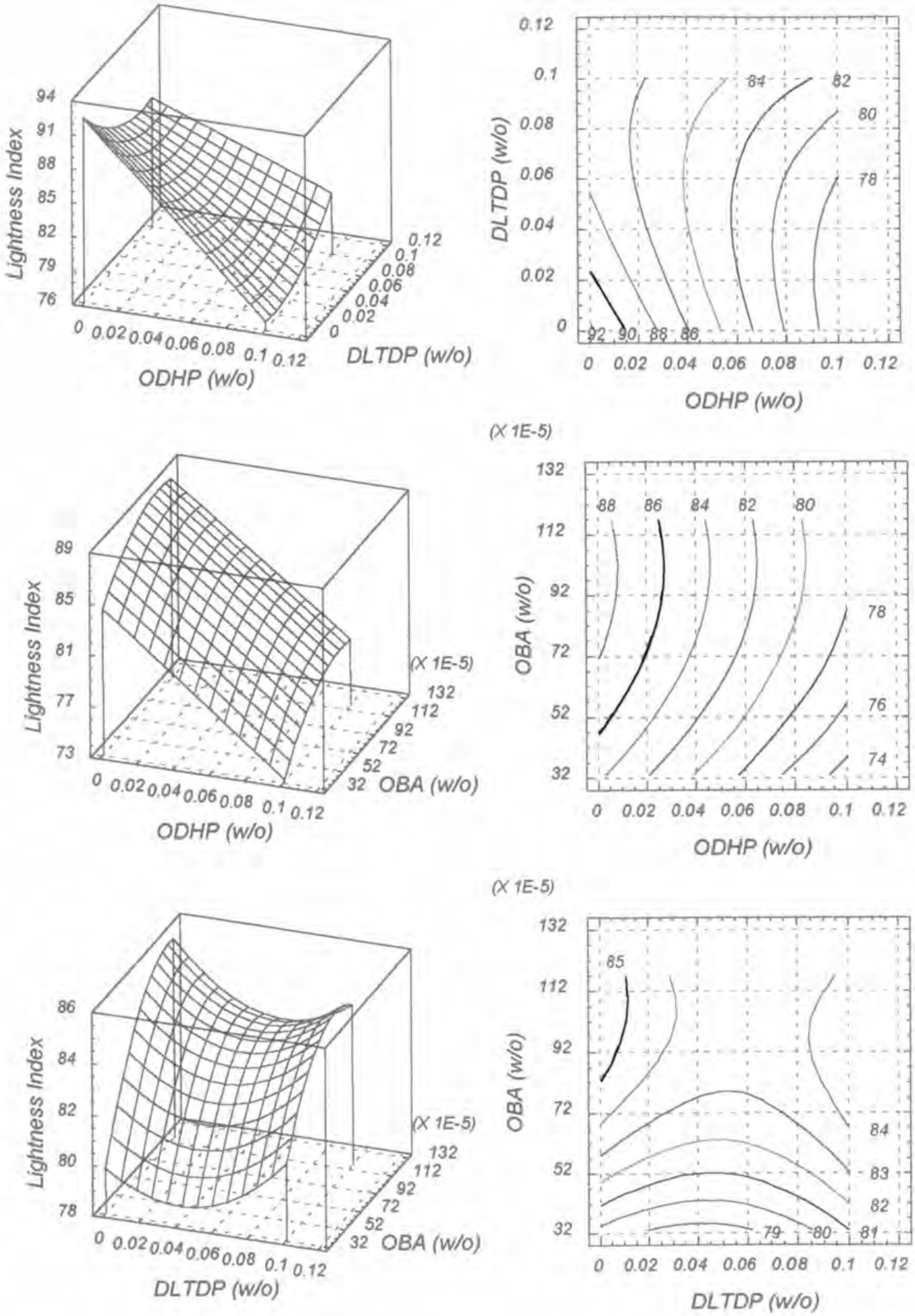

Figure 5.8 : Interaction of ODHP, DLTDP and OBA on Lightness index (L_c) upon first pass.

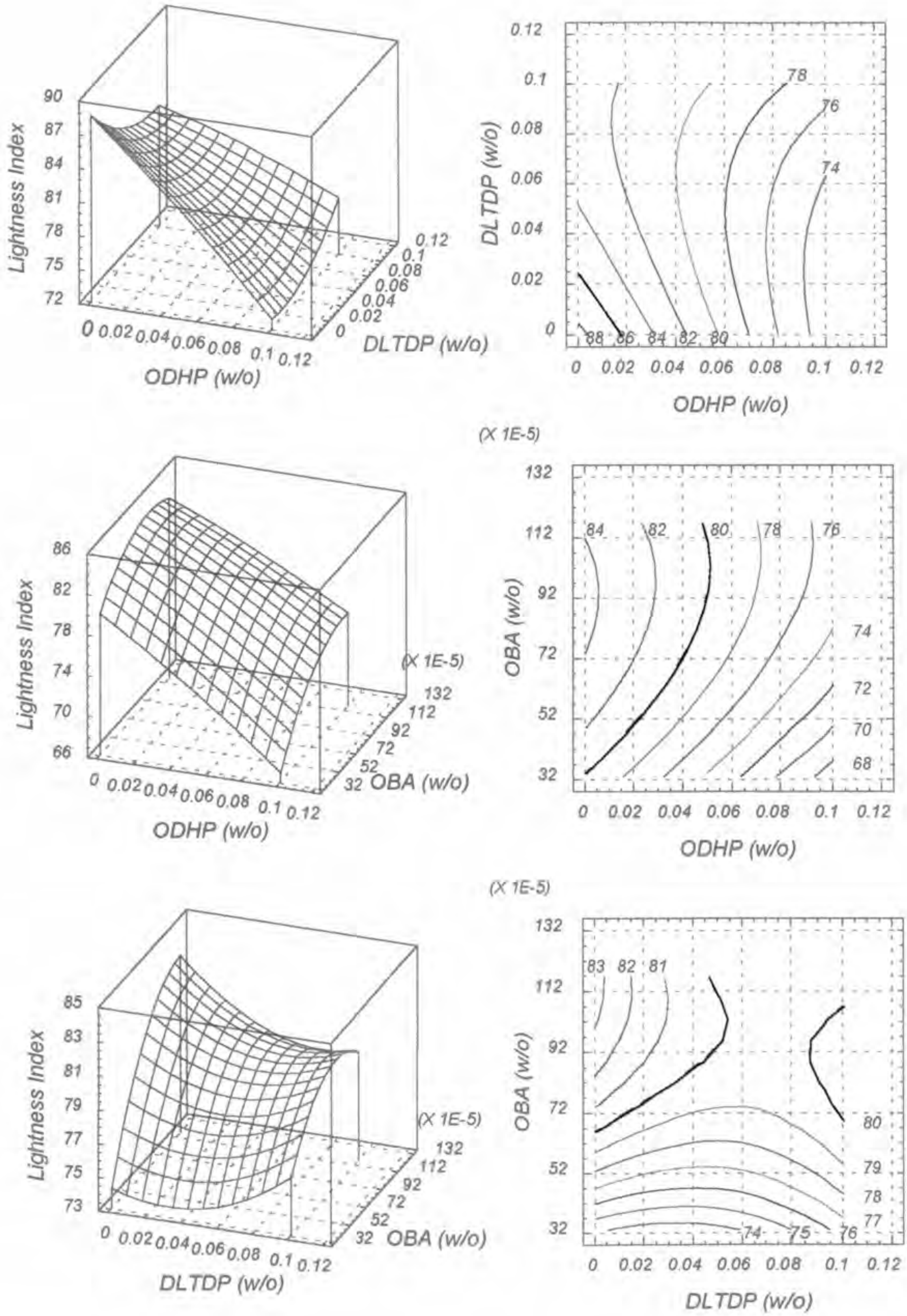

Figure 5.9 : Interaction of ODHP, DLTDP and OBA on Lightness index (L_c) upon third pass.

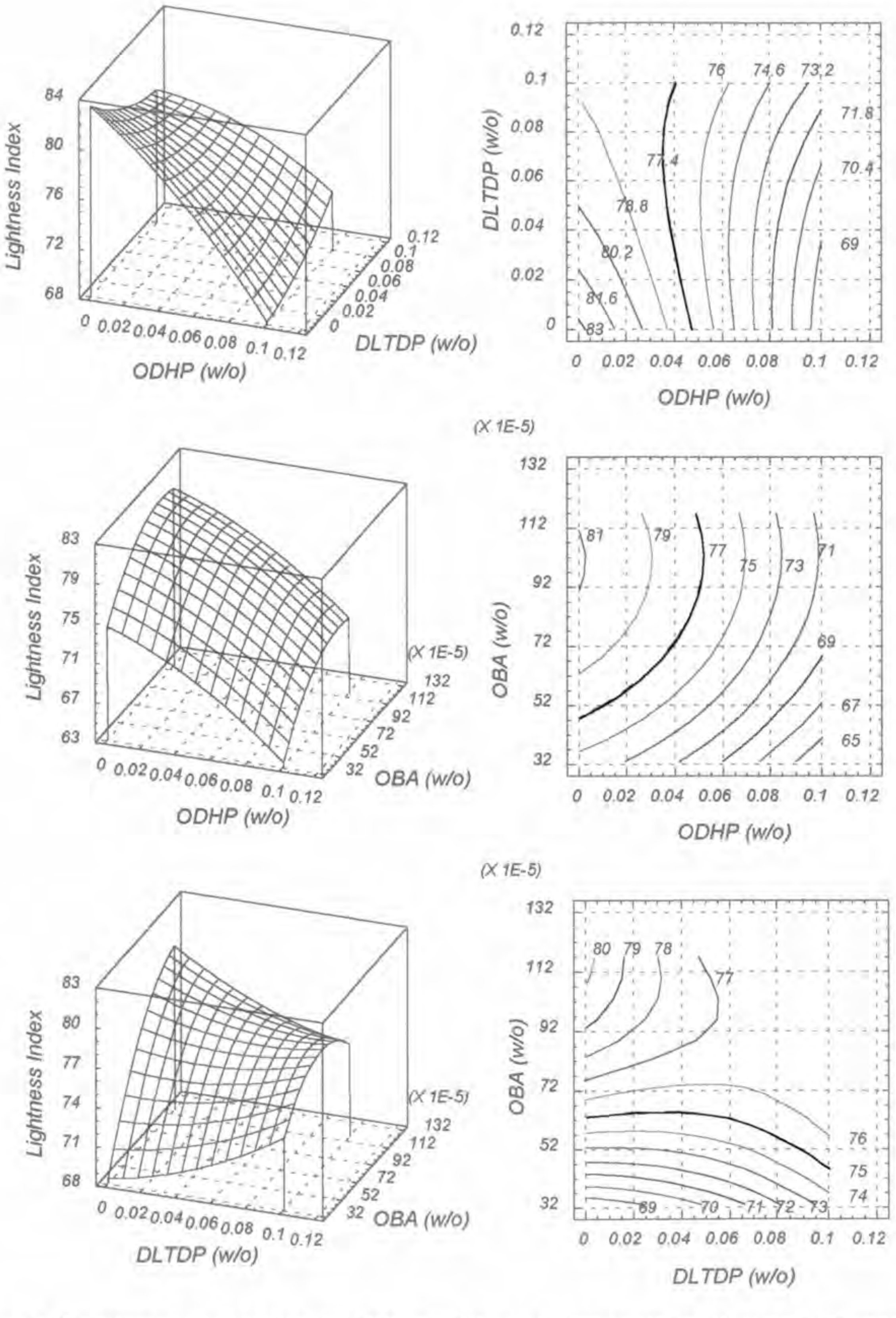

Figure 5.10 : Interaction of ODHP, DLTDP and OBA on Lightness index (L_c) upon fifth pass.

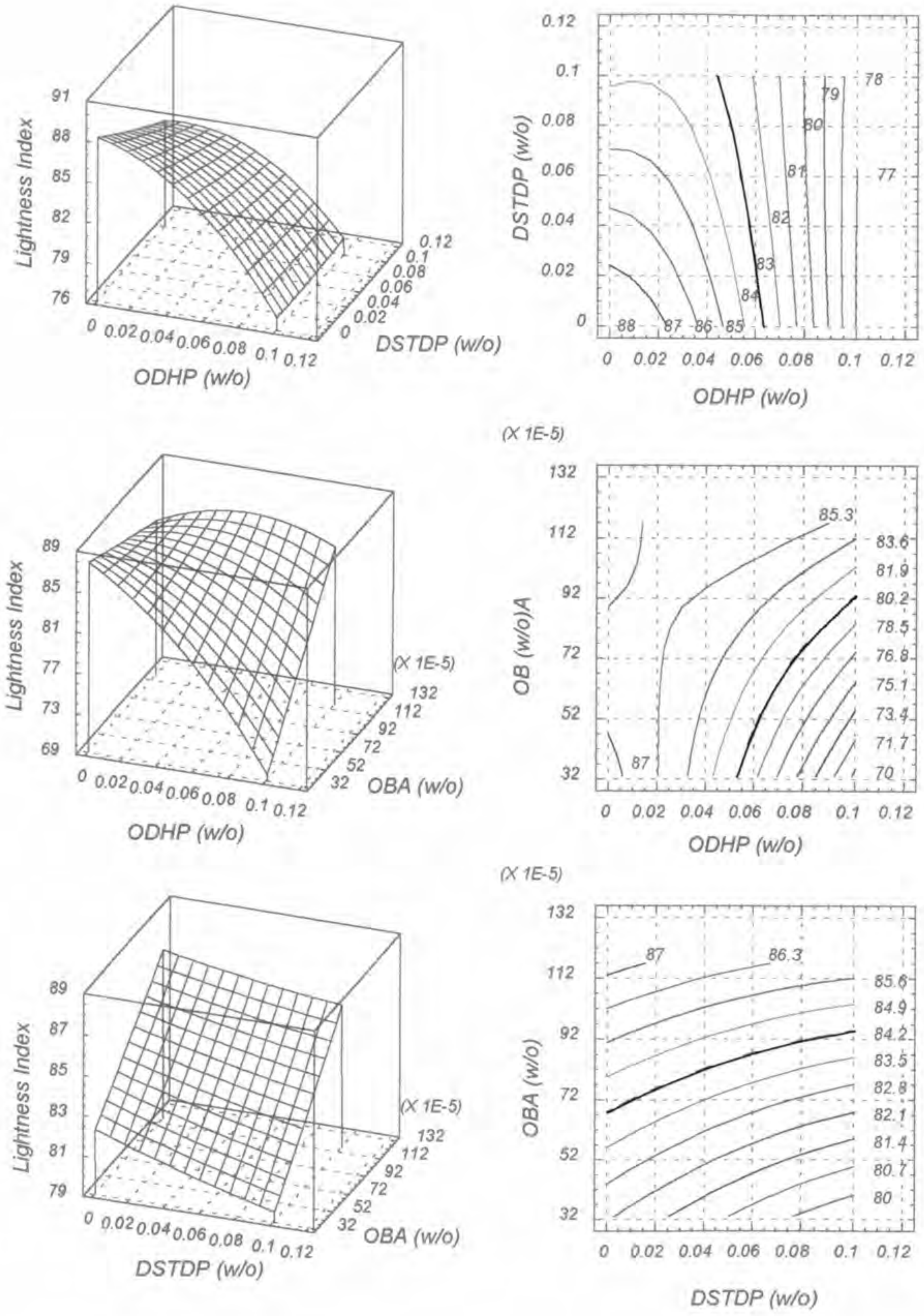

Figure 5.11 : Interaction of ODHP, DSTDP and OBA on Lightness index (L_c) upon first pass.

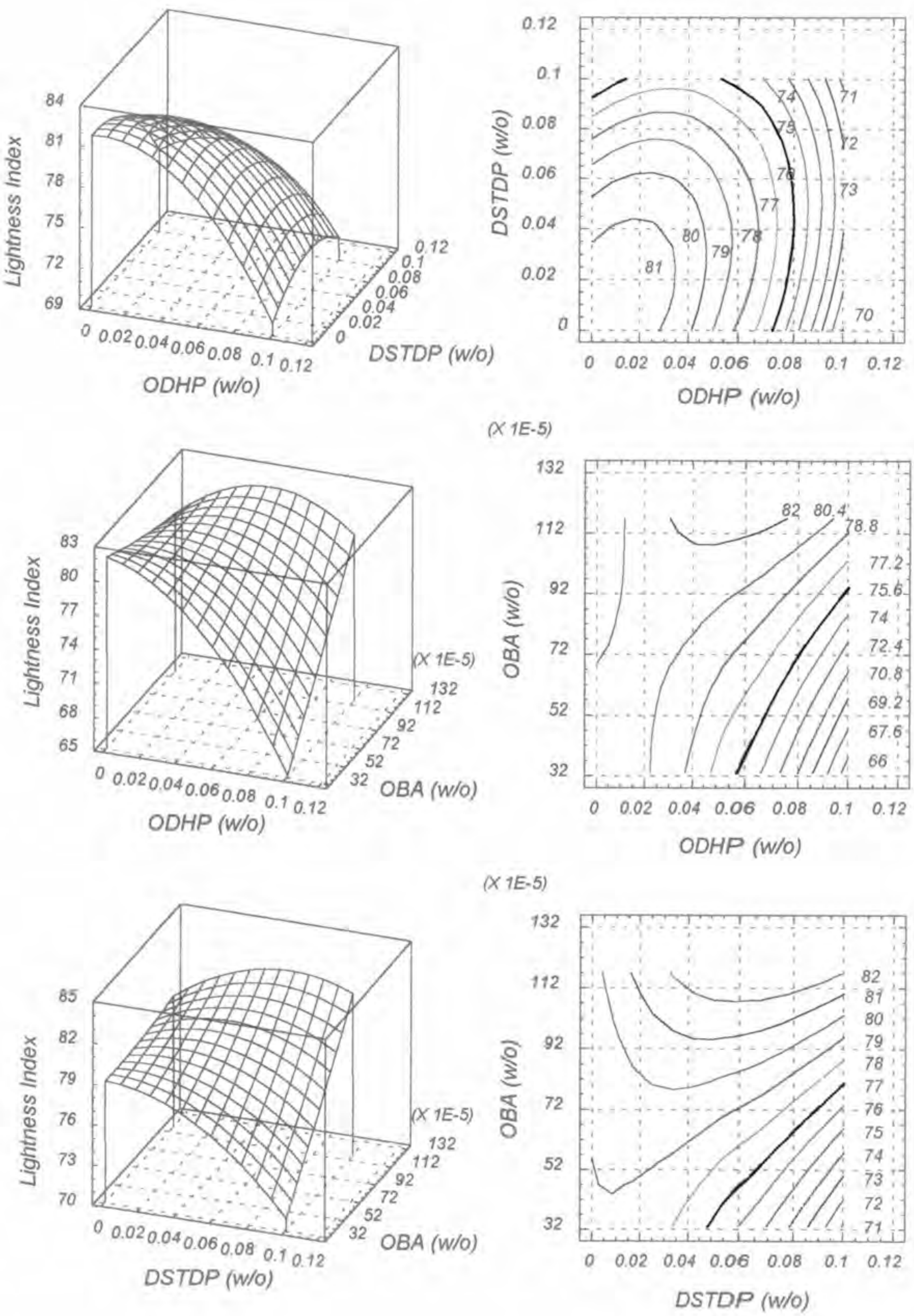

Figure 5.12 : Interaction of ODHP, DSTDP and OBA on Lightness index (L_c) upon third pass.

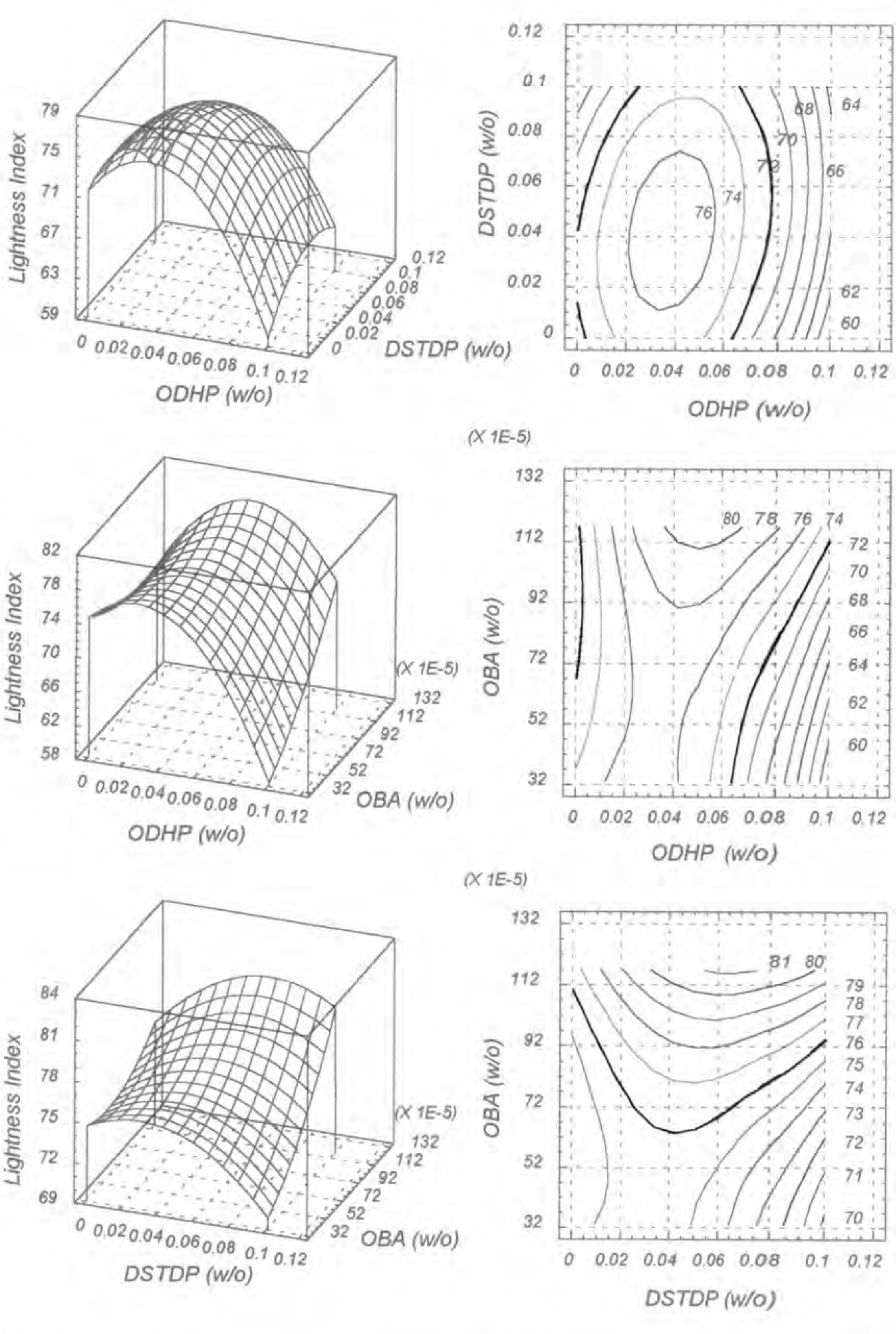

Figure 5.13 : Interaction of ODHP, DSTDP and OBA on Lightness index (L_c) upon fifth pass.

DSTDP had a slight effect on the L_c. In this system, the DSTDP was not so effective in improving the color of the compounded HDPE.

Interaction of DAT, DLTDP and OBA

Figures 5.14 to 5.16 show the interaction of DAT, DLTDP and OBA on the Lightness index (L_c) upon the first to the fifth processing pass. When the concentration of the DAT was increased, the L_c was greatly lowered. At a low concentration of DAT, an increase in the concentration of either the DLTDP or the OBA led to an enhancement in the L_c. At the high concentration of DAT, the combination of DLTDP and OBA had only a slight effect on the L_c. The quantity of DAT greatly affected the compounded HDPE that it greatly lowered the L_c when the concentration of DAT was raised.

Interaction of DAT, DSTDP and OBA

Figures 5.17 to 5.19 show the interaction of DAT, DSTDP and OBA on the Lightness index (L_c) upon the first to the fifth processing pass. When the amount of DAT was increased, the L_c was greatly lowered. At a high concentration of DAT, the OBA had a minute effect on the L_c. At a low concentration of DAT, when the quantity of the OBA was increased, the L_c was slightly increased. In this system, DSTDP had only very slight effect on the L_c.

In the present study, color measurement is expressed as Lightness index which is a reflect of the whiteness of polymers. The Lightness corrected is used to determine the color of polymers in plastic industries. The higher the value of the Lightness corrected, the whiter the polymer appears.

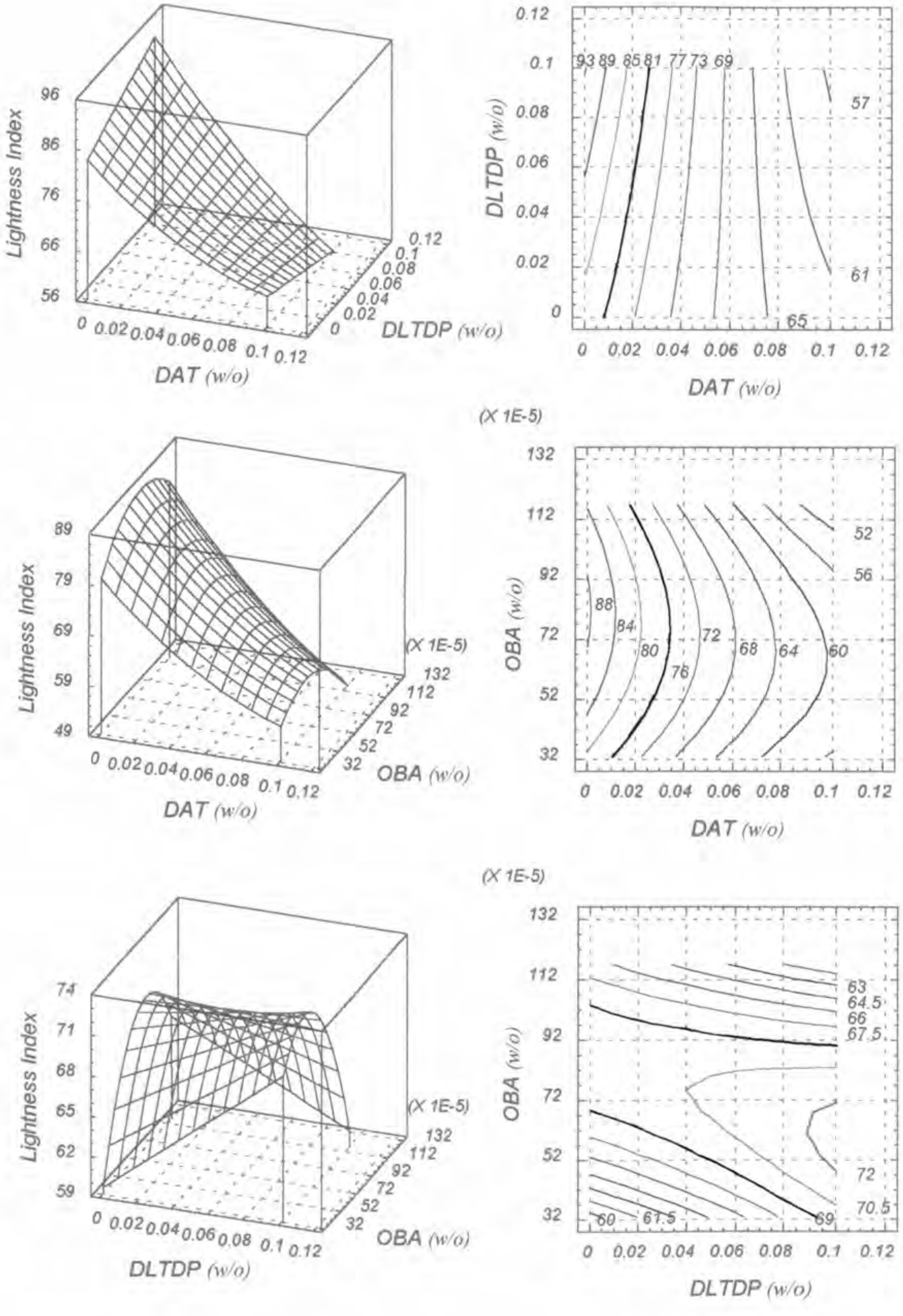

Figure 5.14 : Interaction of DAT, DLTDP and OBA on Lightness index (L_c) upon first pass.

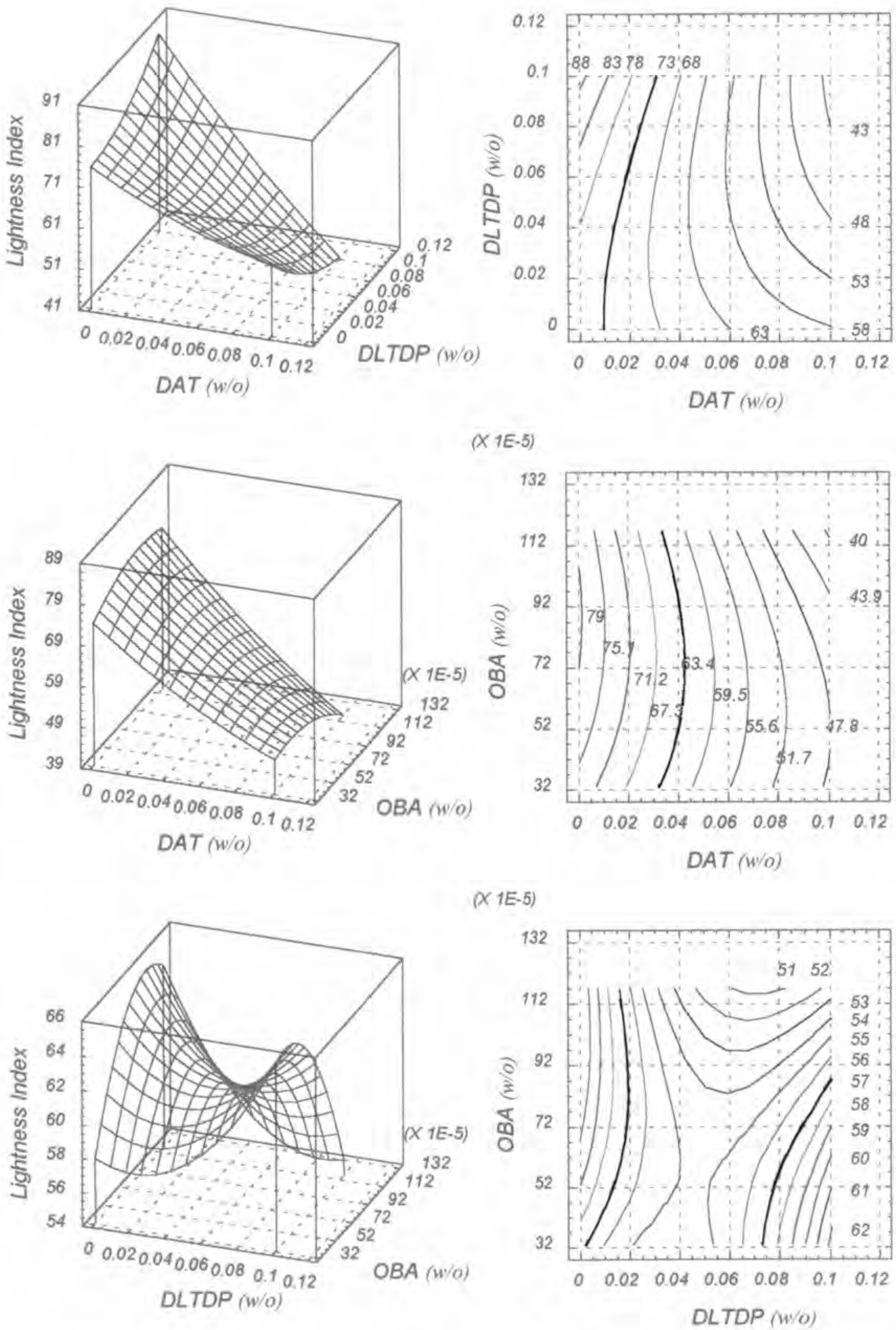

Figure 5.15 : Interaction of DAT, DLTDP and OBA on Lightness index (L_c) upon third pass.

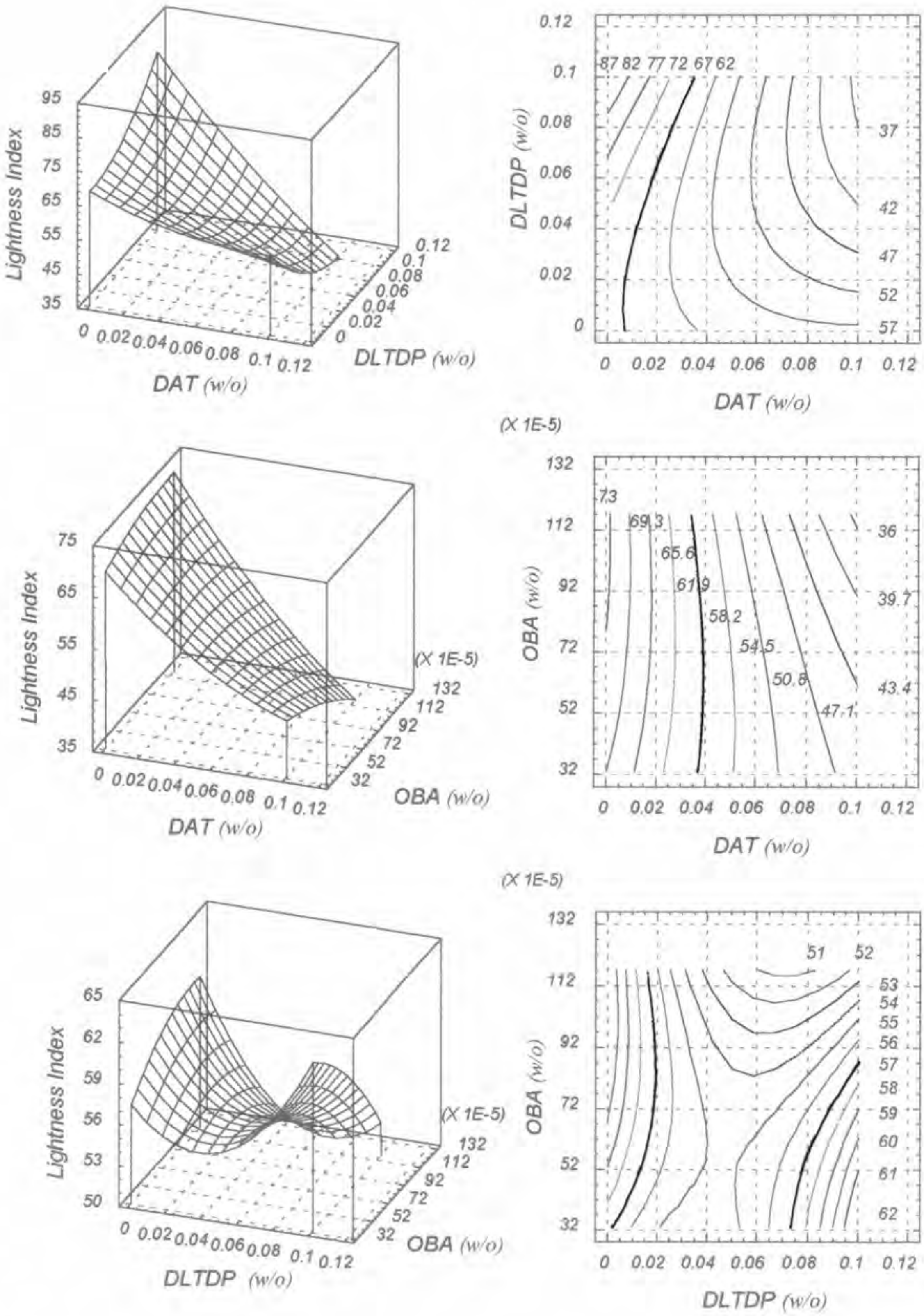

Figure 5.16 : Interaction of DAT, DLTDP and OBA on Lightness index (L_c) upon fifth pass.

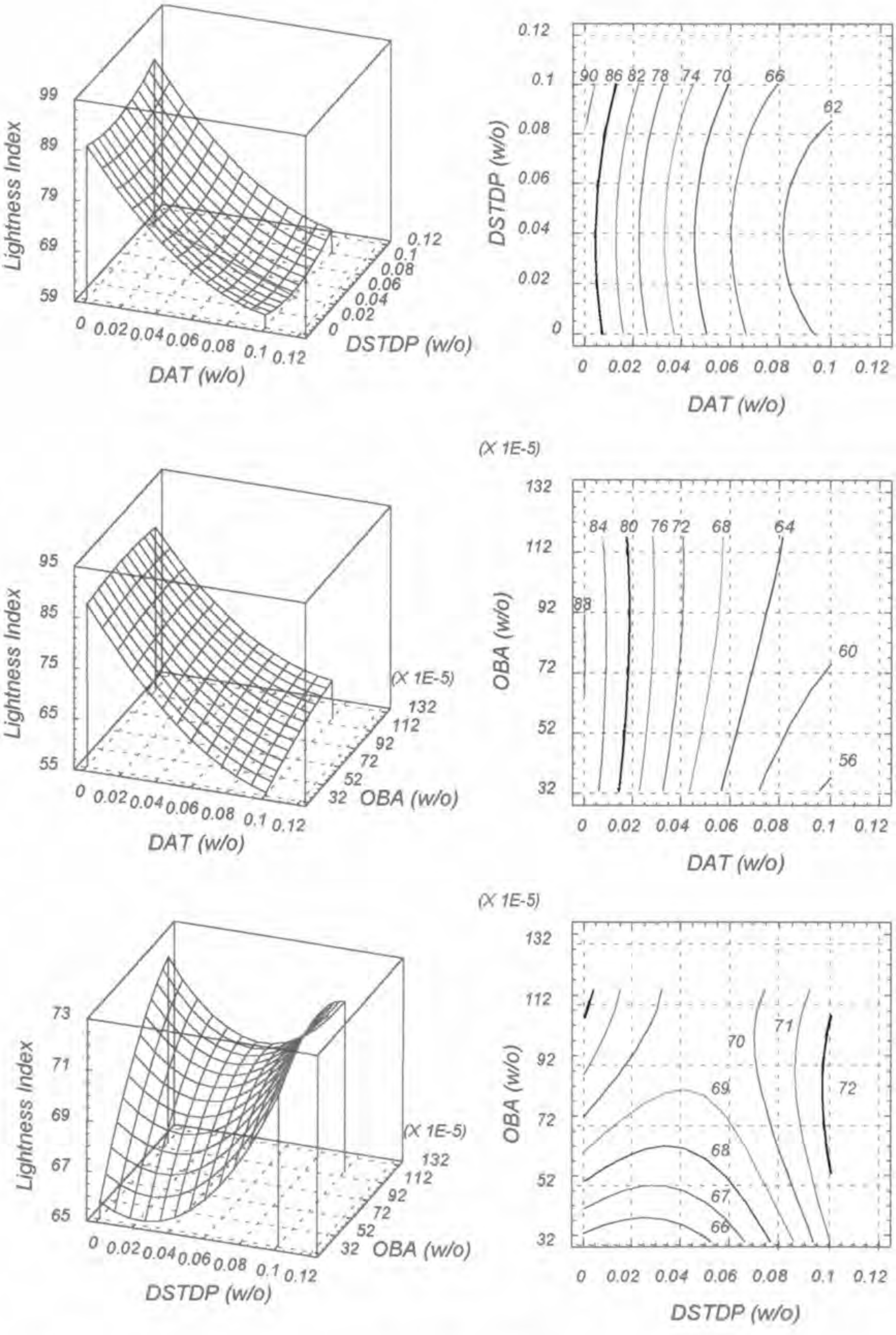

Figure 5.17 : Interaction of DAT, DSTDP and OBA on Lightness index (L_c) upon first pass.

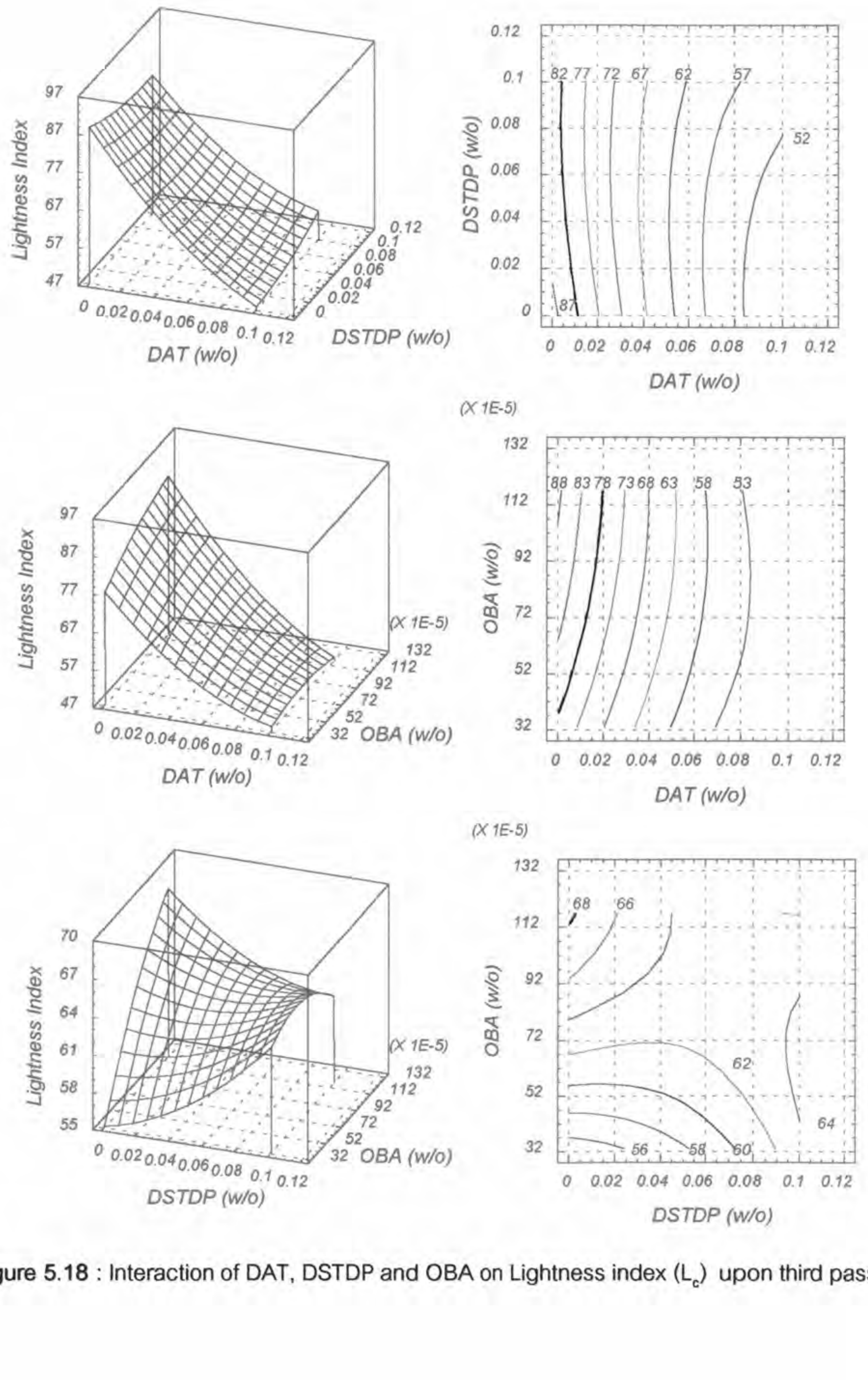

Figure 5.18 : Interaction of DAT, DSTDP and OBA on Lightness index (L_c) upon third pass.

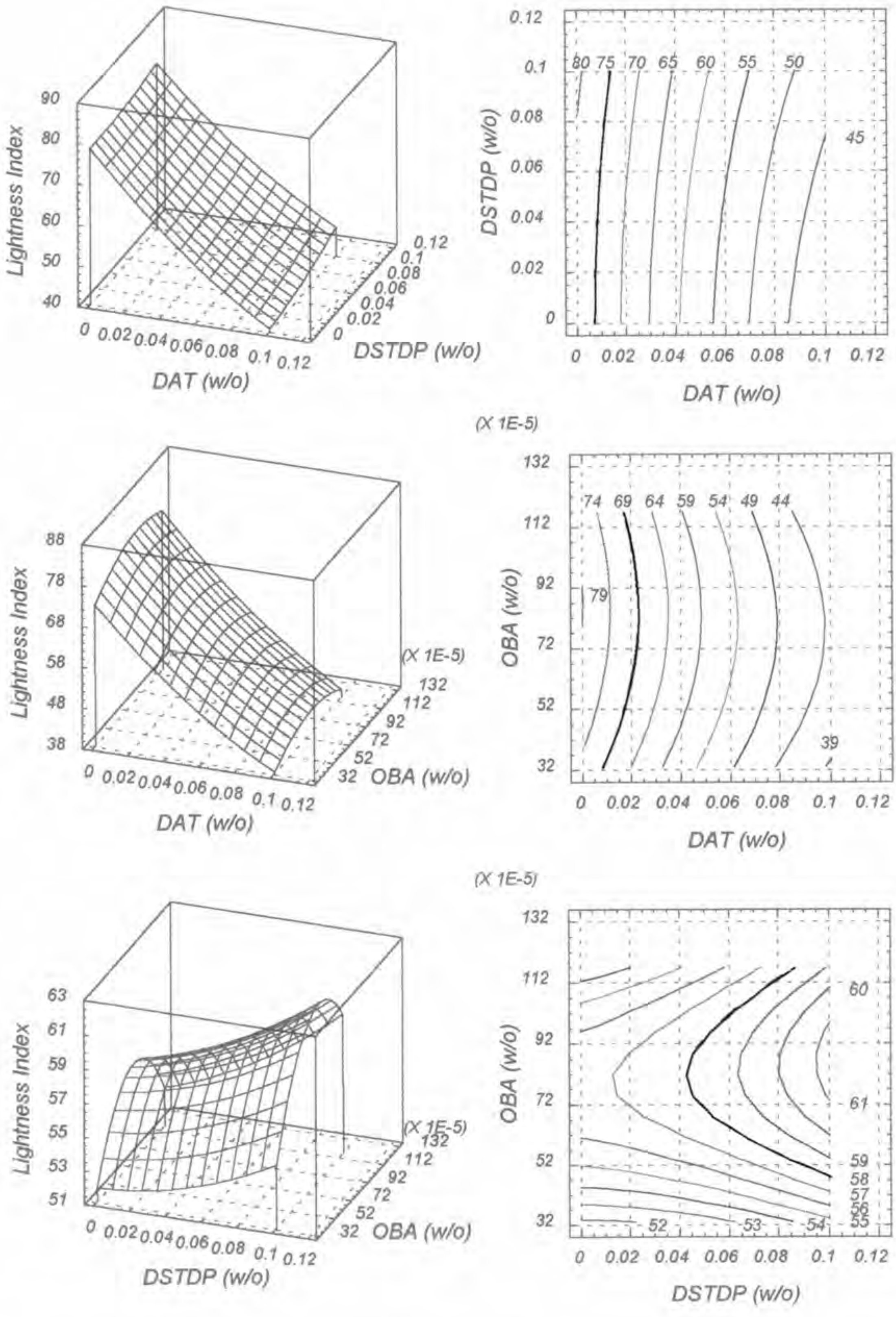

Figure 5.19 : Interaction of DAT, DSTDP and OBA on Lightness index (L_c) upon fifth pass.

The change in the color of the compounded HDPE during multiple extrusion is illustrated in terms of the Lightness index. It was found that there is a reduction in the Lightness index or an increase in the yellowness. All of the color curves evidently verify that the more the number of passes of re-processing, the greater is the decrease in the Lightness index. The phenolic antioxidant reacted with some free radical (R•, RO•,ROO•, HO•, etc.) occurred when the HDPE molecules was subjected to heat during compounding. When the concentrations of the phenolic antioxidants, namely the PATHP, ODHP and DAT, increased, the Lightness index was reduced. This is because the phenolic antioxidant mixed therein the HDPE during compounding may have produced a quinone compound as shown in Figure 2.4. Quinone is generally highly colored, hence its presence has led to the yellowness in the HDPE appearance. The addition of the thioester antioxidant in combination with the optical brightener into the HDPE when the phenolic antioxidant is used could improve the color of HDPE by ameliorating the discoloration that generally occurs due to the quinoid product.

Thioesters are known to be highly effective peroxide decomposer for long-term stability to polymers. DLTDP and DSTDP are the most commonly used sulfur-containing secondary antioxidants[19]. Sulfoxides, the active forms of sulfides, are capable of decomposing many hydroperoxide to form stable products. They are useful in increasing the heat stability performance of the phenolic antioxidants. Hence, thioester antioxidant can remedy the problem of yellowness.

The presence of the optical brightener significantly reduced the level of discoloration in most cases. As a result of its chemical structure, the optical brightener is capable of absorbing invisible UV radiation in the wavelength range of about 360 to 380 nm by converting it to longer wavelength and reemitting it as visible blue or violet light (430-450 nm). Thereby, the unwanted yellowish cast of the substrate is compensated. In addition, more visible light in the range of 400 to 600 nm is reflected than was originally incident; hence the HDPE compounded with the OBA tends to appear whiter, brighter and more brilliant [3].

5.3.2 Oxidative Induction Time Test

Interaction of blended antioxidant and OBA

Figure 5.20 show the interaction of the blended antioxidant and the OBA on Oxidative Induction Time (OIT) upon the first to the fifth processing pass. At a low concentration of the blended antioxidants, when the quantity of the OBA was increased, the OIT slightly decreased. At a high concentration of the blended antioxidants, when the concentration of the OBA increased, the OIT also increased. A combination of the blended antioxidants and the OBA evidently give a strong synergistic effect as depicted in Figure 5.3.

Interaction of PATHP, DLTDP and OBA

Figures 5.21 to 5.23 show the interaction of PATHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon the first to the fifth processing pass. When the concentration of the PATHP increased, the OIT also becomes longer. The OIT was shortened at the concentration of the DLTDP around 0.07-0.08%. The OBA had only a minute effect over the OIT.

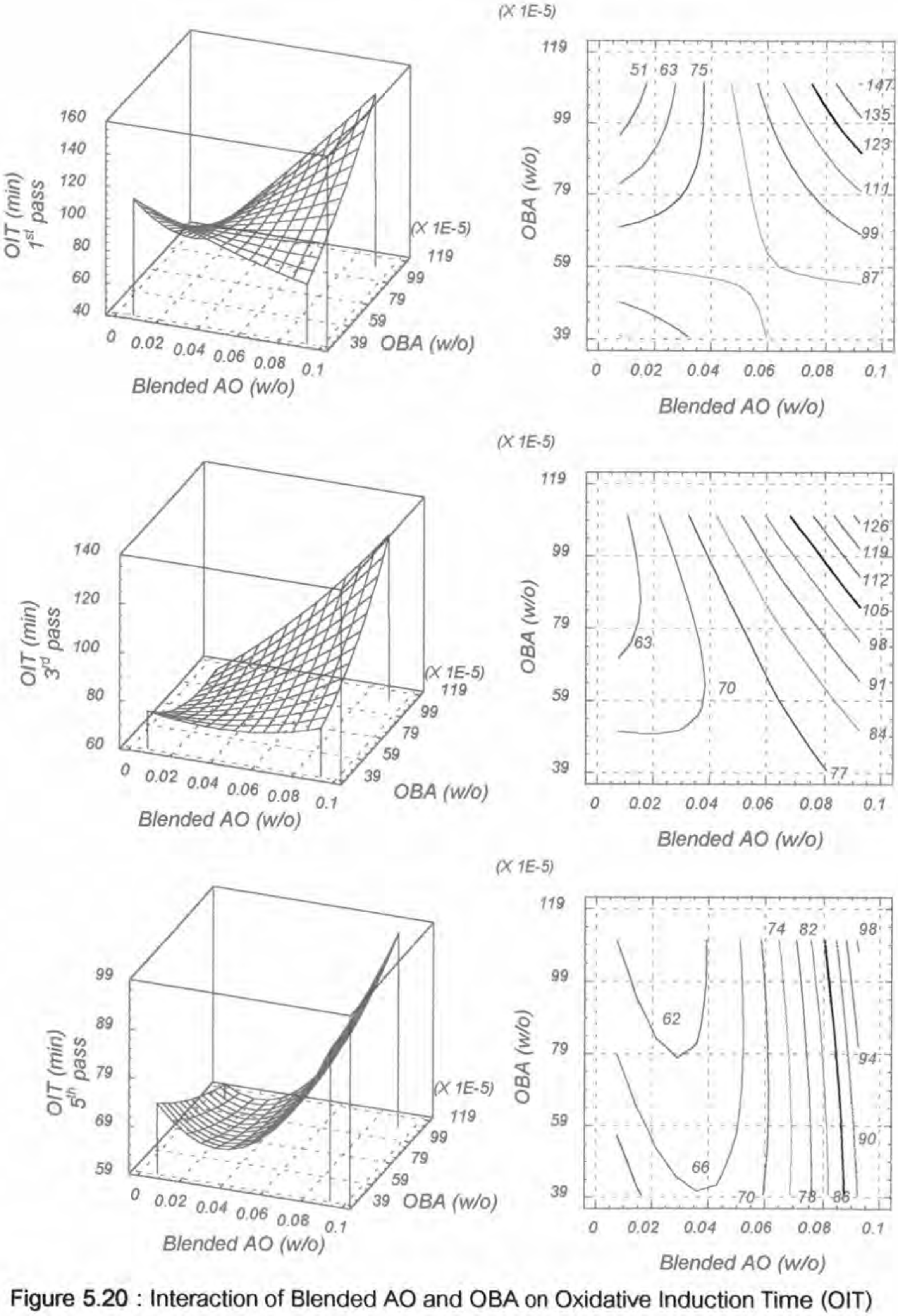

Figure 5.20 : Interaction of Blended AO and OBA on Oxidative Induction Time (OIT) upon first to fifth pass.

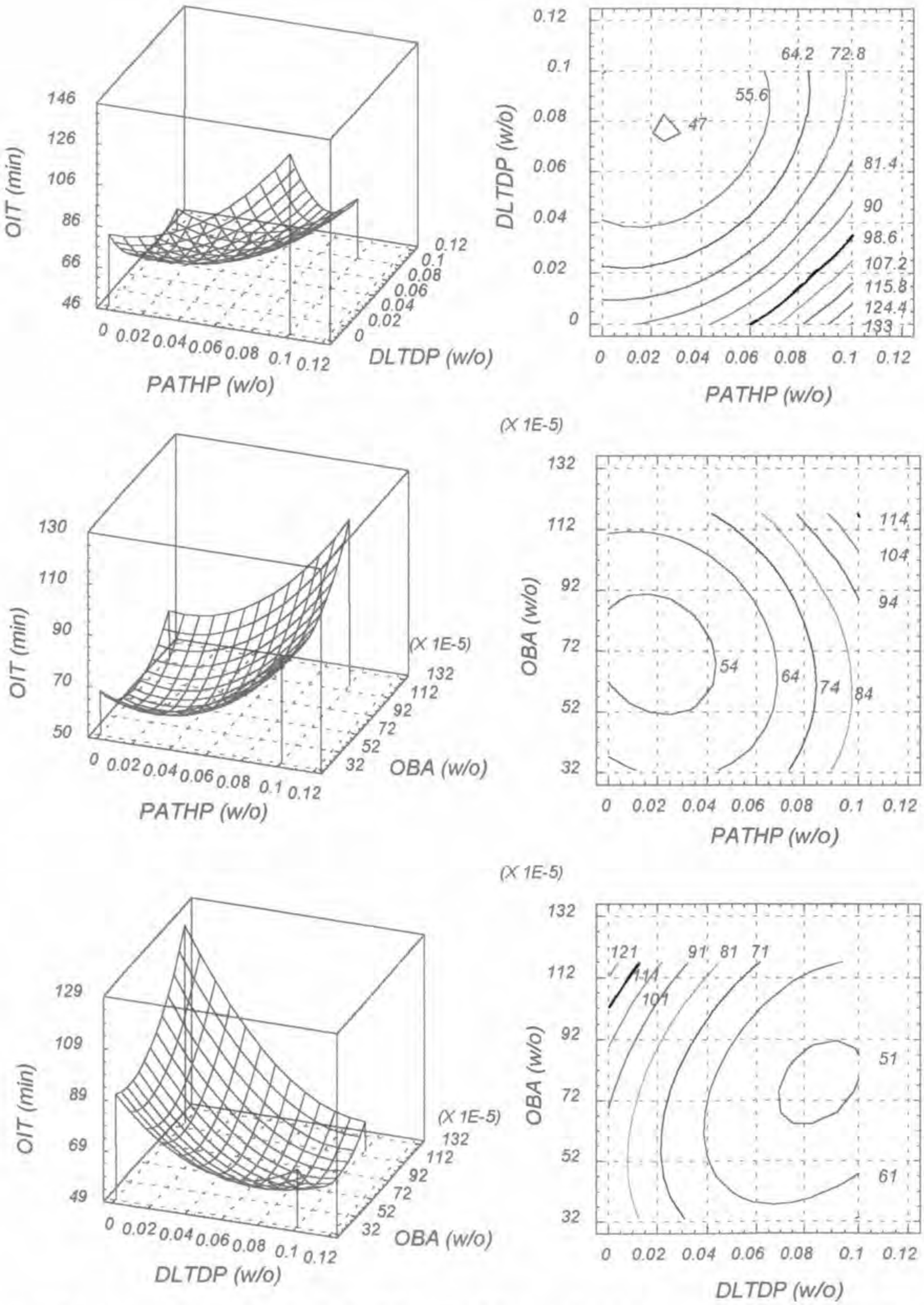

Figure 5.21 : Interaction of PATHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon first pass.

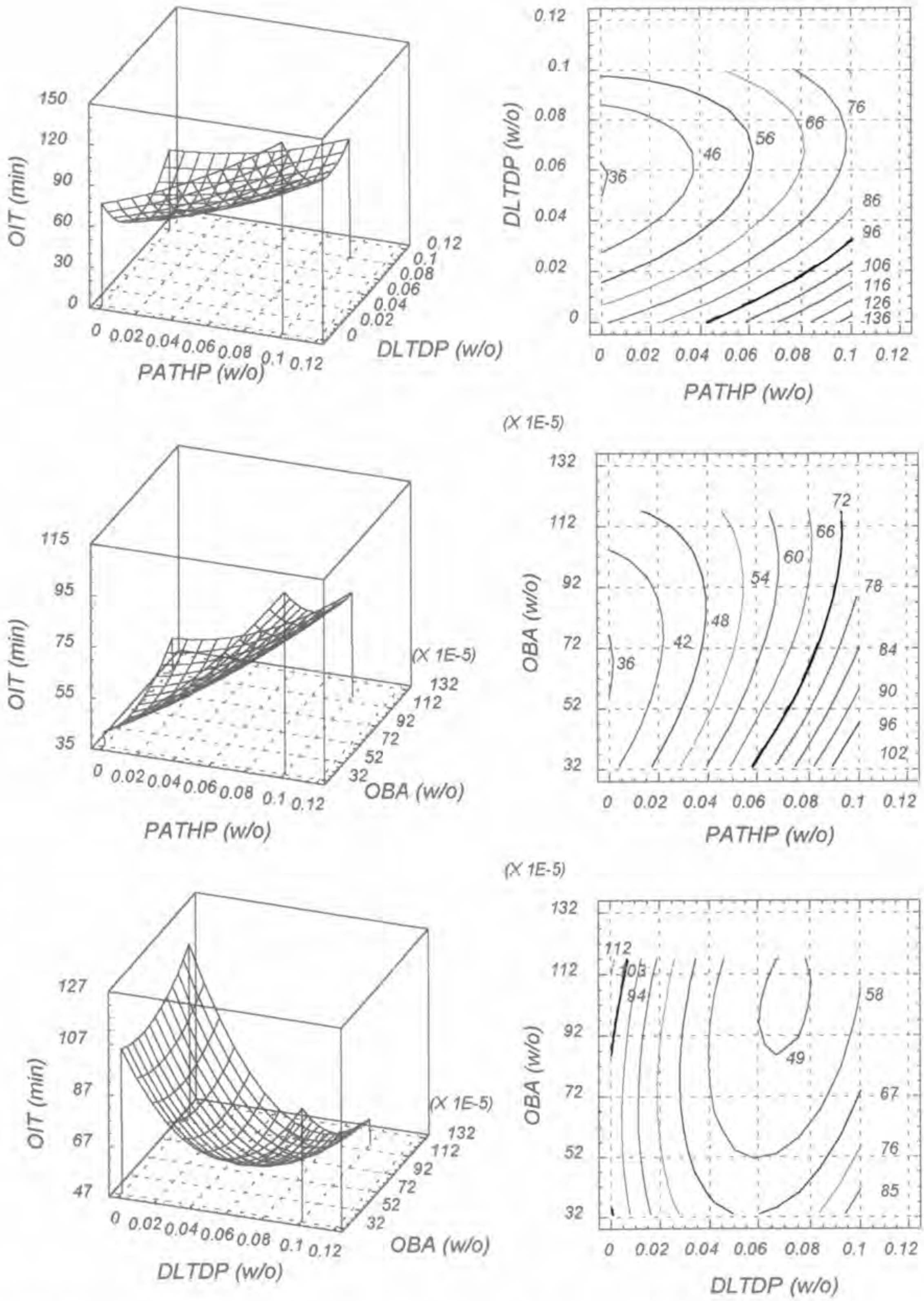

Figure 5.22 : Interaction of PATHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon third pass.

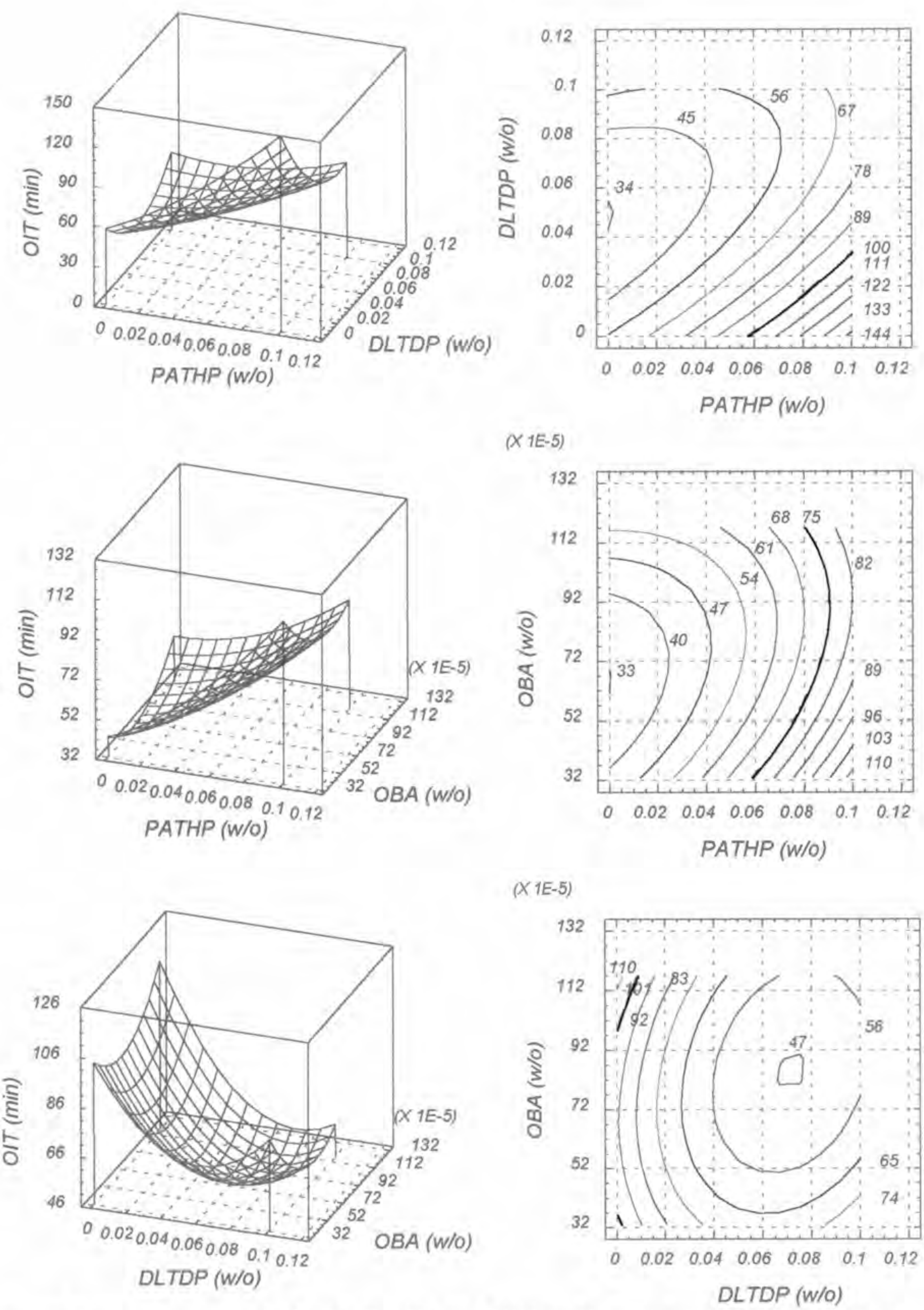

Figure 5.23 : Interaction of PATHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon fifth pass.

Interaction of PATHP, DSTDP and OBA

Figures 5.24 to 5.26 show the interaction of PATHP, DSTDP and OBA on Oxidative Induction Time (OIT) upon the first to the fifth processing pass. When the amount of the PATHP is increased, the OIT is significantly raised. At a low quantity of the PATHP, the OBA helps elevating the OIT. However, at a high amount of the PATHP, the OBA had very little effect on the OIT. A very low OIT was found when the concentration of the DSTDP was around 0.06-0.08%.

Interaction of ODHP, DLTDP and OBA

Figures 5.27 to 5.29 show the interaction of ODHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon the first to the fifth processing pass. A longer OIT was achieved at the concentration of the ODHP around 0.06% and that of the OBA around 0.0006%. At a low concentration of ODHP, the OIT was lowered even when the concentration of the DLTDP was raised. At a high ODHP, the DLTDP had very slight effect on the OIT.

Interaction of ODHP, DSTDP and OBA

Figures 5.30 to 5.32 show the interaction of ODHP, DSTDP and OBA on Oxidative Induction Time (OIT) upon the first to the fifth processing pass. At a low concentration of the ODHP, an increase the amount of OBA resulted in a raise in the OIT. At a high concentration of the ODHP, the OIT was decreased when the amount of the DSTDP was increased. The OIT is best found at the concentration of the ODHP around 0.06%, the DSTDP around 0.02% and the OBA around 0.0007%. A synergistic effect for the best OIT is achieved in the HDPE formulation containing 0.06% of ODHP, 0.02% of DSTDP and 0.0007% of OBA.

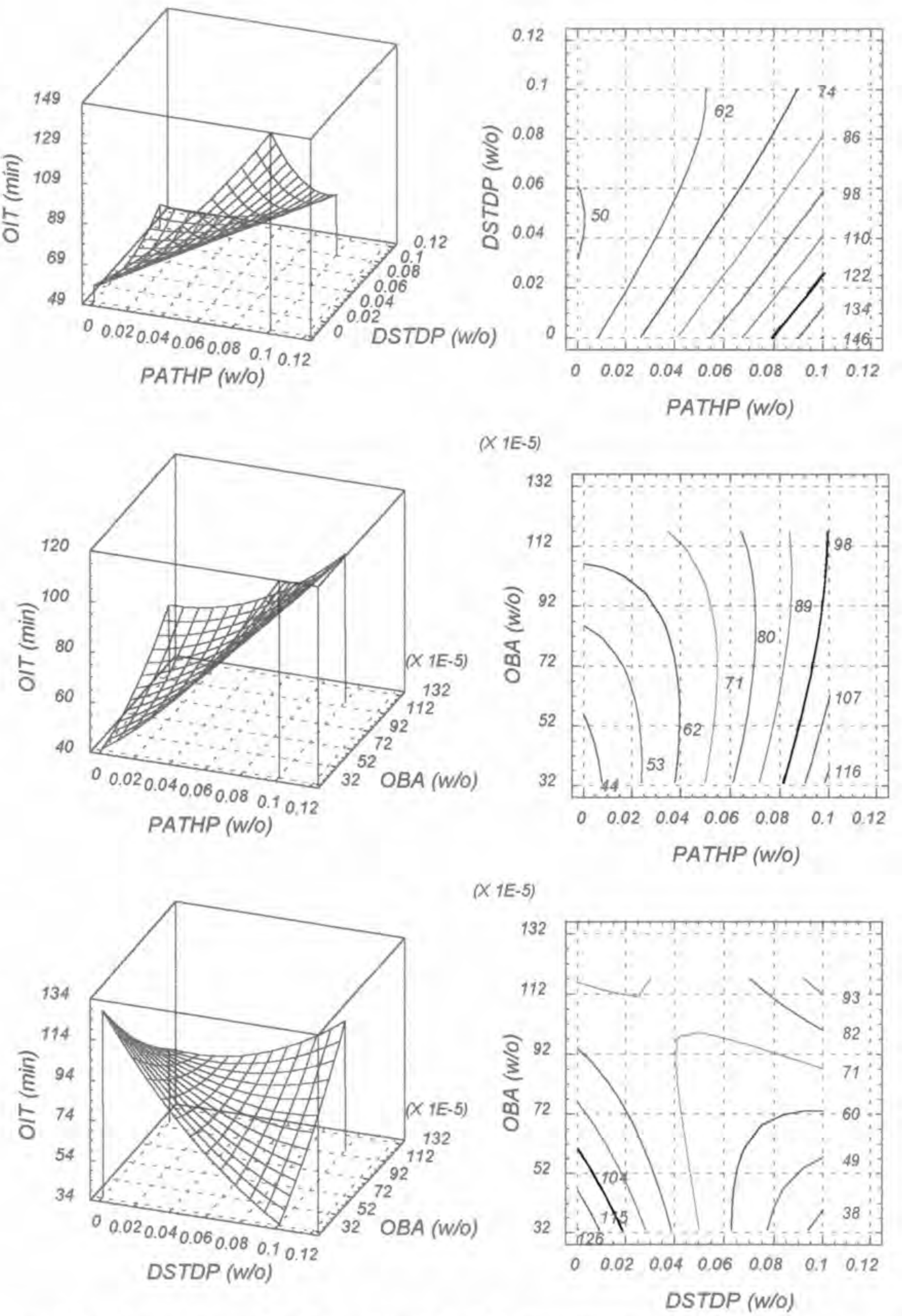

Figure 5.24 : Interaction of PATHP, DSTDP and OBA on Oxidative Induction Time (OIT) upon first pass.

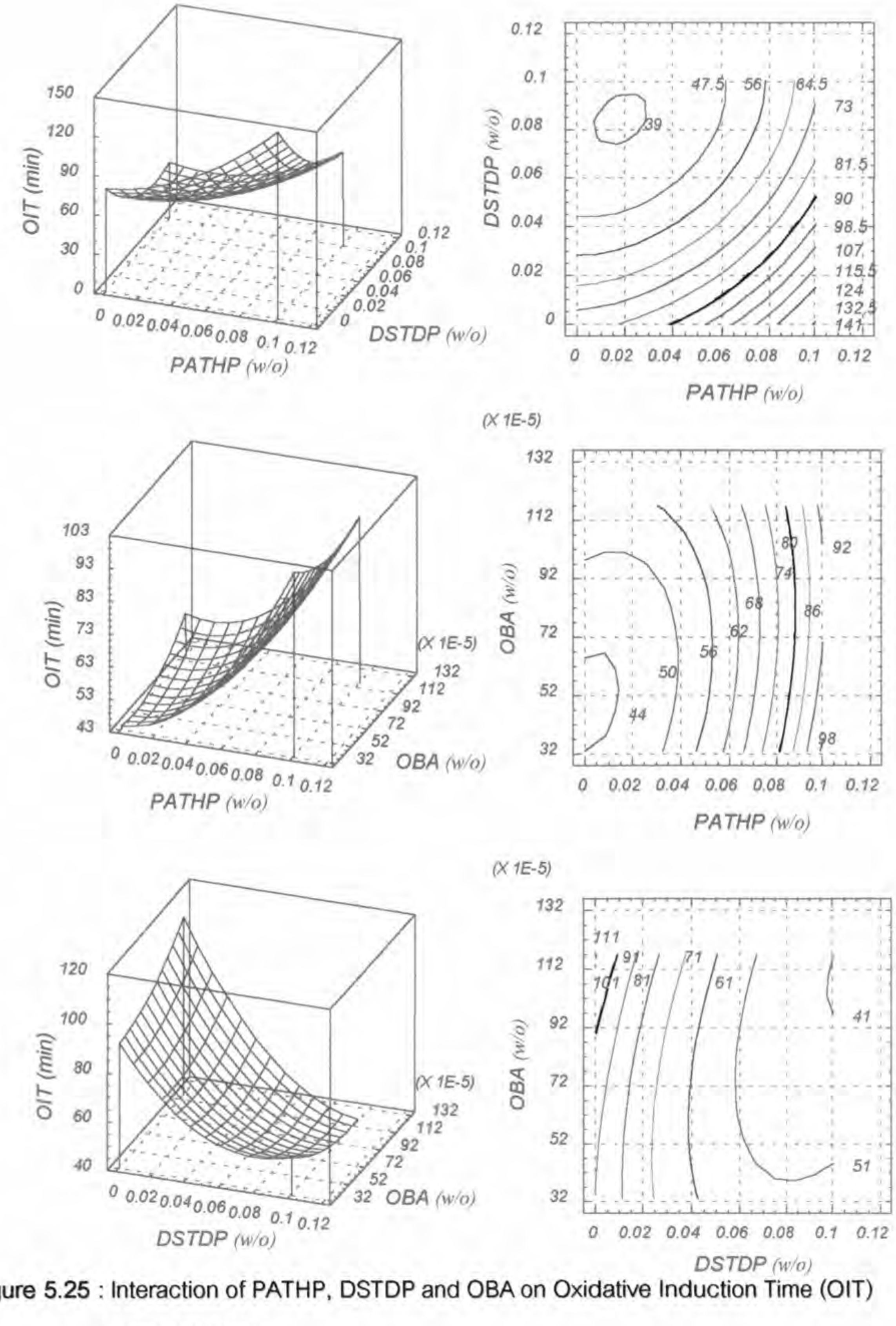

Figure 5.25 : Interaction of PATHP, DSTDP and OBA on Oxidative Induction Time (OIT) upon third pass.

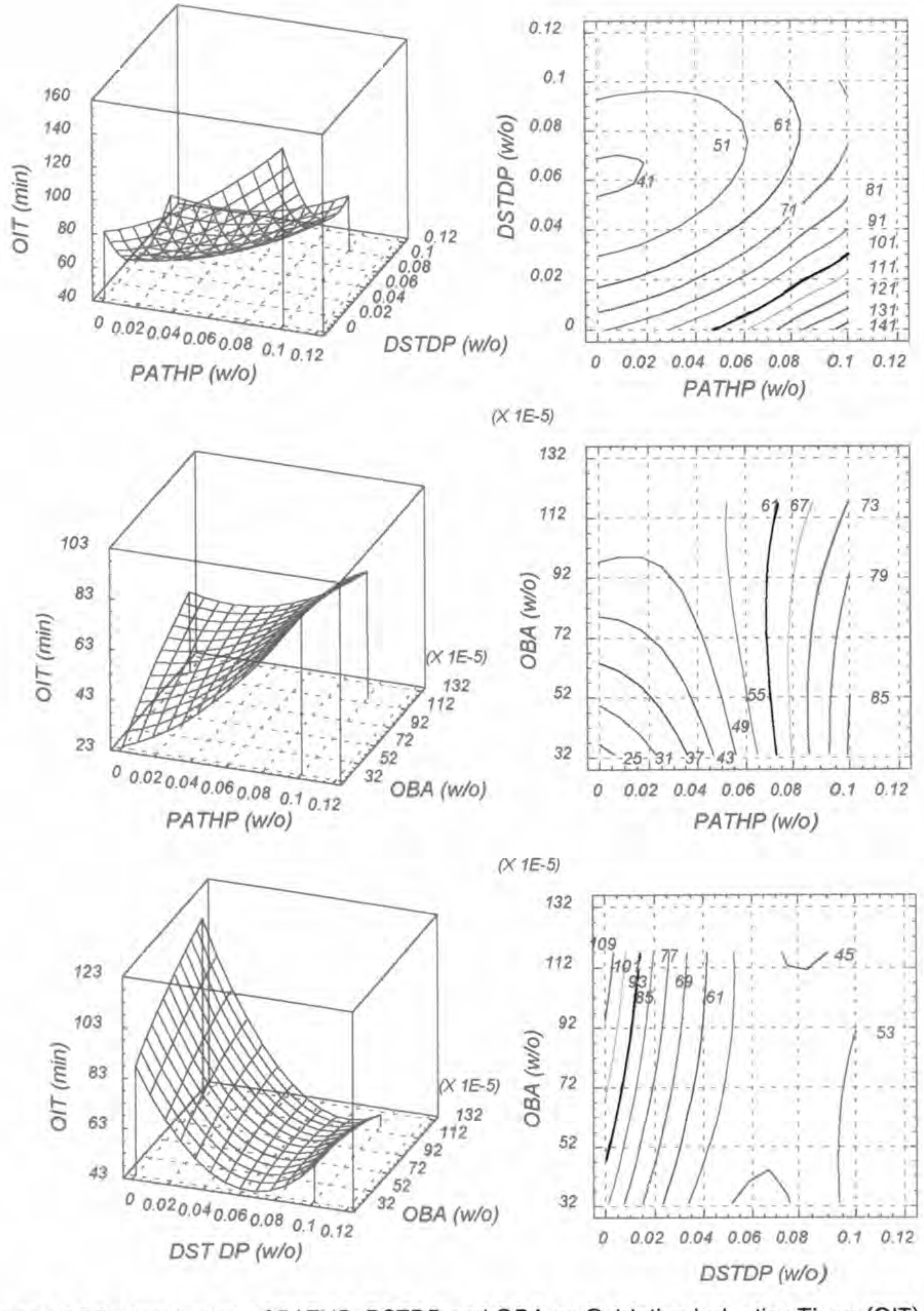

Figure 5.26 : Interaction of PATHP, DSTDP and OBA on Oxidative Induction Time (OIT) upon fifth pass.

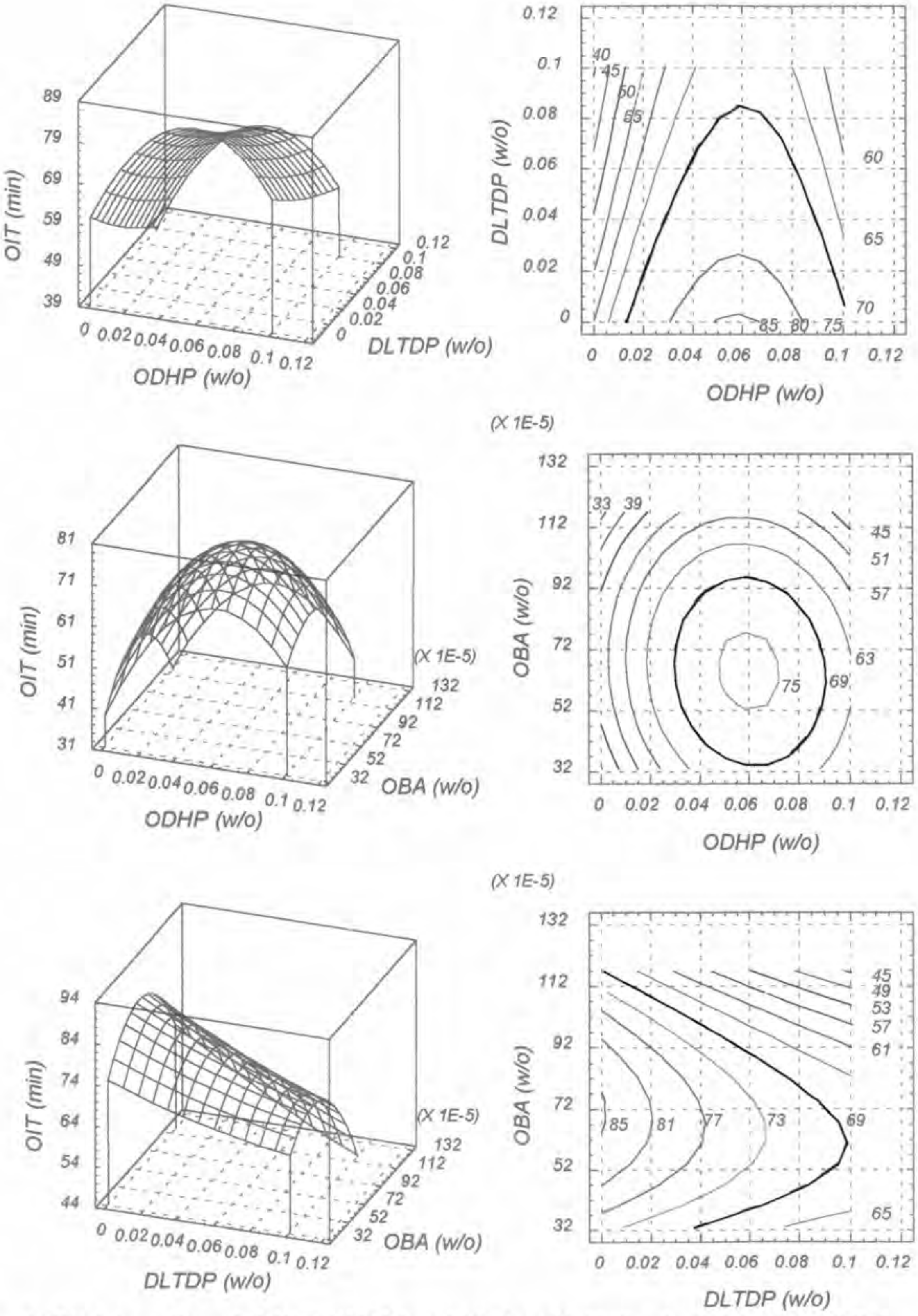

Figure 5.27 : Interaction of ODHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon first pass.

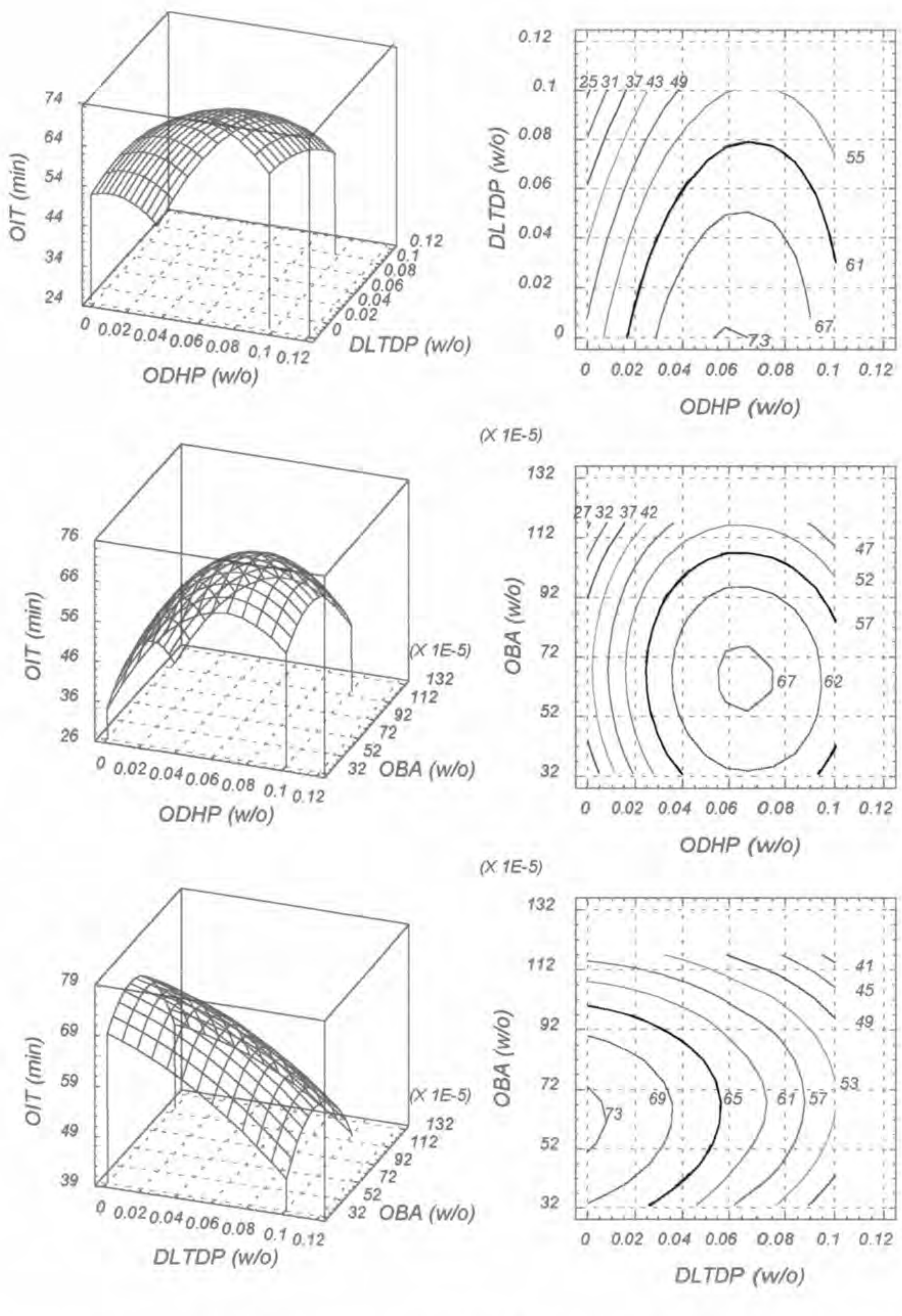

Figure 5.28 : Interaction of ODHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon third pass.

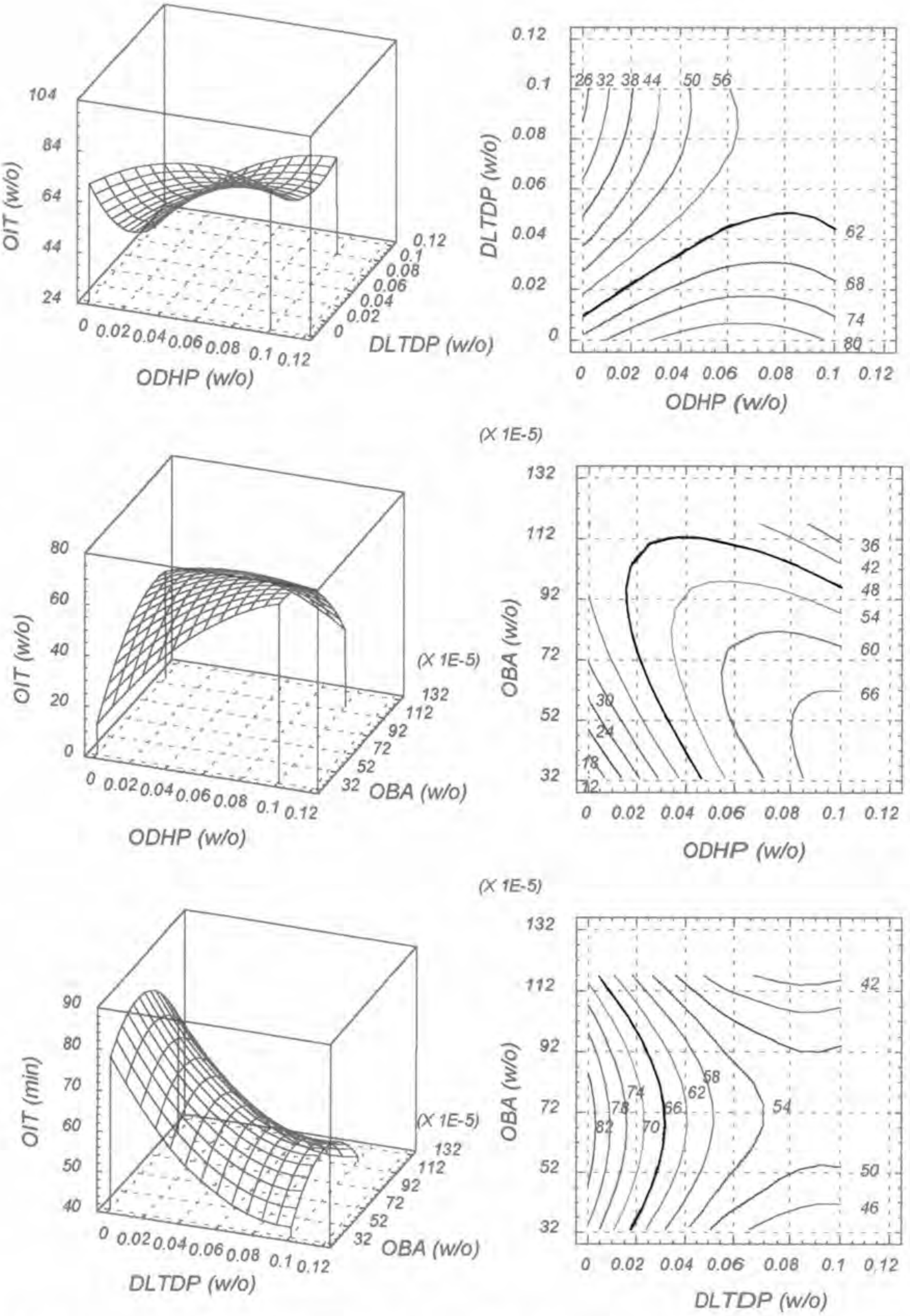

Figure 5.29 : Interaction of ODHP, DLTDP and OBA on Oxidative Induction Time (OIT) upon fifth pass.

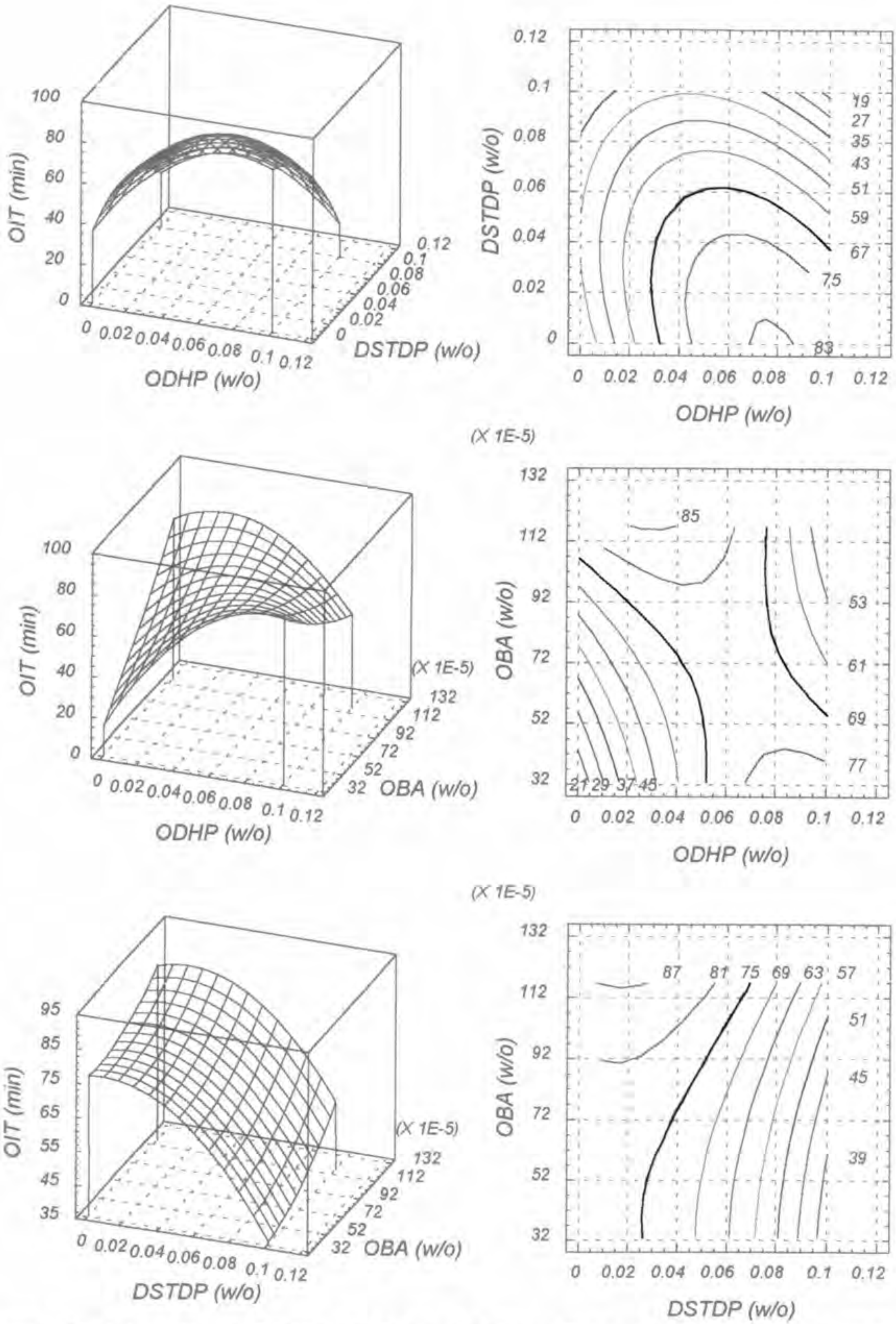

Figure 5.30 : Interaction of ODHP, DSTDP and OBA on Oxidative Induction Time (OIT) upon first pass.

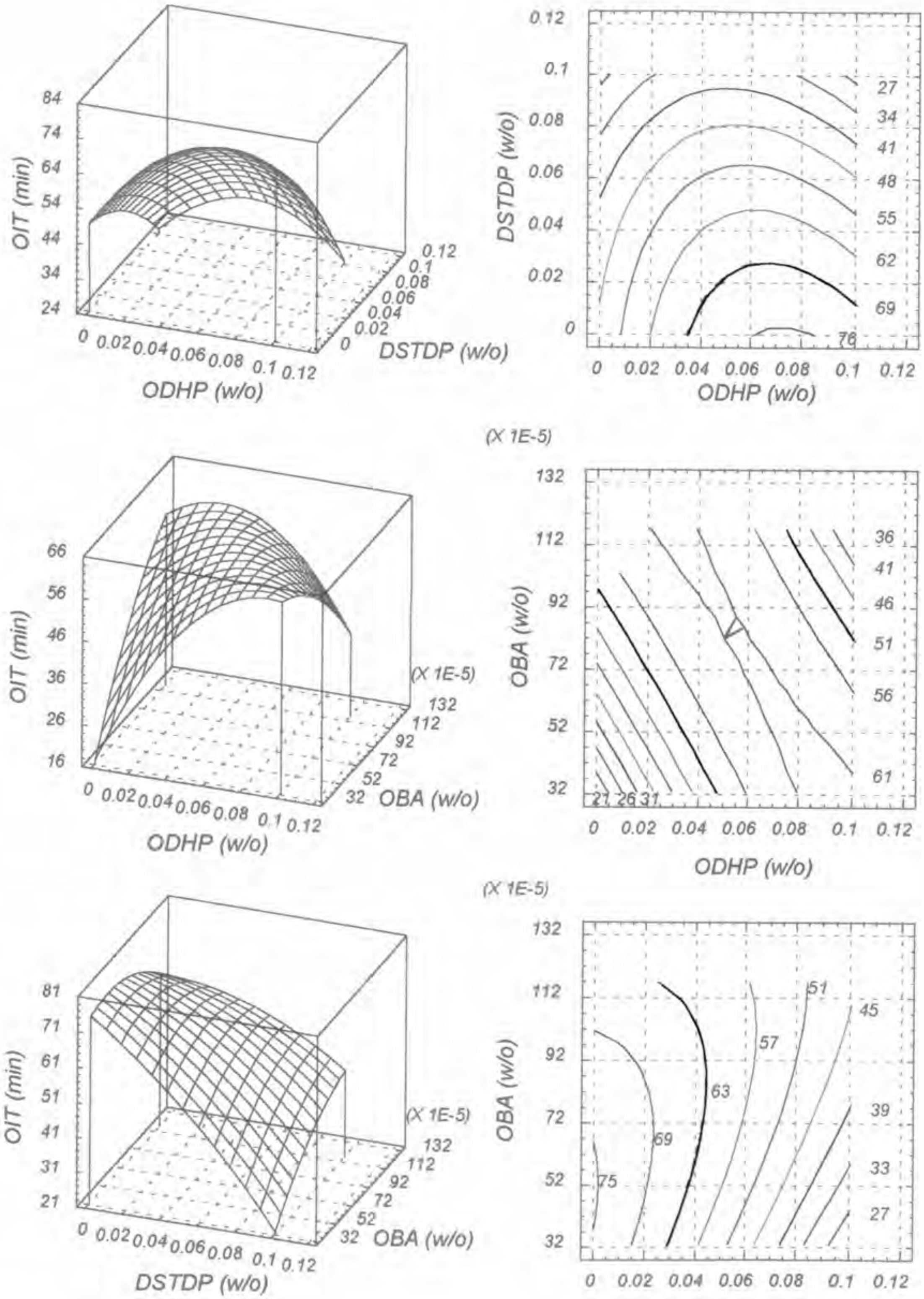

Figure 5.31 : Interaction of ODHP, DSTDP and OBA on Oxidative Induction Time (OIT) upon third pass.

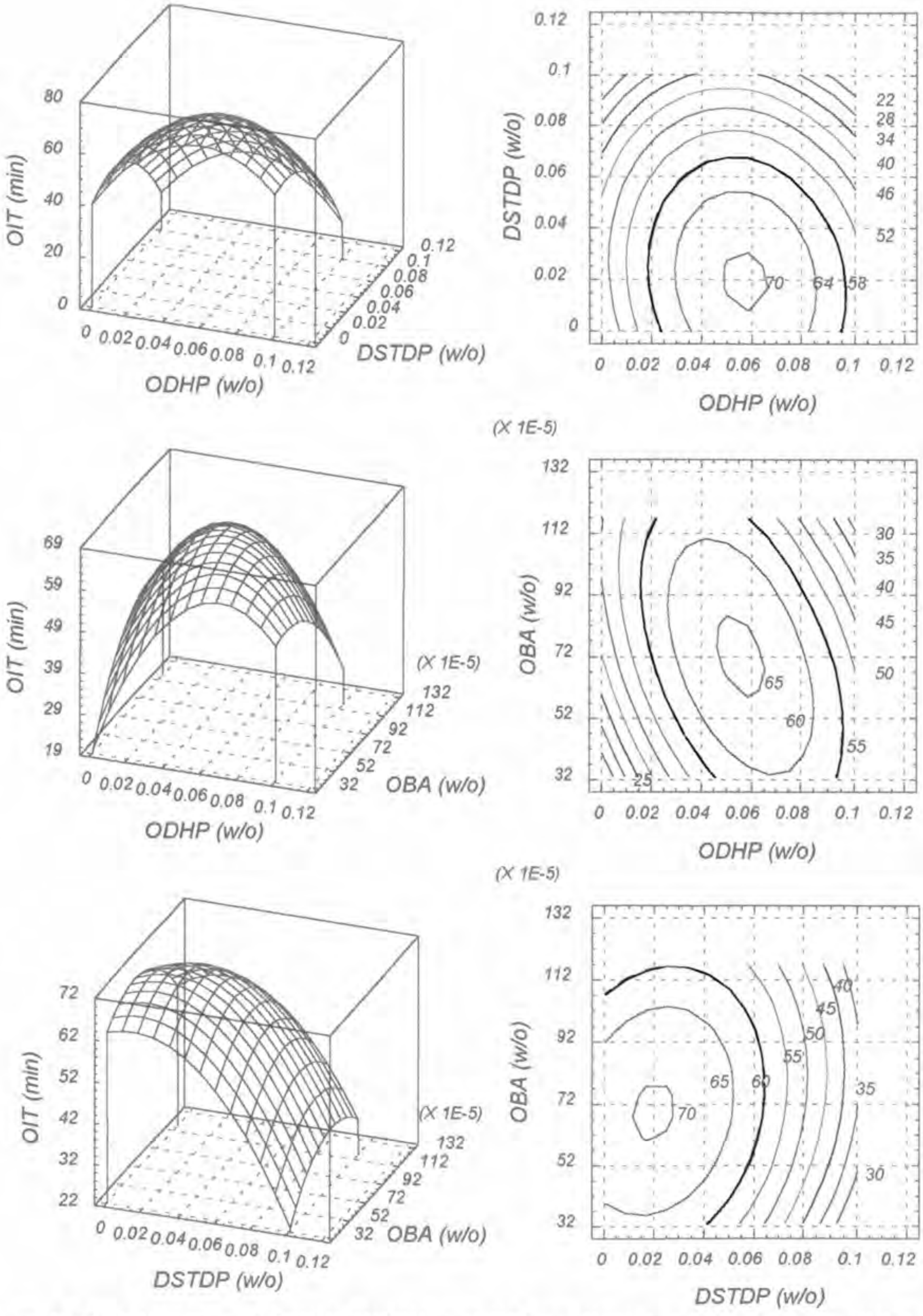

Figure 5.32 : Interaction of ODHP, DSTDP and OBA on Oxidative Induction Time(OIT) upon fifth pass.

Interaction of DAT, DLTDP and OBA

Figures 5.33 to 5.35 show the interaction of DAT, DLTDP and OBA on Oxidative Induction Time (OIT) upon the first to the fifth processing pass. When the concentration of DAT was increased, the OIT becomes longer. The highest OIT was achieved when DAT was around 0.08%. The OBA had only a slight effect on the OIT. DLTDP, at the concentration around 0.06-0.07%, gave a low OIT.

Interaction of DAT, DSTDP and OBA

Figures 5.36 to 5.38 show the interaction of DAT, DSTDP and OBA on Oxidative Induction Time (OIT) upon the first to the fifth processing pass. When the concentration of the DAT was raised, the corresponding OIT was found to be enhanced. At the concentration of DSTDP around 0.06%, the OIT was apparently very low. The OBA had insignificant effect on the OIT. At a high concentration of the DAT, DSTDP had only a minute effect on the OIT.

OIT measurements can be utilized as a tool for quality control of the stabilizer system. Over the concentrations within the range studied, it can be seen that when the phenolic antioxidant content increases, the OIT tends to also be increased. The phenolic antioxidant is capable of terminating the chain propagation by trapping the free radicals formed during thermal oxidation of the compounded HDPE.

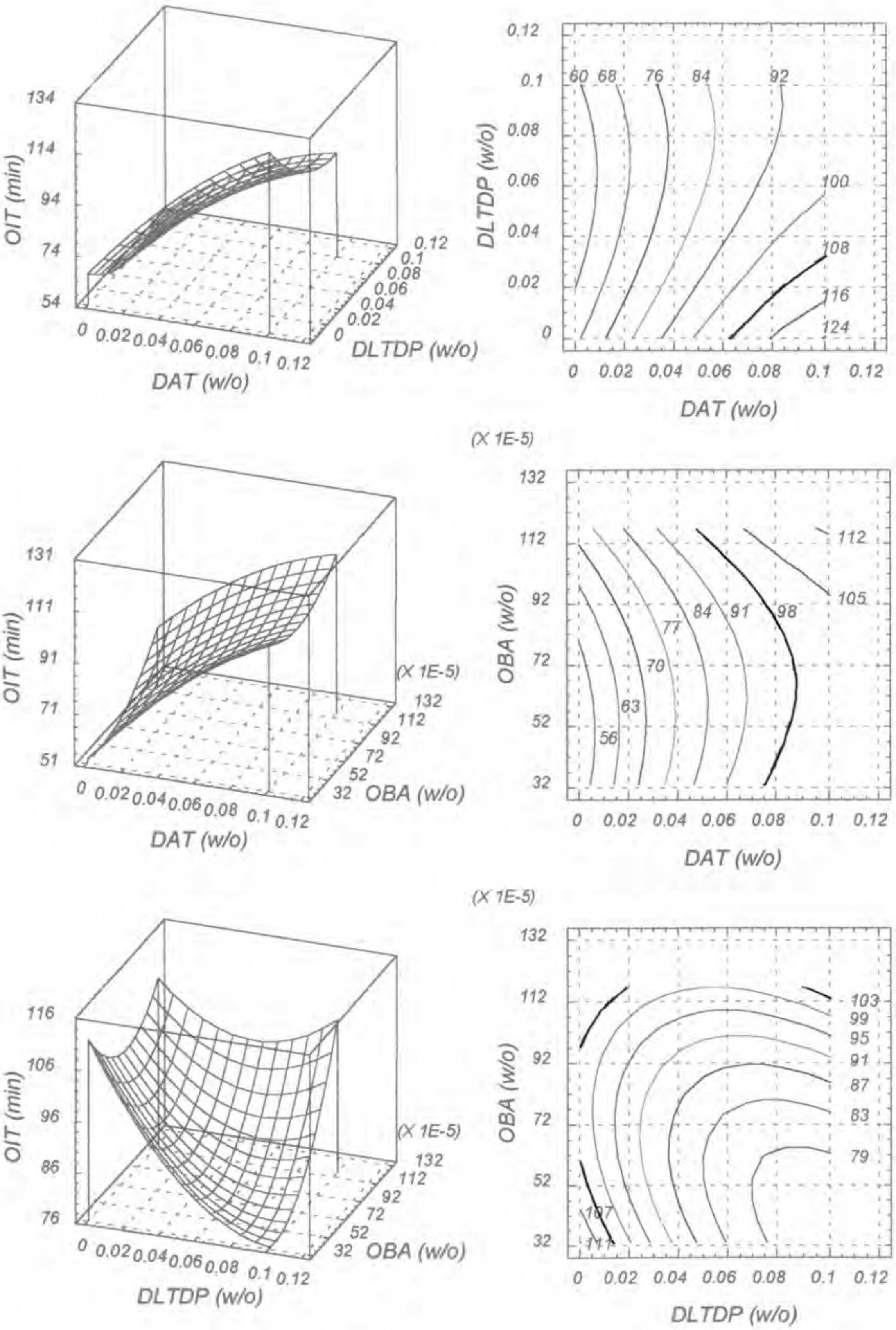

Figure 5.33 : Interaction of DAT, DLTDP and OBA on Oxidative Induction Time (OIT) upon first pass.

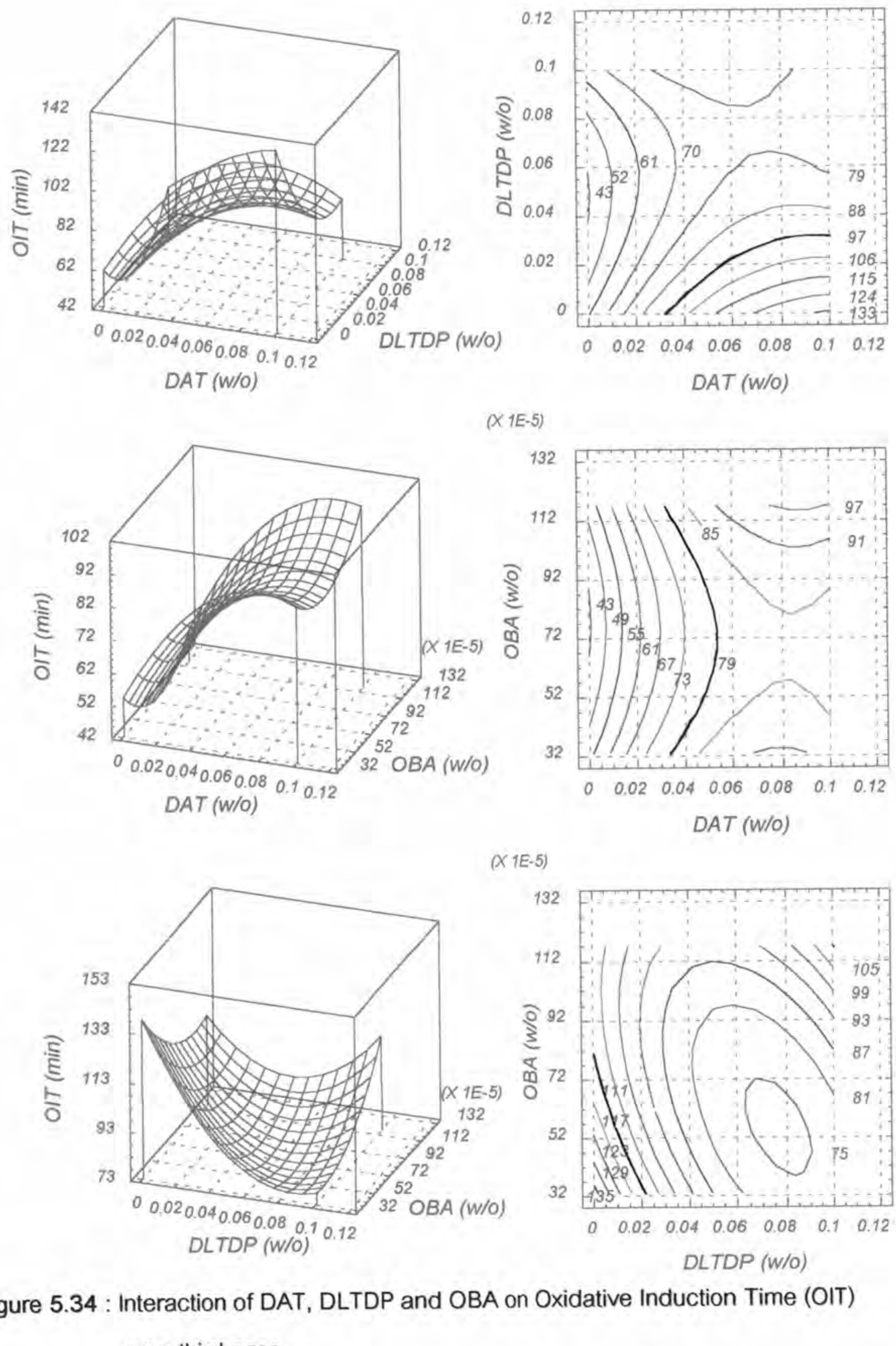

Figure 5.34 : Interaction of DAT, DLTDP and OBA on Oxidative Induction Time (OIT) upon third pass.

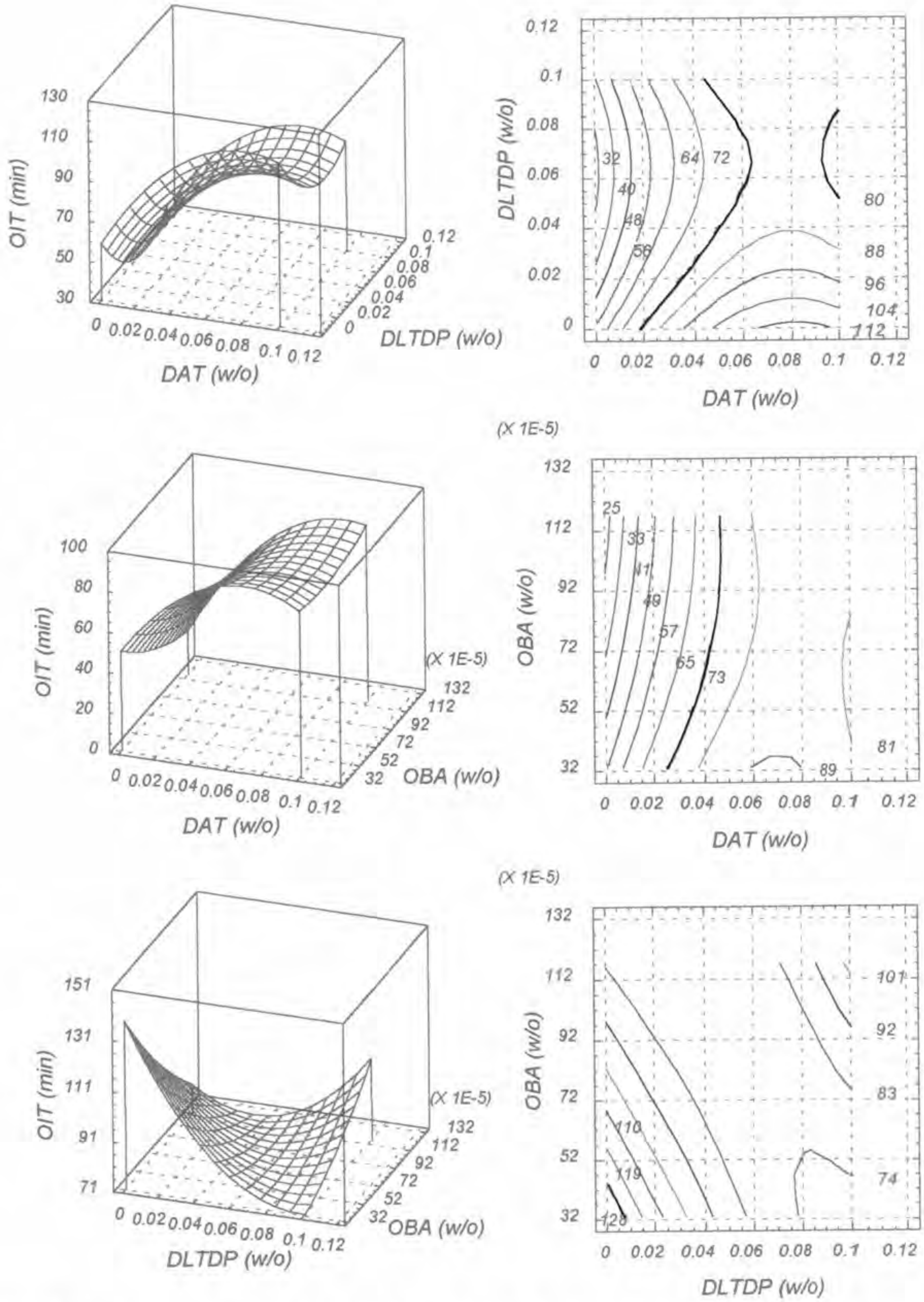

Figure 5.35 : Interaction of DAT, DLTDP and OBA on Oxidative Induction Time (OIT) upon fifth pass.

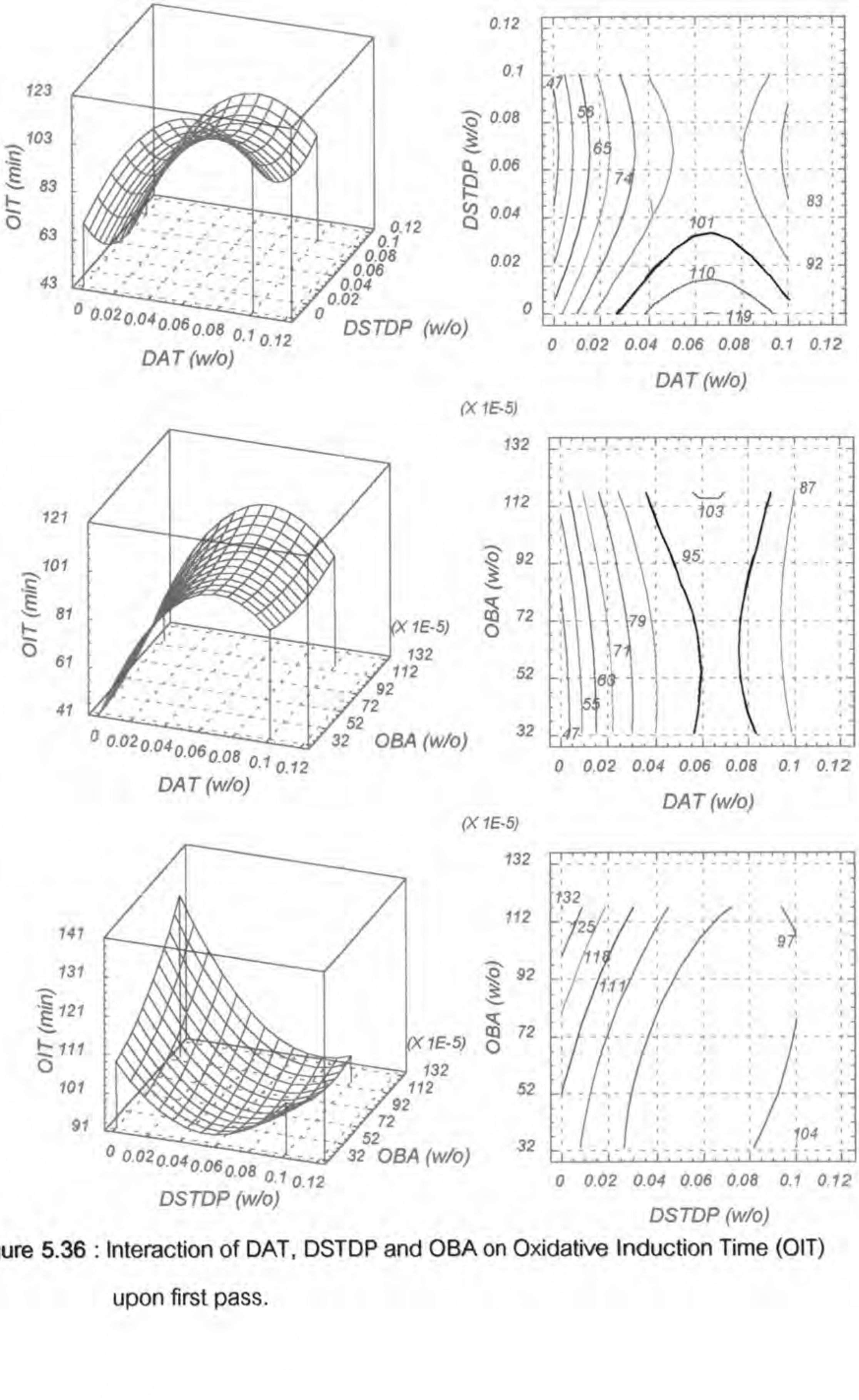

Figure 5.36 : Interaction of DAT, DSTDP and OBA on Oxidative Induction Time (OIT) upon first pass.

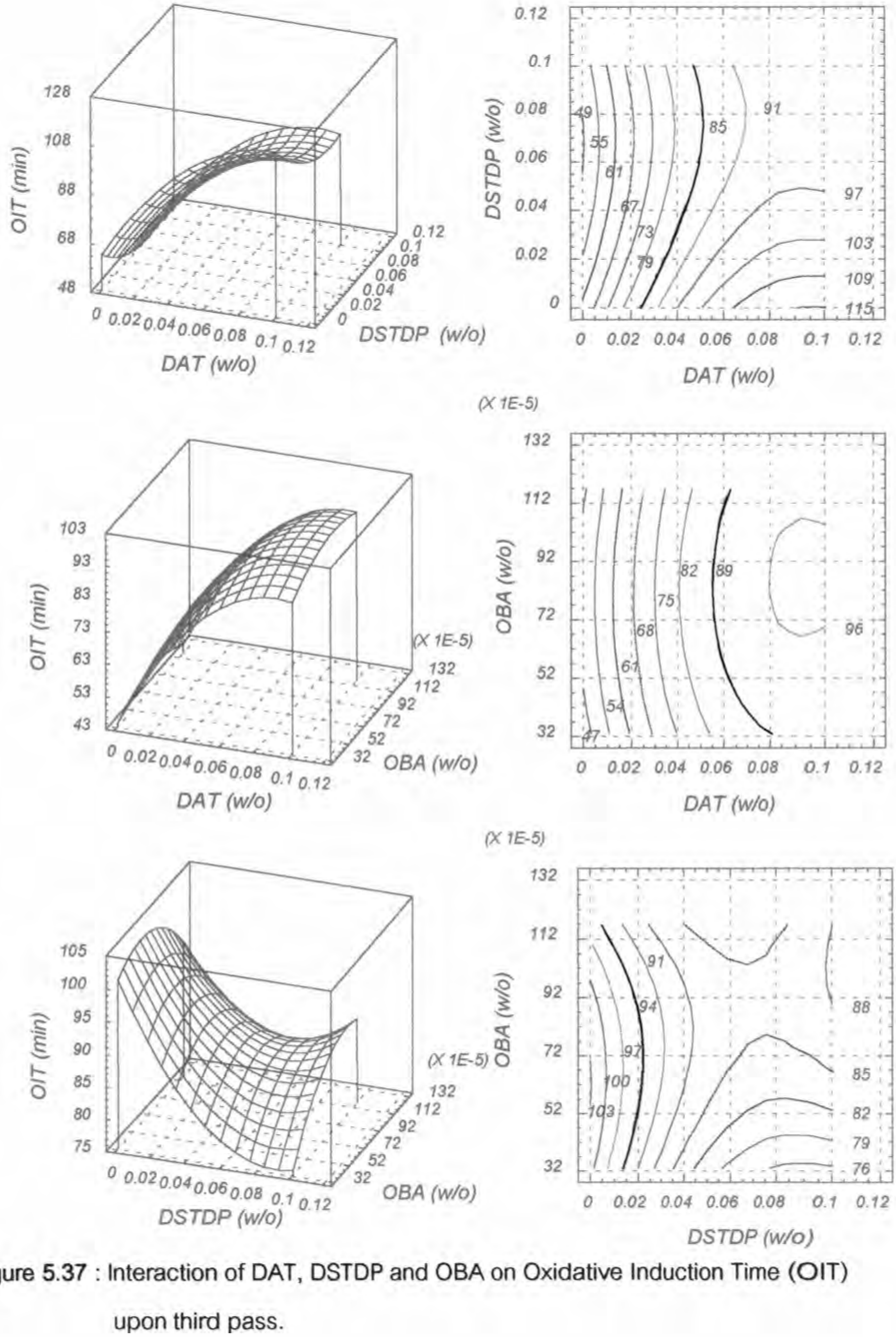

Figure 5.37 : Interaction of DAT, DSTDP and OBA on Oxidative Induction Time (OIT) upon third pass.

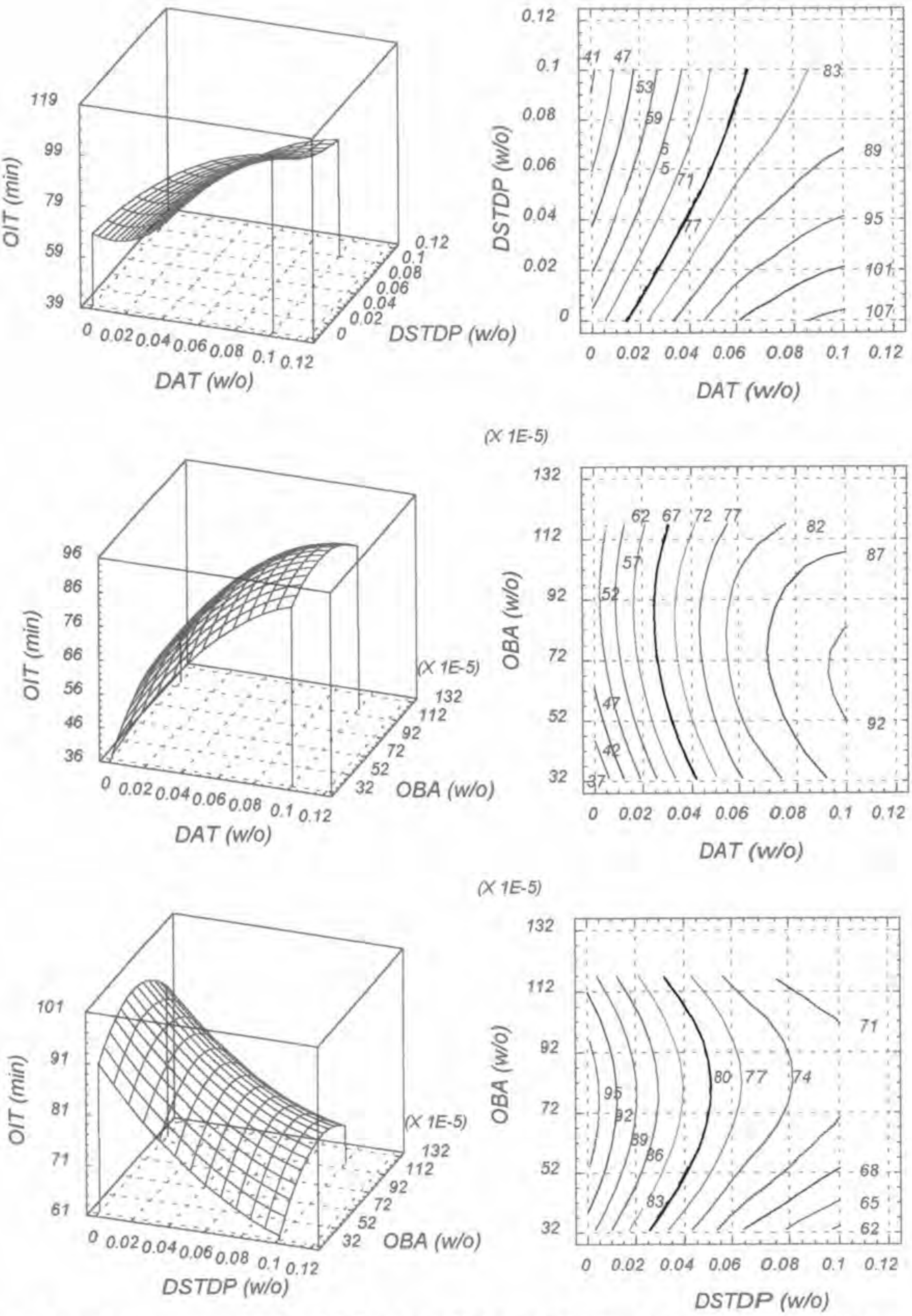

Figure 5.38 : Interaction of DAT, DSTDP and OBA on Oxidative Induction Time (OIT) upon fifth pass.

$$\sim CH_2CH_2CH_2CH_2\sim + O_2 \longrightarrow \sim CH_2\dot{C}HCH_2CH_2\sim + \bullet OOH$$

$$\sim CH_2\dot{C}HCH_2CH_2\sim + O_2 \longrightarrow \sim CH_2CH(OO\bullet)CH_2CH_2\sim$$

$$\sim CH_2CH(OO\bullet)CH_2CH_2\sim + AH \longrightarrow \sim CH_2CH(OOH)CH_2CH_2\sim + A\bullet$$

where AH is the phenolic antioxidant and A• is the antioxidant radical. Hence, molecules of stable radicals are formed and provide a prolong induction period to the compounded HDPE.

The effectiveness of the phenolic antioxidant seems to be dependent upon the number of reactive groups and its own chemical structure which is shown in Figure 4.1. The more number of reactive groups there is in the phenolic antioxidant, the greater the number of sites there are to react with the free radicals. The chemical structure of the antioxidant also affects the transformation of the antioxidant radicals into a stable form in order to prevent the continuation of the propagation of new radicals. As a consequence, the efficiency is then increased. The phenolic antioxidants are capable of undergoing fast reactions with peroxy radical. The antioxidant radicals are stabilized via their electron delocalization or resonance.

Nampetch Prommana's research investigated the effectiveness of individual antioxidant on HDPE by multiple extrusion. The OIT results of individual antioxidant on the first, third and fifth pass are tabulated in Table 5.26 [20].

Table 5.26 : The OIT (min) value of various antioxidants at 0.05% concentration.

Antioxidant	OIT after re-extrusion passes (min)		
	1st pass	3rd pass	5th pass
Blended antioxidant	11.295	11.123	10.903
PATHP	22.121	19.464	18.967
ODHP	15.694	13.365	13.134
DAT	23.646	22.074	20.359
DLTDP	23.548	22.429	22.120
DSTDP	8.202	8.022	7.995

When compared with experimental results on the OIT when each antioxidant was applied individually and when they were used as designed in the present study, the interaction of mixing primary antioxidant, secondary antioxidant, optical brightener and HALS becomes more apparent. Synergistic and non-synergistic combination of primary and secondary antioxidant are more clearly defined and predicted through the plots shown in Figures 5.20 to 5.38. It was found the OIT's of the HDPE with combined primary, secondary antioxidant, optical brightener and HALS are higher than in the case of using a single antioxidant alone. The system of the blended antioxidant with the OBA gave strong synergistic effect on OIT. As for other combination systems, it was found that an increase in the concentration of the thioester antioxidant over certain range would reduce the OIT, though this reduction in the OIT is still higher than that found when either one of the antioxidants is used alone. Yan Qing and Xu Wenying [9], referred to the study of G. Scott [9], suspected that concluded that this was probably because when HALS was used together with the thioesters antioxidant, the reaction of nitroxyl radicals with sulfenyl radicals gave inactive sulfonamides. The decomposition of hydroperoxides by thioester antioxidant also prevents the formation of nitroxyl radicals. Since the nitroxyl radicals are believed to be the main effective species in the course of stabilization by piperidine derivatives, these reactions will reduce the efficiency of HALS [9]. Therefore, the use of thioesters might affect negatively the performance of HALS. A combination of the 0.06% ODHP, 0.02% DSTDP and 0.00072% OBA was found to give the best OIT in the present study. Their effect on the capability of the optical brightening agent is not yet well understood.

5.3.3 Melt Flow Rate Test

Interaction of Blended antioxidant and OBA

Figure 5.39 show the interaction of the blended antioxidant and the OBA on Melt Flow Rate (MFR) upon the first to the fifth processing pass. At the concentration of the blended antioxidant around 0.03-0.05% and that of the OBA around 0.0009%, the MFR was quite high. At a low concentration of the blended antioxidant, the MFR was increased when the OBA concentration was raised.

Interaction of PATHP, DLTDP and OBA

Figures 5.40 to 5.42 show the interaction of PATHP, DLTDP and OBA on Melt Flow Rate (MFR) upon the first to the fifth processing pass. When the concentration of the DLTDP increased, the MFR became greater. However, at a high amount of the OBA, DLTDP had only a slight effect on the MFR. A very low MFR was found when the concentration of the PATHP was around 0.07% and the OBA was around 0.0008%.

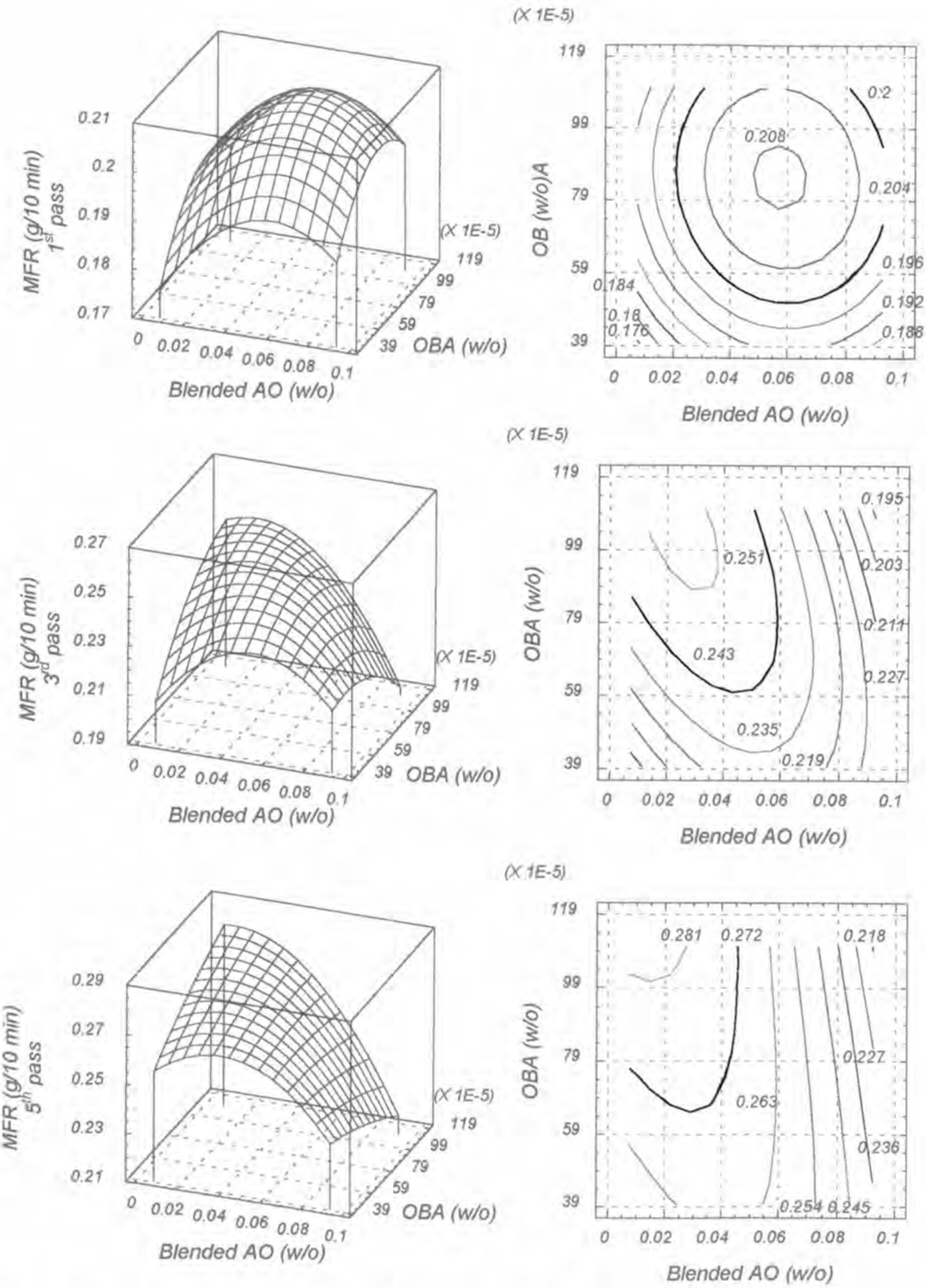

Figure 5.39 : Interaction of Blended AO and OBA on Melt Flow Rate (MFR) upon first to fifth pass.

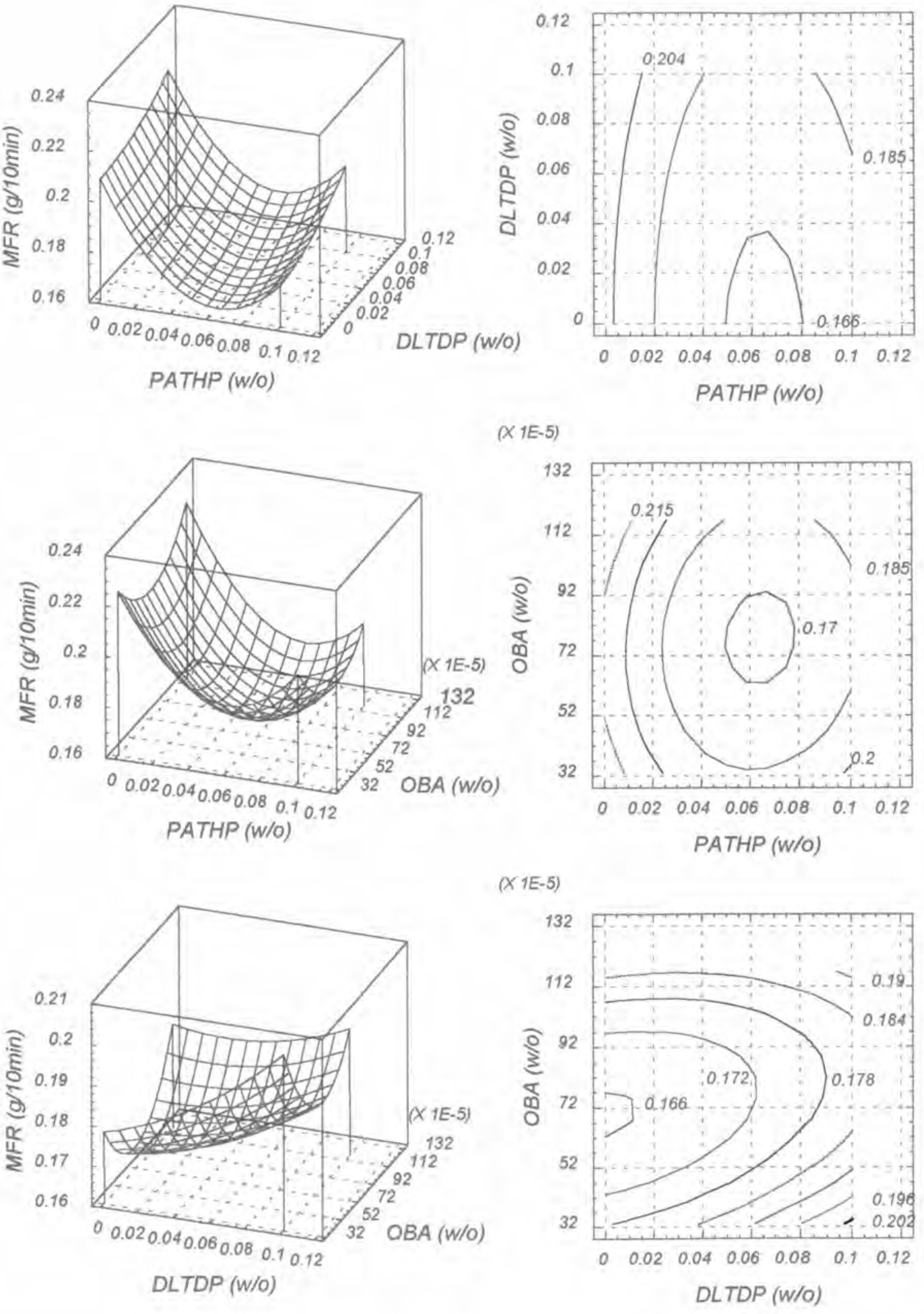

Figure 5.40 : Interaction of PATHP, DLTDP and OBA on Melt Flow Rate (MFR) upon first pass.

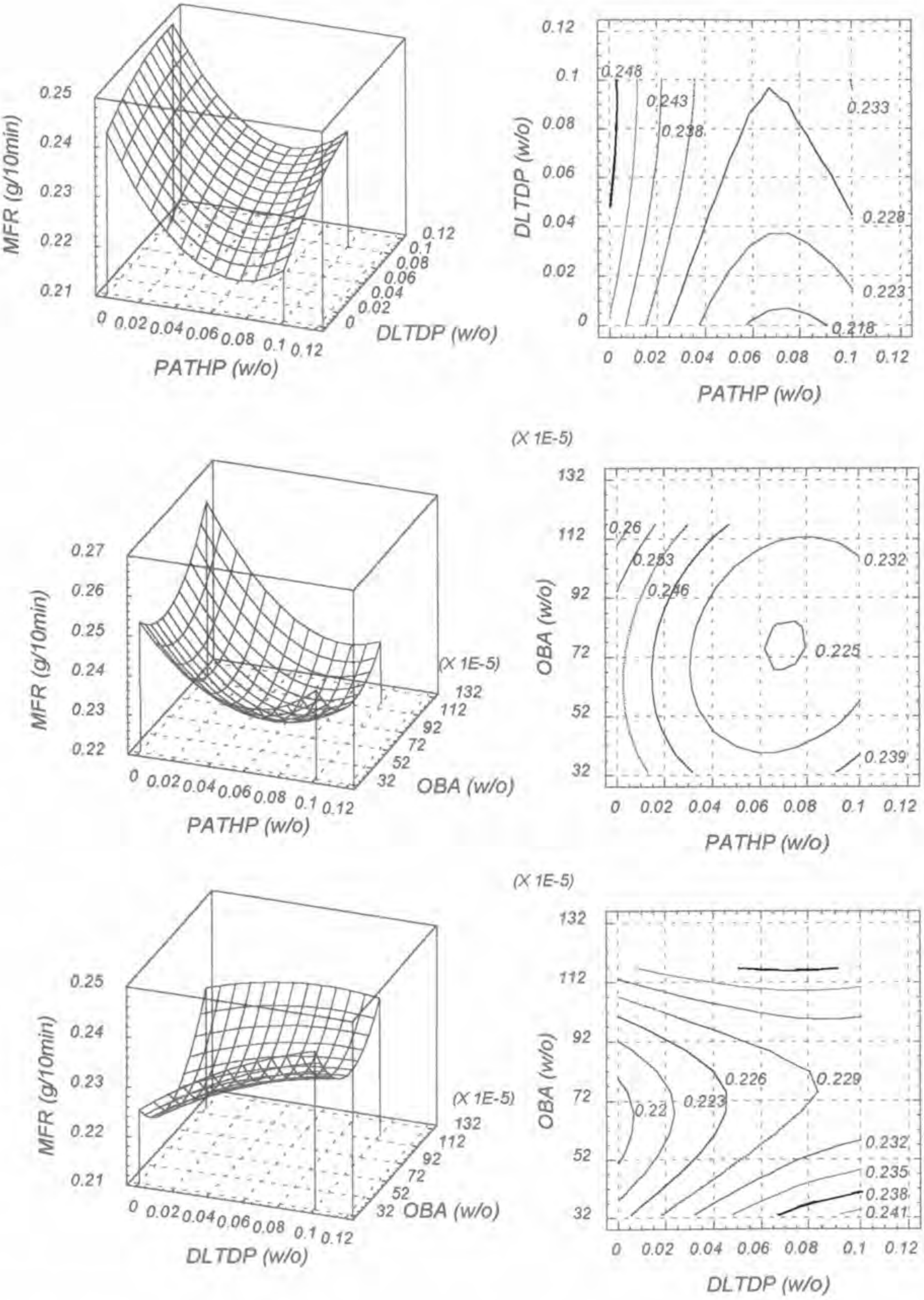

Figure 5.41 : Interaction of PATHP, DLTDP and OBA on Melt Flow Rate (MFR) upon third pass.

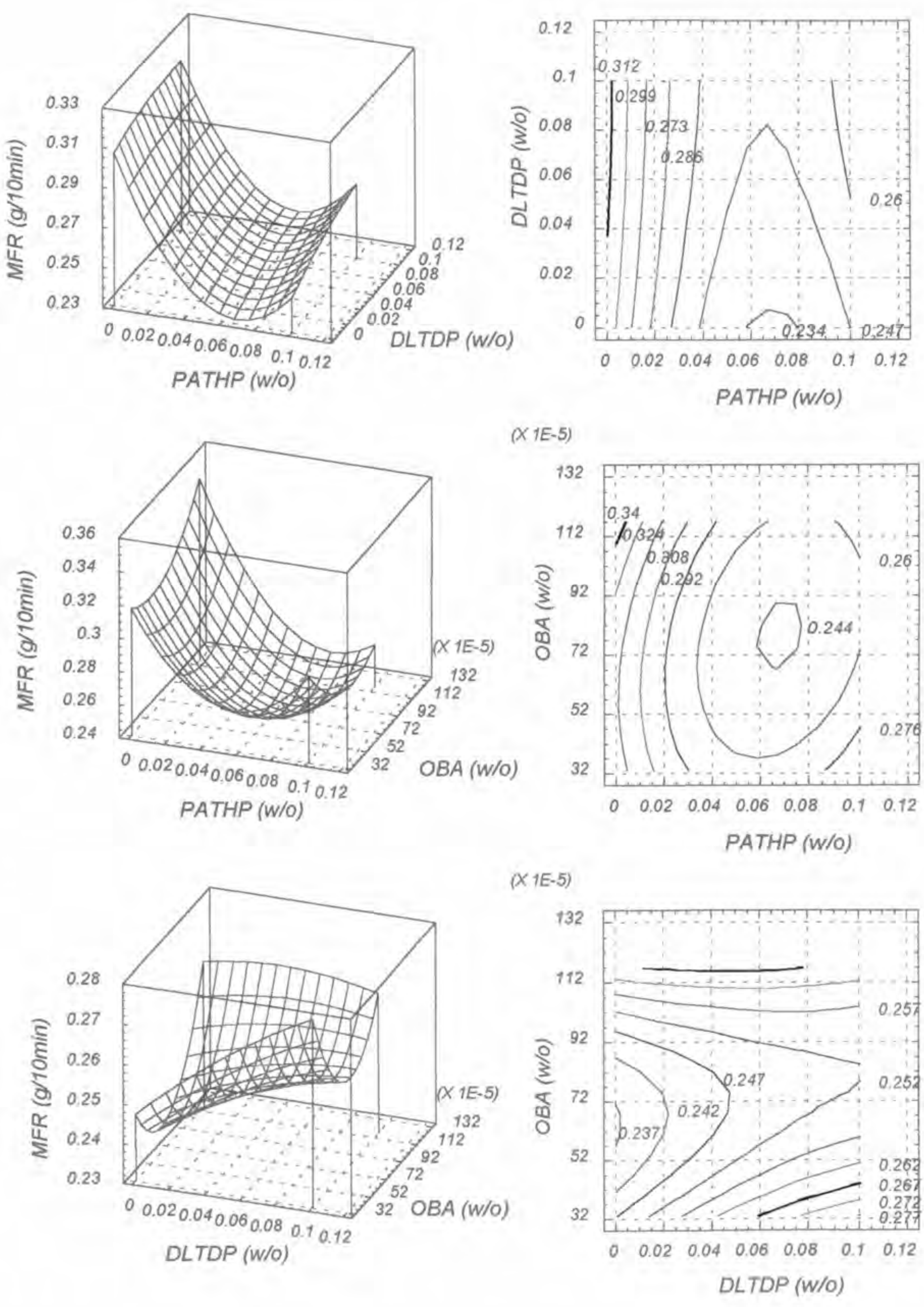

Figure 5.42 : Interaction of PATHP, DLTDP and OBA on Melt Flow Rate (MFR) upon fifth pass.

Interaction of PATHP, DSTDP and OBA

Figures 5.43 to 5.45 show the interaction of the PATHP, DSTDP and the OBA on Melt Flow Rate (MFR) upon the first to the fifth processing pass. At the concentration of the PATHP of around 0.05-0.07%, the DSTDP around 0.06-0.08% and the OBA around 0.0006-0.0008%, MFR was evidently low.

Interaction of ODHP, DLTDP and OBA

Figures 5.46 to 5.48 shows the interaction of the ODHP, DLTDP and the OBA on Melt Flow Rate (MFR) upon first to fifth pass. A very low MFR was found when the concentration of the ODHP was around 0.04-0.06%, the DLTDP was around 0.05% and the OBA was around 0.0007%.

Interaction of ODHP, DSTDP and OBA

Figures 5.49 to 5.51 show the interaction of the ODHP, DSTDP and the OBA on Melt Flow Rate (MFR) upon the first to the fifth processing pass. The concentration of the ODHP of around 0.05%, the DSTDP around 0.05% and the OBA around 0.0006-0.0008% was found to be the saddle point of MFR.

Interaction of DAT, DLTDP and OBA

Figures 5.52 to 5.54 show the interaction of the DAT, DLTDP and the OBA on Melt Flow Rate (MFR) upon the first to the fifth processing pass. A lowest MFR was found when the concentration of the DAT was around 0.06%, the DLTDP was around 0.06% and the OBA was around 0.00082%. At a low concentration of the DAT, MFR was increased when the concentration of the DLTDP or the OBA was increased.

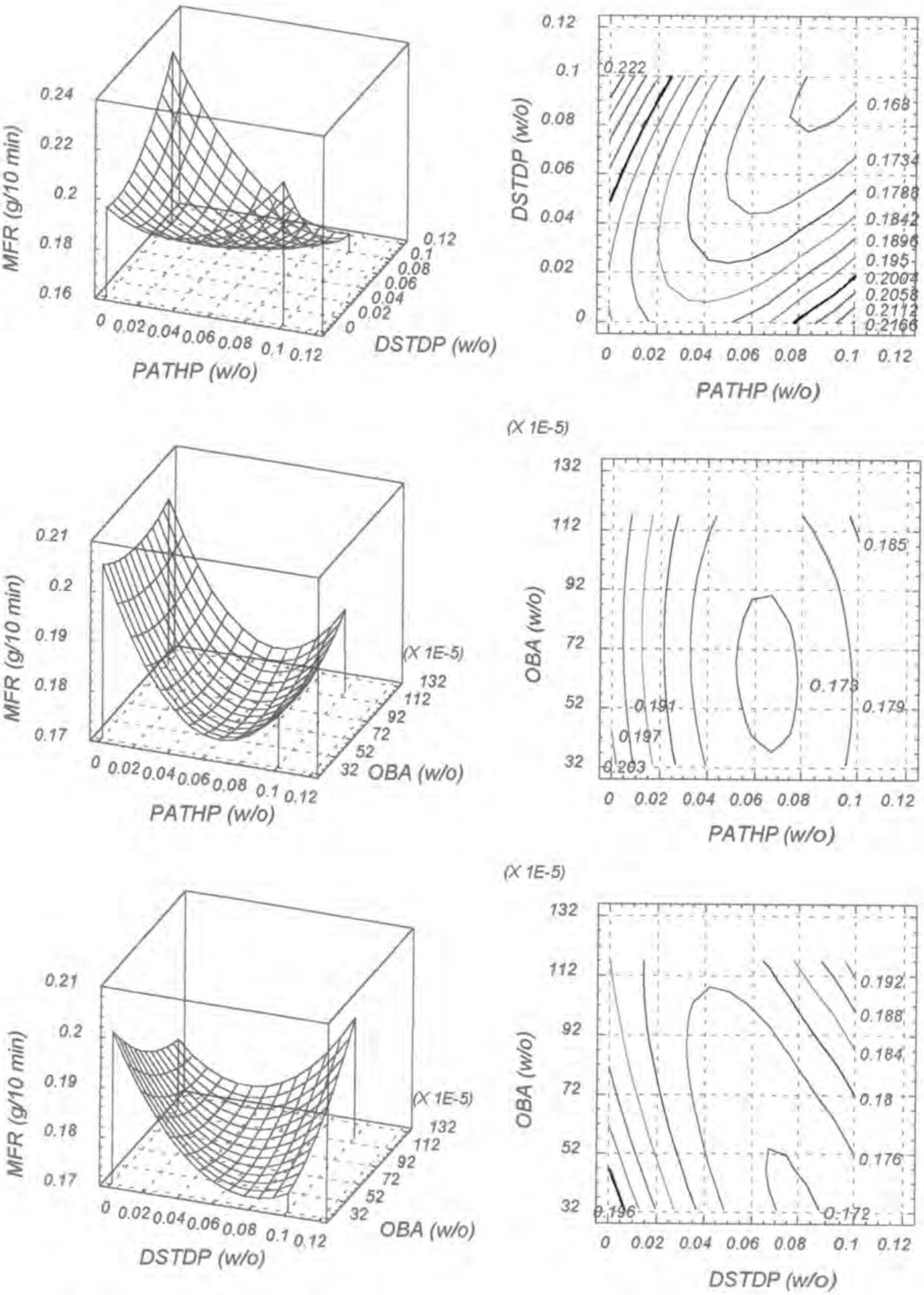

Figure 5.43 : Interaction of PATHP, DSTDP and OBA on Melt Flow Rate (MFR) upon first pass.

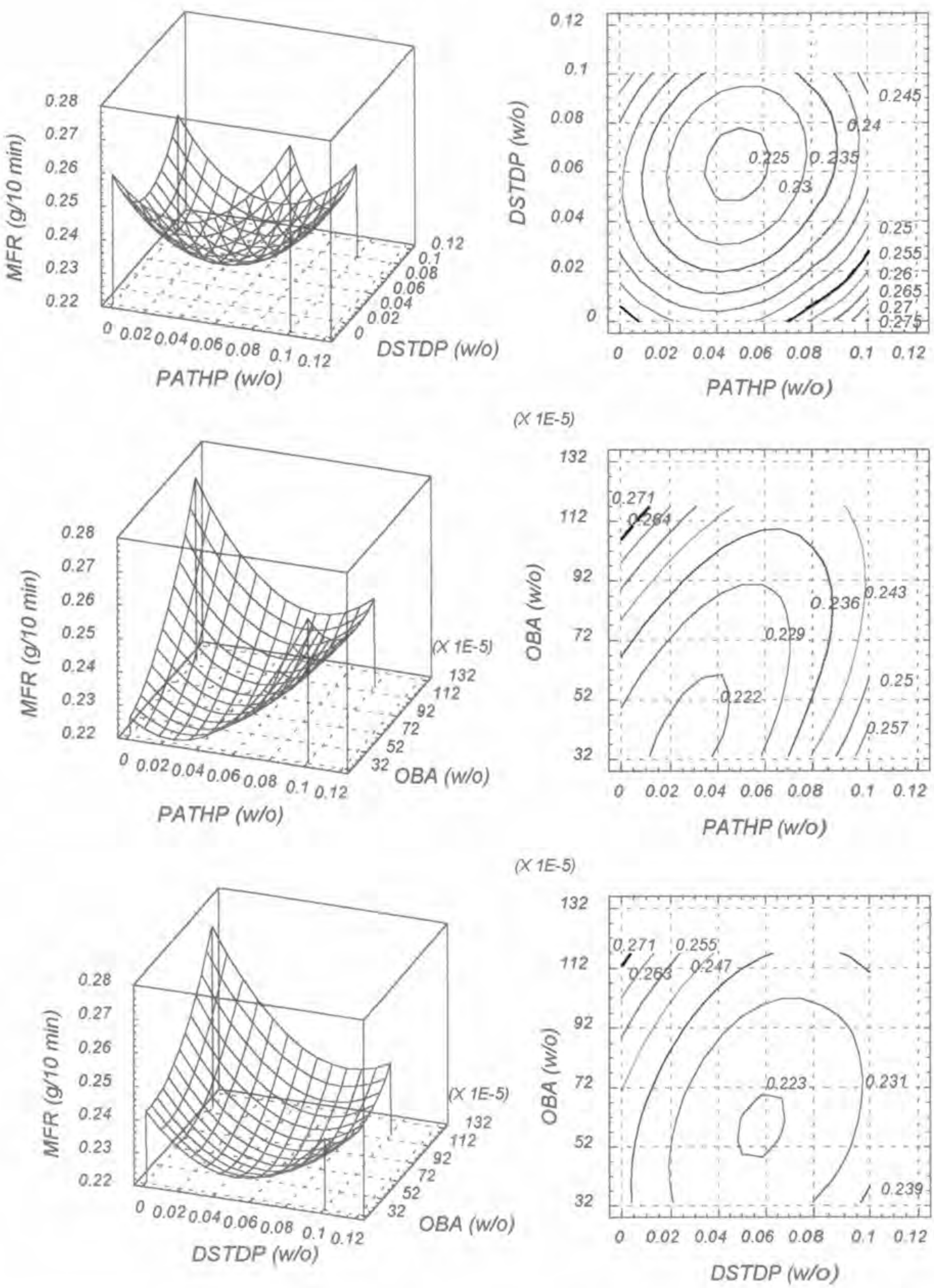

Figure 5.44 : Interaction of PATHP, DSTDP and OBA on Melt Flow Rate (MFR) upon third pass.

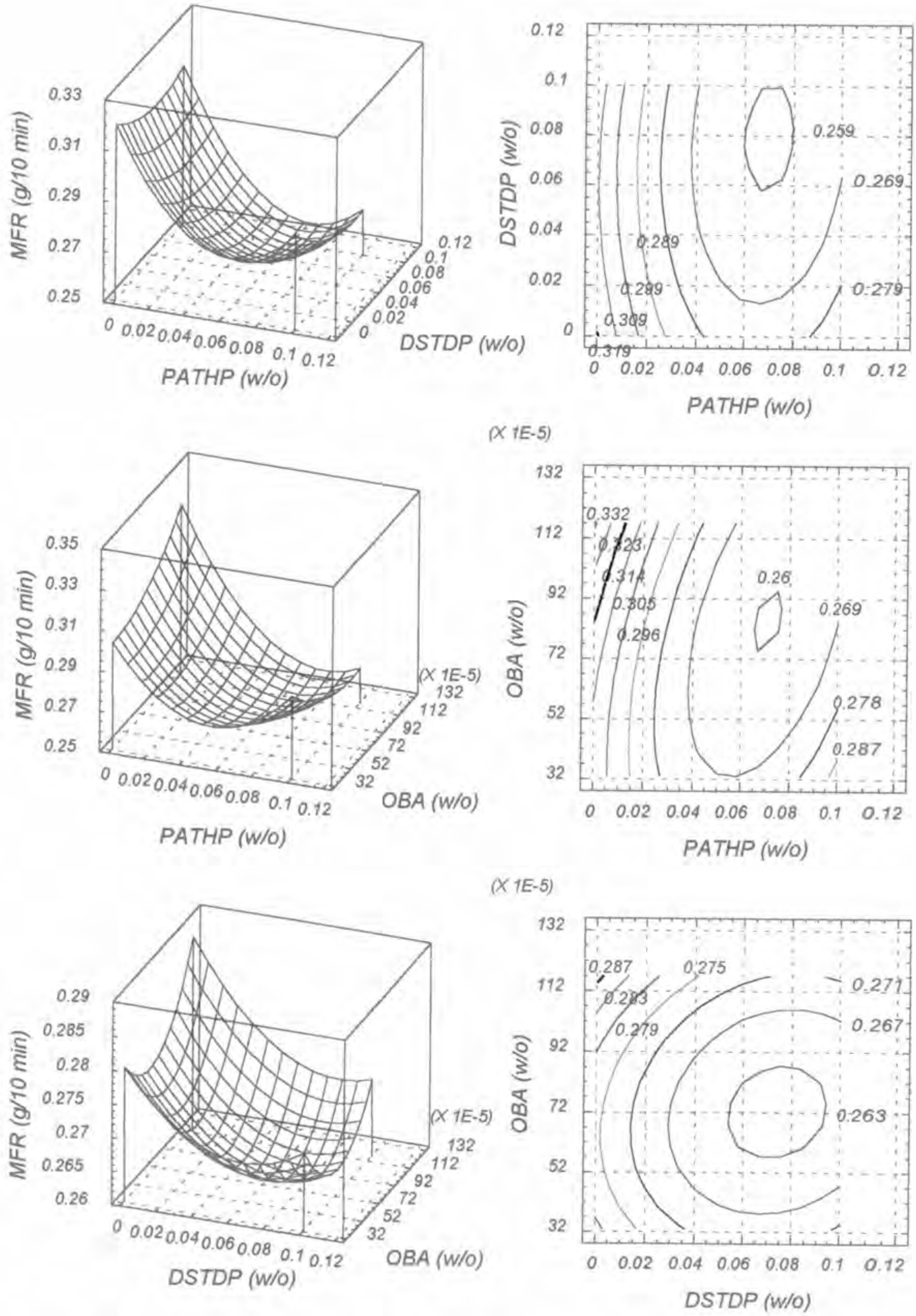

Figure 5.45 : Interaction of PATHP, DSTDP and OBA on Melt Flow Rate (MFR) upon fifth pass.

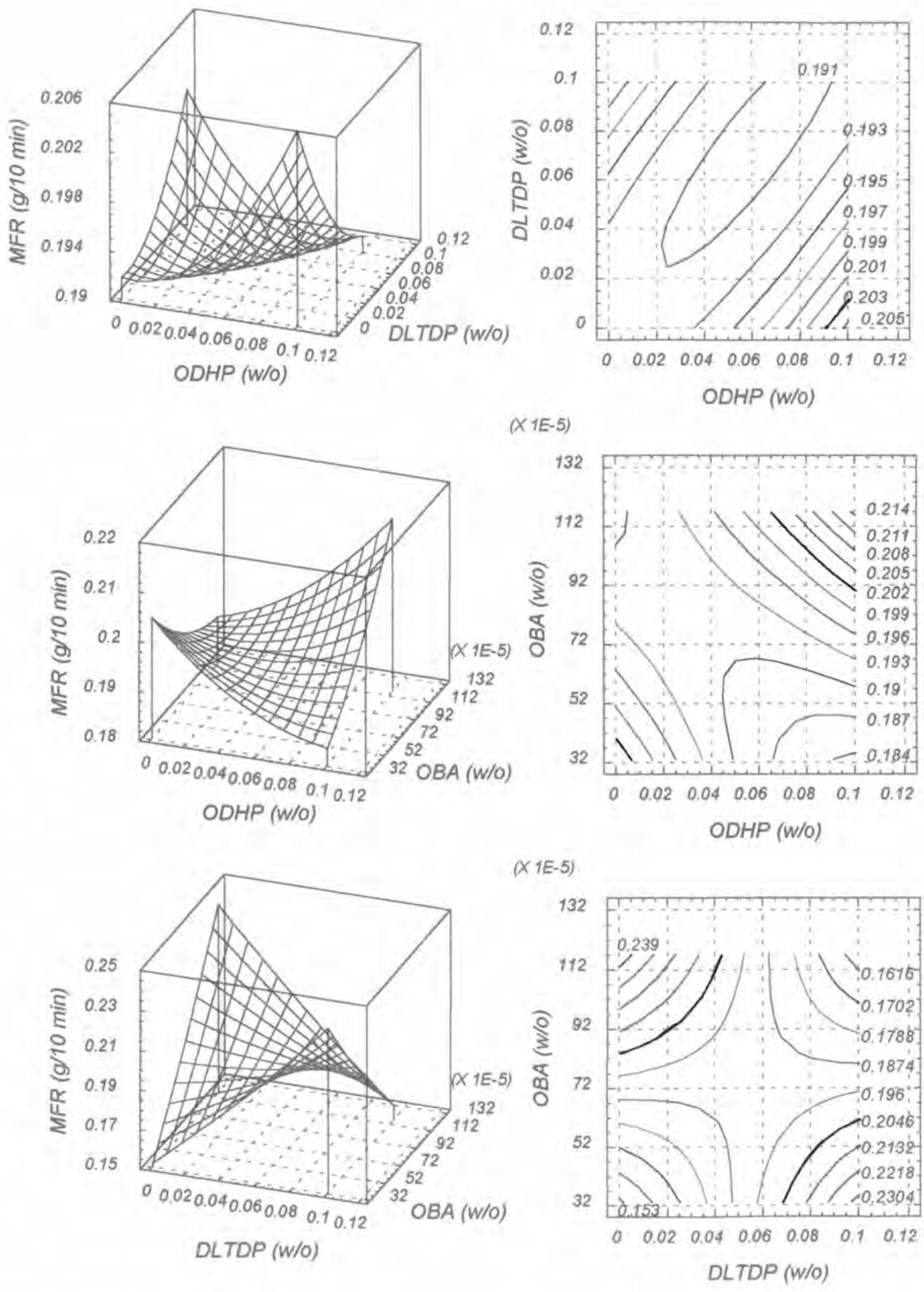

Figure 5.46 : Interaction of ODHP, DLTDP and OBA on Melt Flow Rate (MFR) upon first pass.

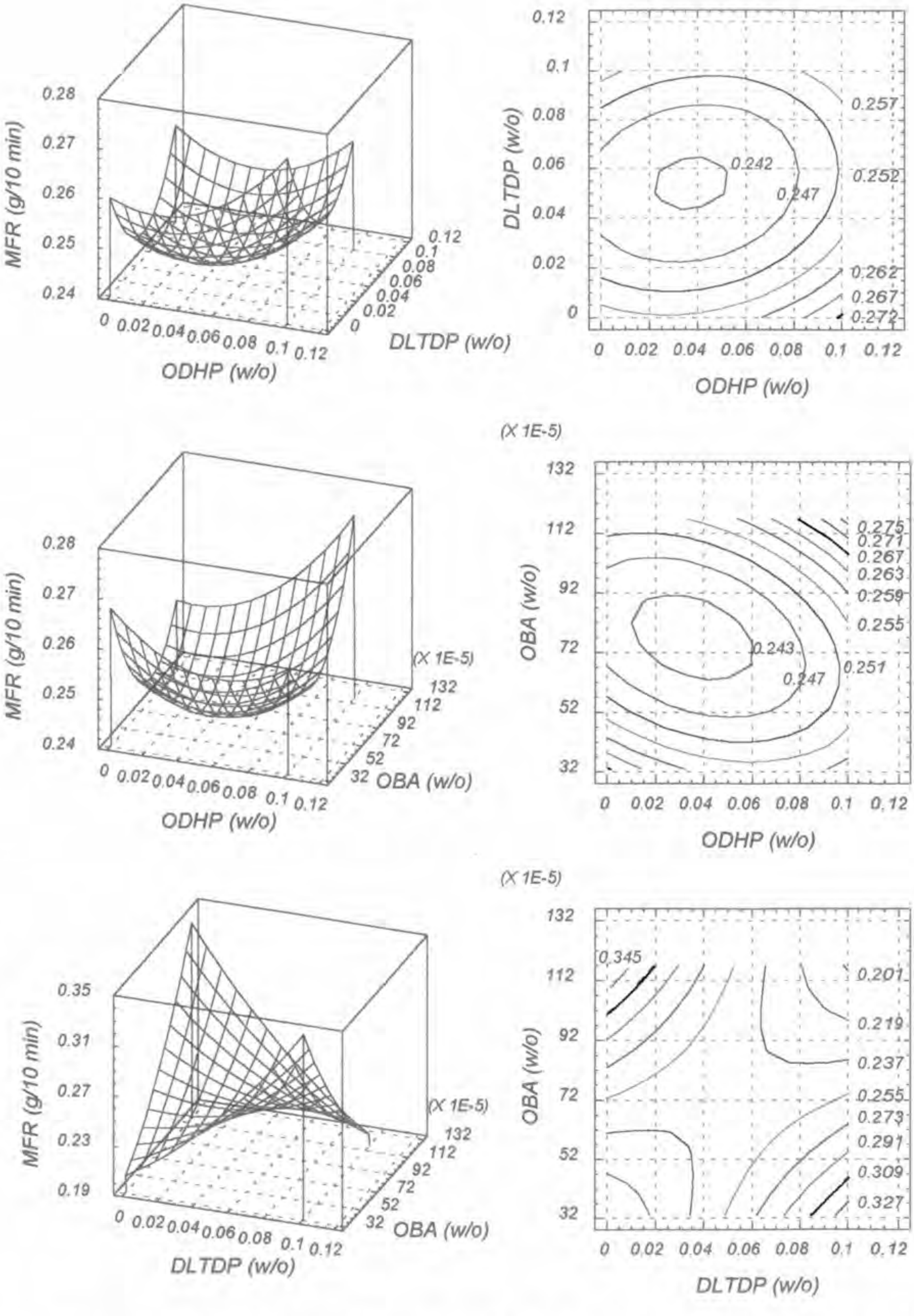

Figure 5.47 : Interaction of ODHP, DLTDP and OBA on Melt Flow Rate (MFR) upon third pass.

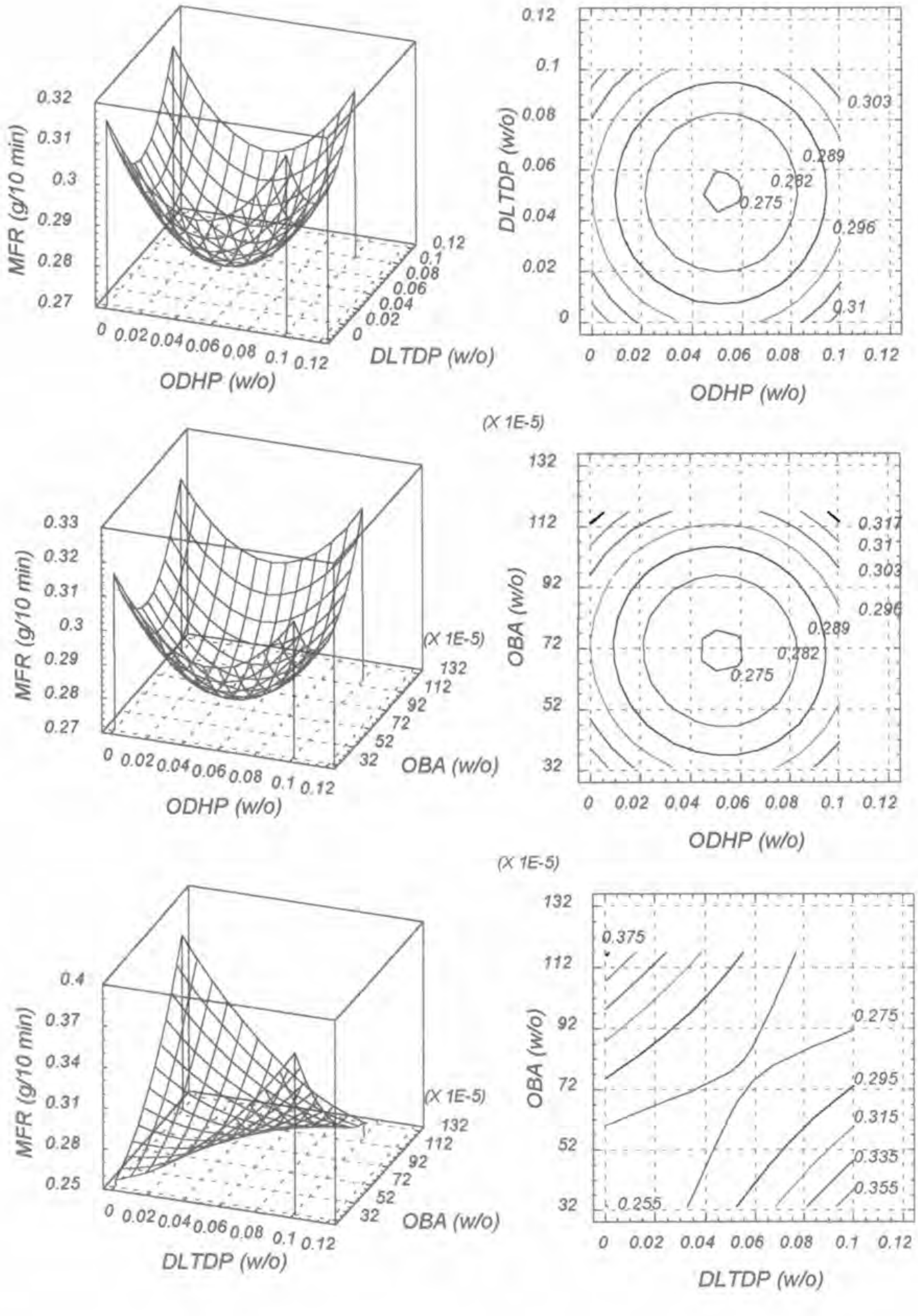

Figure 5.48 : Interaction of ODHP, DLTDP and OBA on Melt Flow Rate (MFR) upon fifth pass.

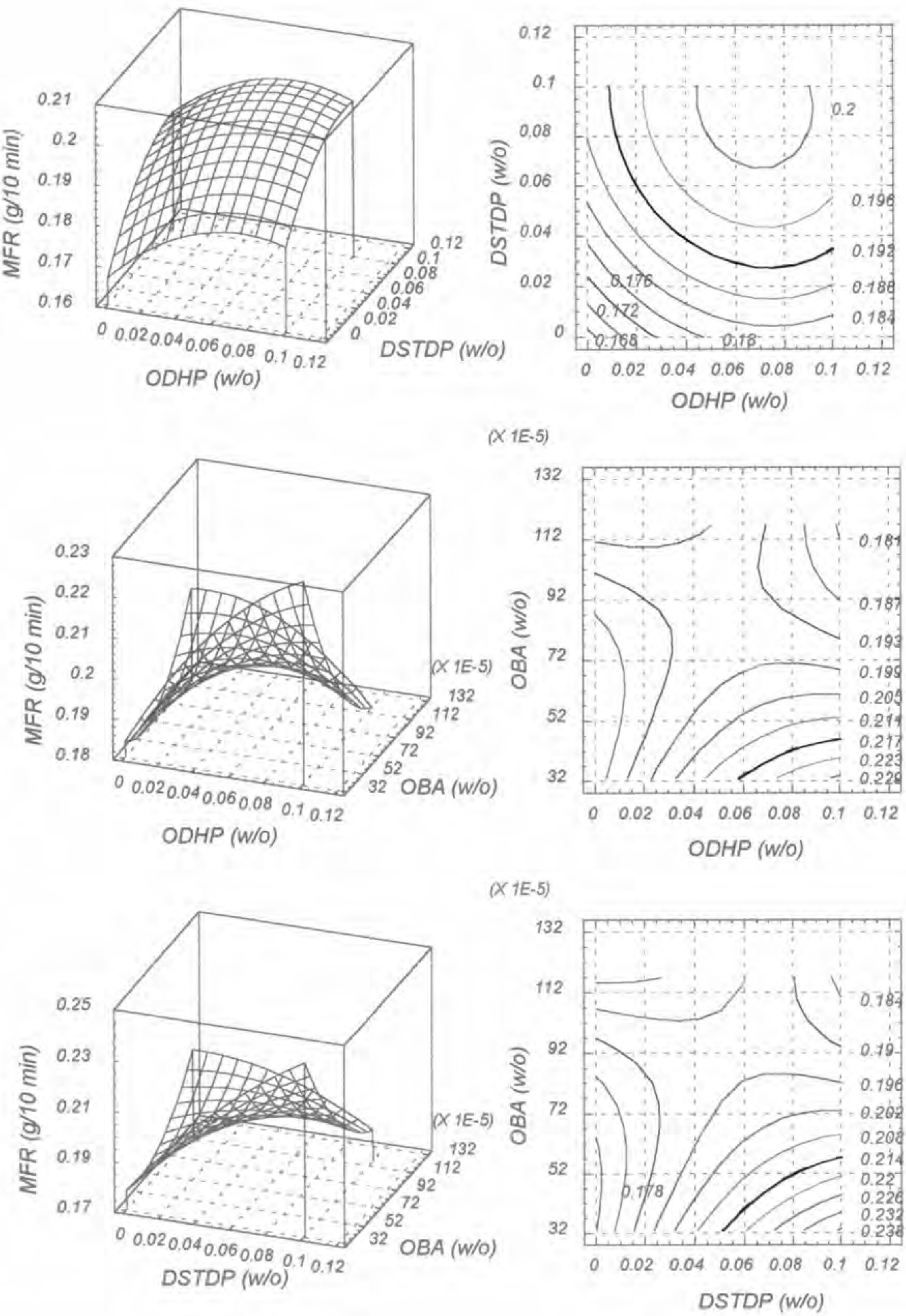

Figure 5.49 : Interaction of ODHP, DSTDP and OBA on Melt Flow Rate (MFR) upon first pass.

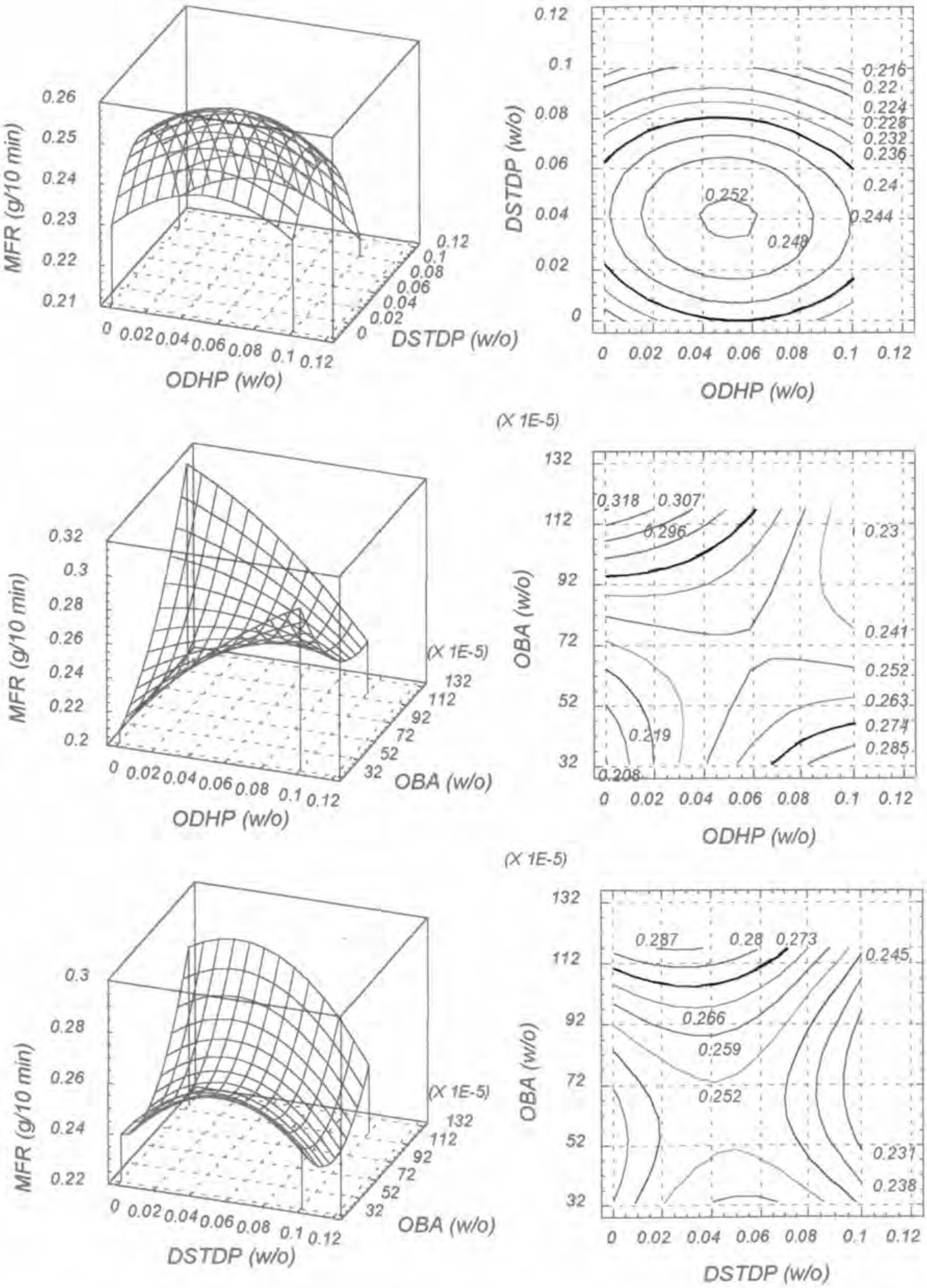

Figure 5.50 : Interaction of ODHP, DSTDP and OBA on Melt Flow Rate (MFR) upon third pass.

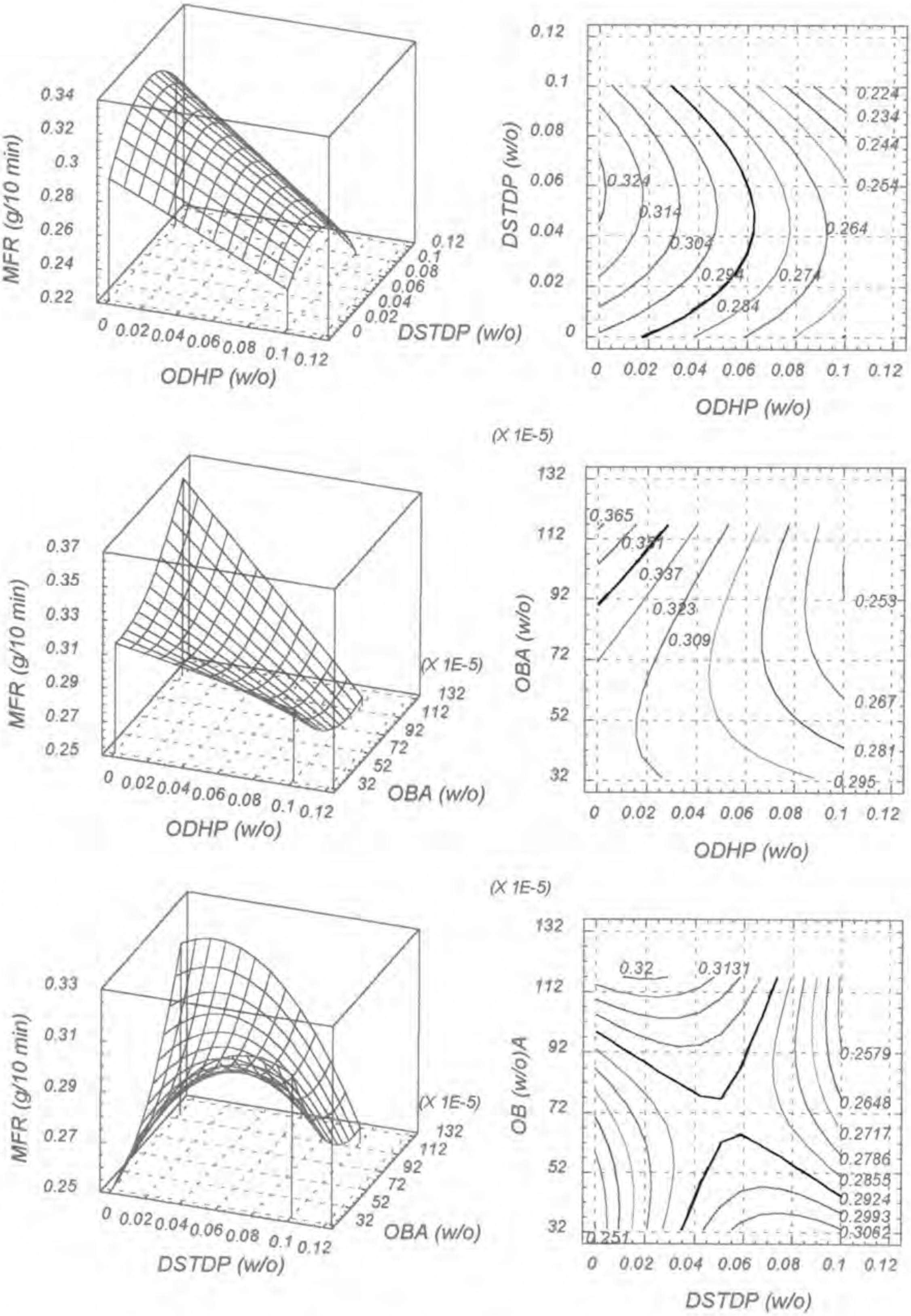

Figure 5.51 : Interaction of ODHP, DSTDP and OBA on Melt Flow Rate (MFR) upon fifth pass.

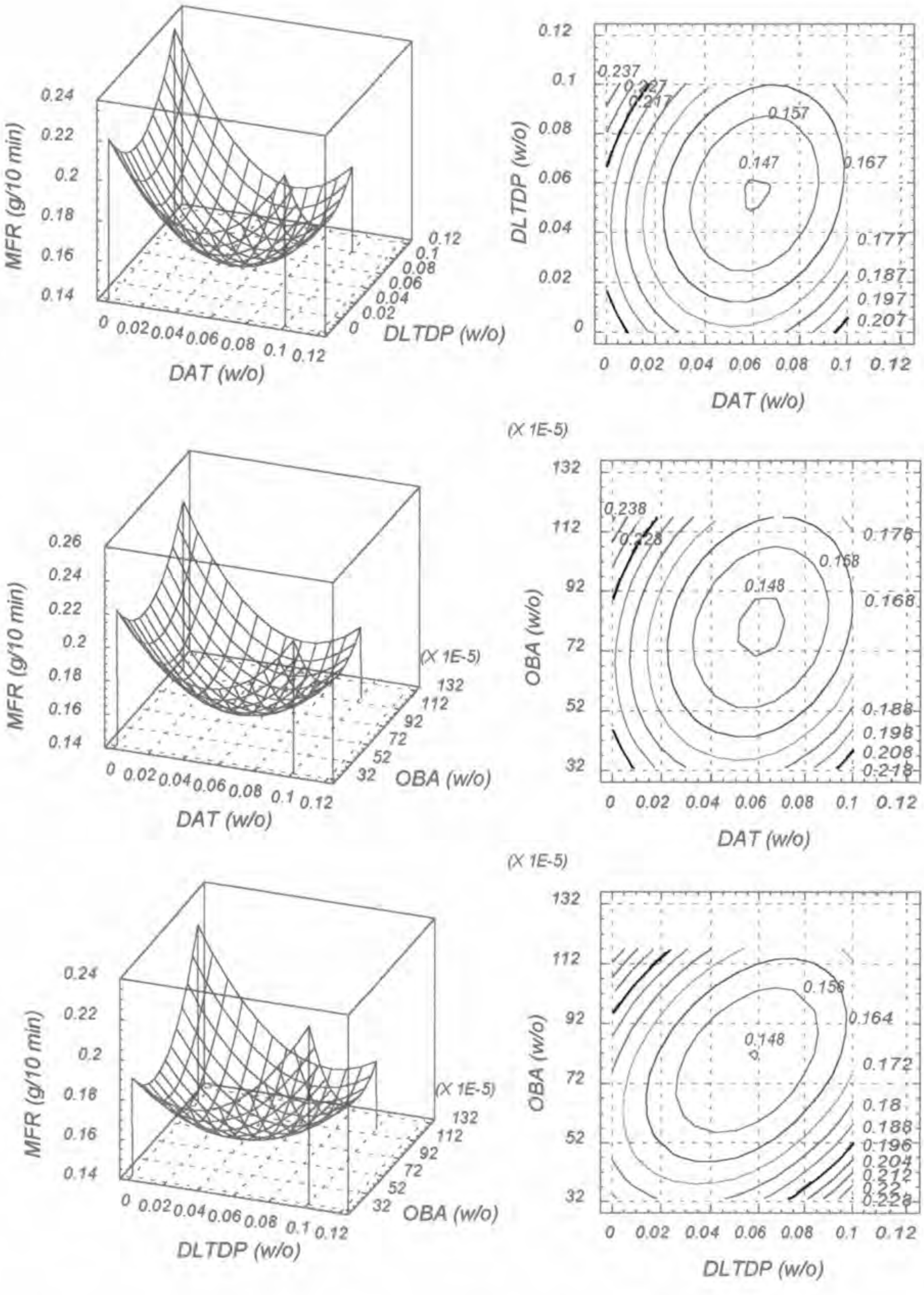

Figure 5.52 : Interaction of DAT, DLTDP and OBA on Melt Flow Rate (MFR) upon first pass.

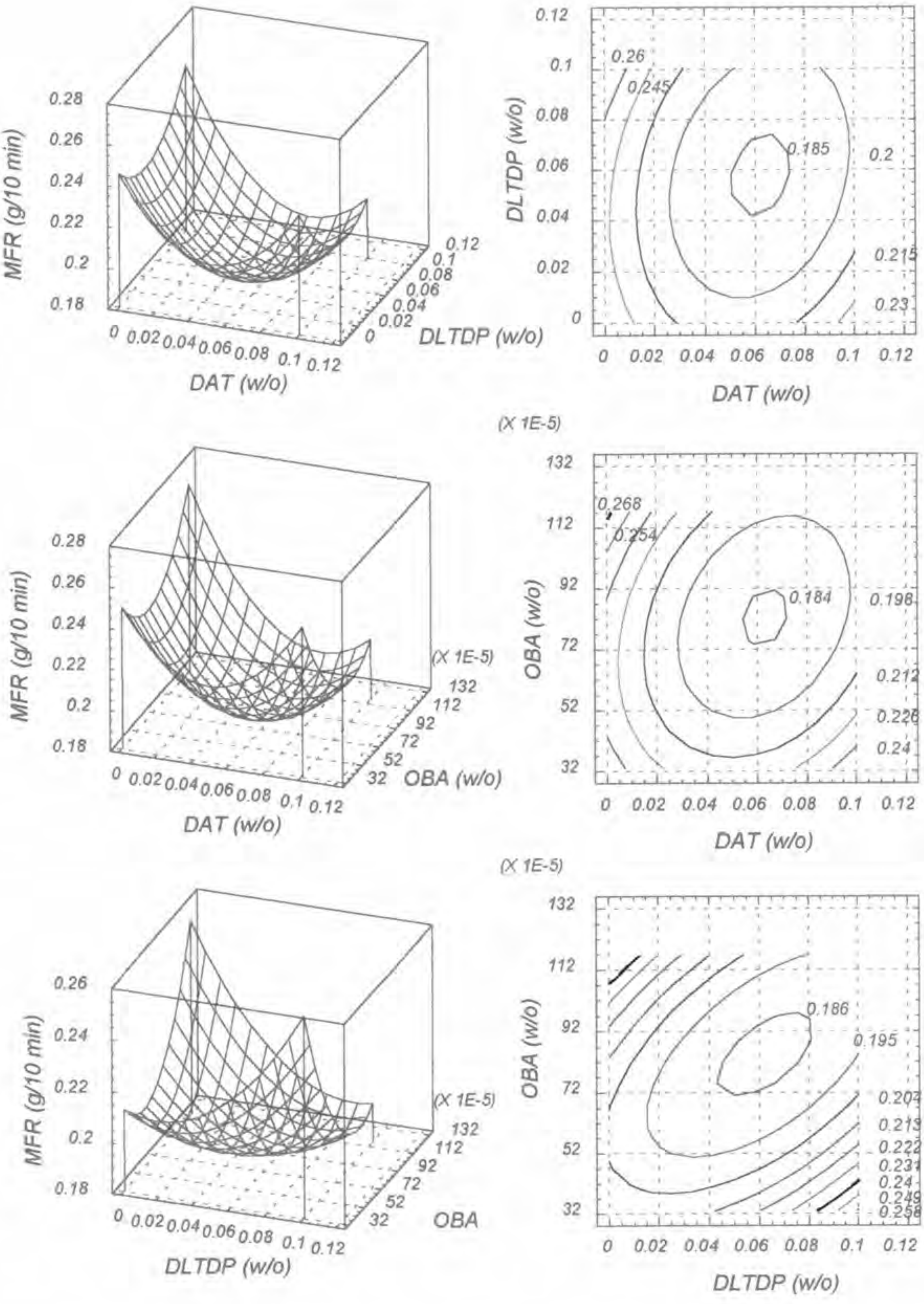

Figure 5.53 : Interaction of DAT, DLTDP and OBA on Melt Flow Rate (MFR) upon third pass.

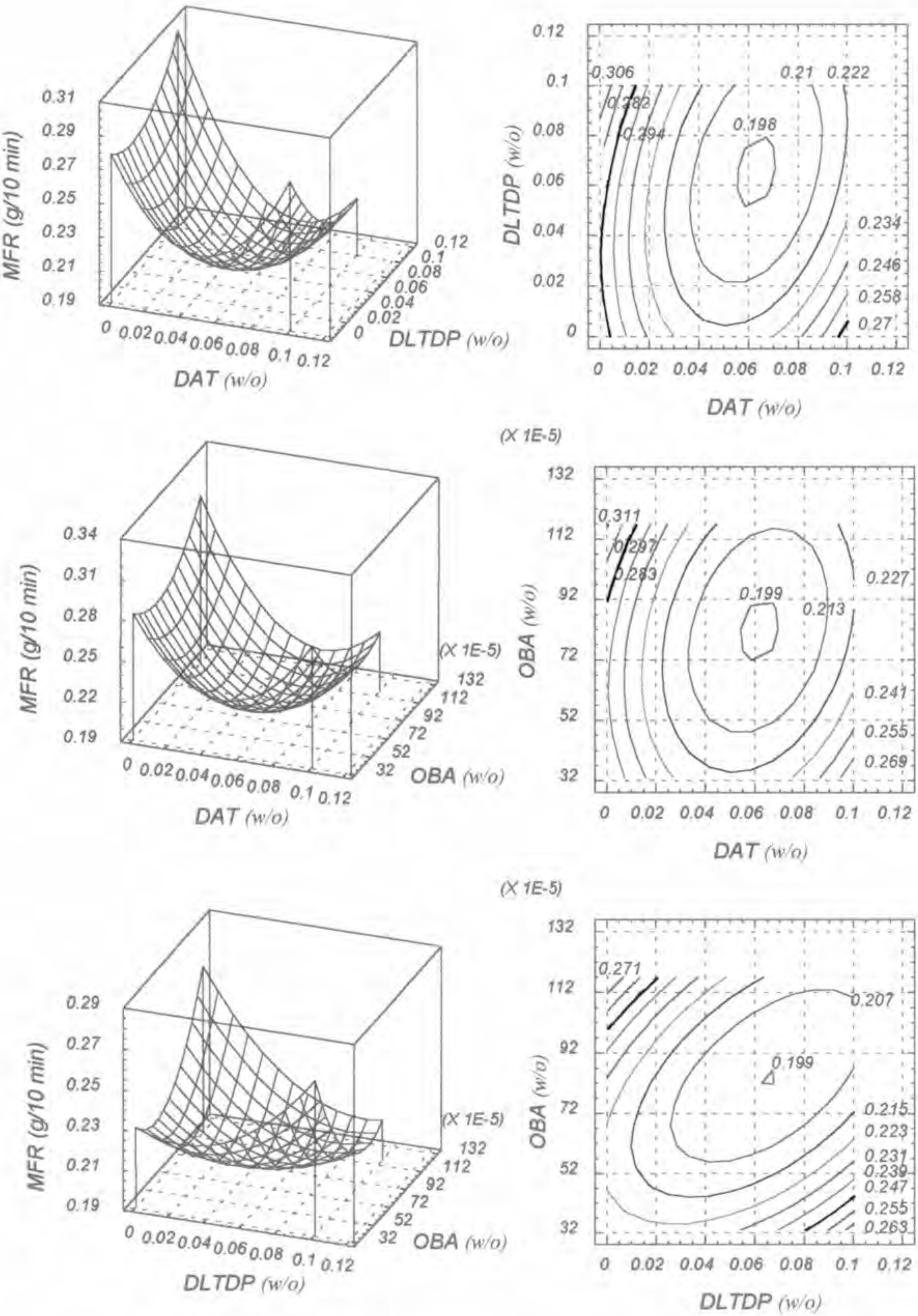

Figure 5-54 : Interaction of DAT, DLTDP and OBA on Melt Flow Rate (MFR) upon fifth pass.

Interaction of DAT, DSTDP and OBA

Figures 5.55 to 5.57 show the interaction of the DAT, DSTDP and the OBA on Melt Flow Rate (MFR) upon the first to the fifth processing pass. When the amount of the DAT was increased, the MFR was decreased. At a high concentration of the DAT, both the DSTDP and the OBA had only a minute effect on the MFR. At the low concentration of the DAT, MFR was increased when the amount of the DSTDP or the OBA was increased.

MFR is a very useful property generally assessed to detect the flowability of a polymer. The MFR's of all the compounded HDPE tend to elevate upon successive passes. The results in the present study clearly imply that the molecular weight of the HDPE had also decreased with the number of extrusion passes. This is believed to be due to chain scissions of the molecules of HDPE which had taken place during re-processing. The molecules of HDPE were continually subjected to both high temperature and high shear stress arisen with the progressive extrusion passes. The molecular chain scission will curtail the chain length of the HDPE molecules hence, the average HDPE molecules become smaller. As a consequence, the MFR's of the compounded HDPE is increased upon further re-extrusion.

From the result of all the tests, the combination and the ratio of additives used had significant effects on the properties of the compounded HDPE. Emphasis is placed on the combination of the blended antioxidant and the OBA which gave the strongest synergistic effects on the OIT. In addition, the HDPE formulation containing 0.06% of ODHP, 0.02% of DSTDP and 0.0007% of OBA gave the best performance on the OIT. The properties of

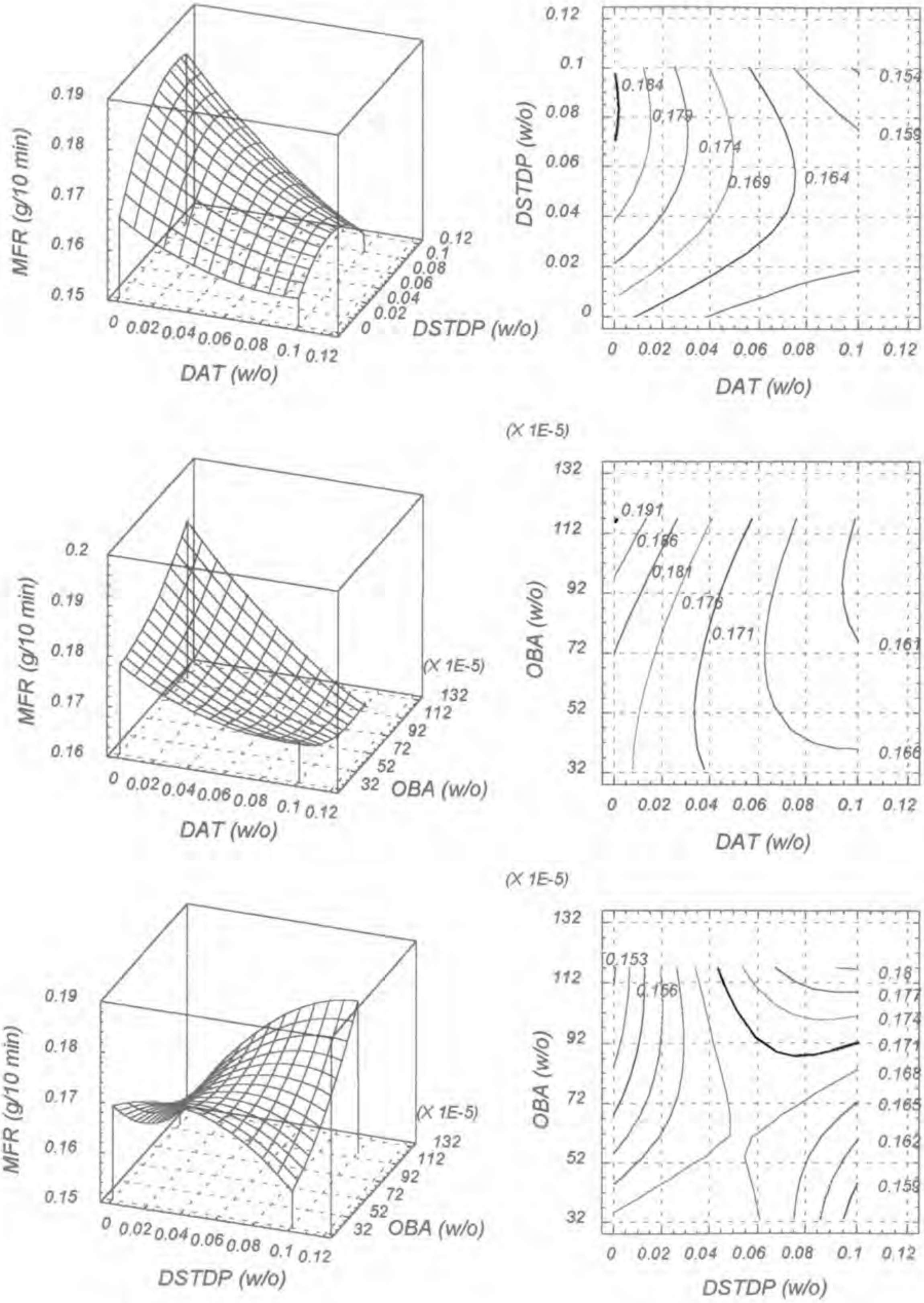

Figure 5.55 : Interaction of DAT, DSTDP and OBA on Melt Flow Rate (MFR) upon first pass.

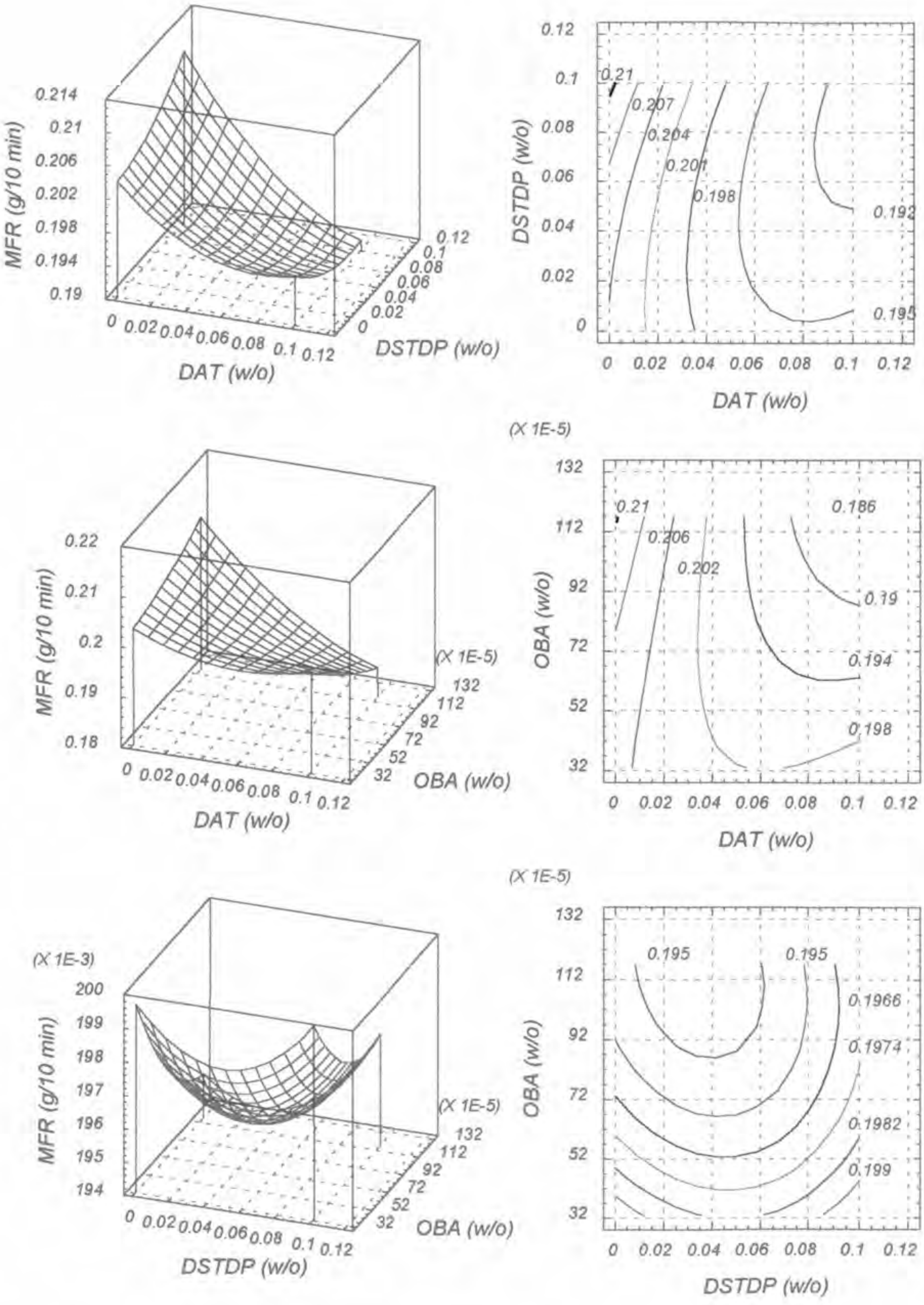

Figure 5.56 : Interaction of DAT, DSTDP and OBA on Melt Flow Rate (MFR) upon third pass.

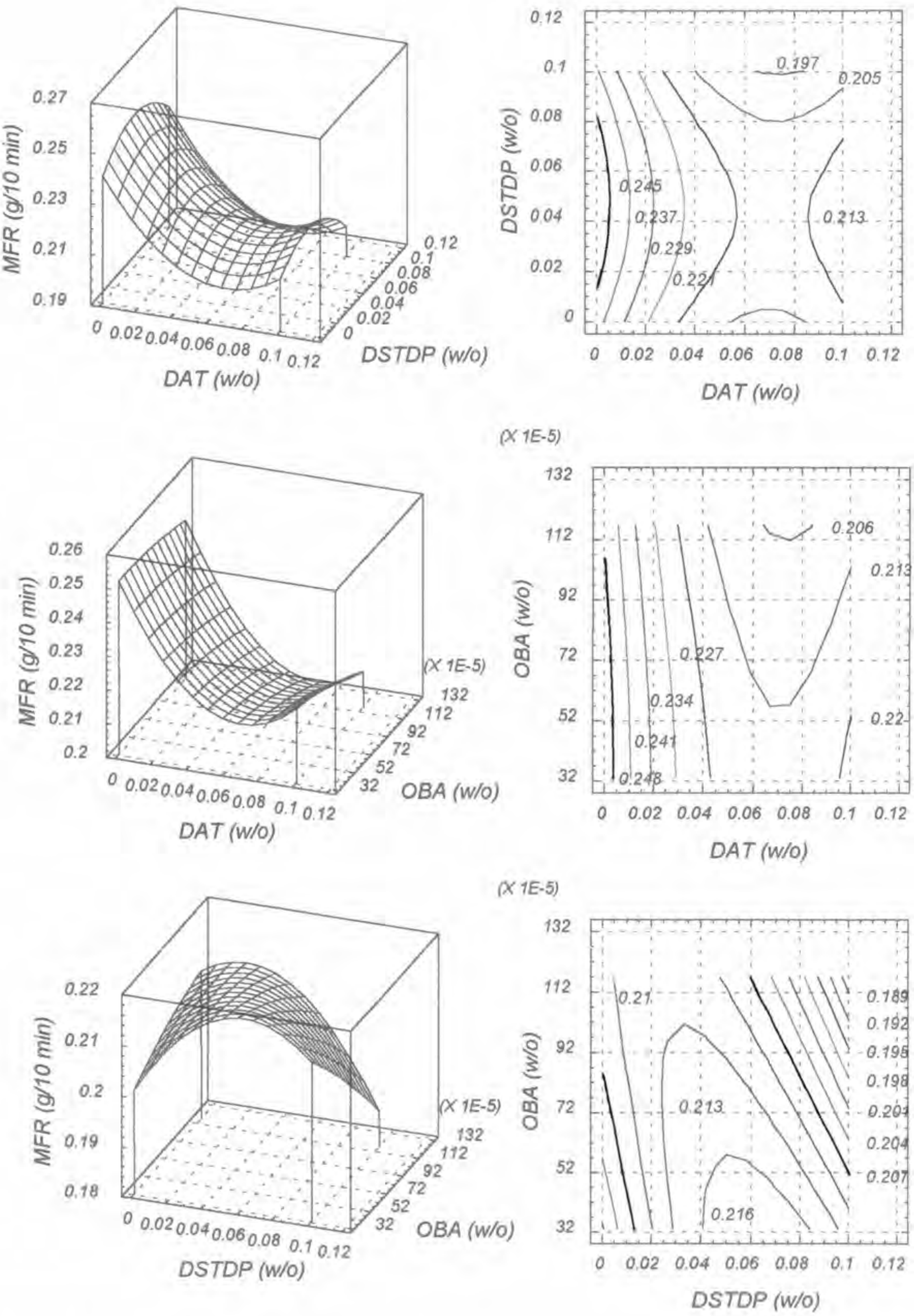

Figure 5-57 : Interaction of DAT, DSTDP and OBA on Melt Flow Rate (MFR) upon fifth pass.

compounded HDPE are predictable by response surface equations as shown in Tables 5.27 to 5.33.

Table 5.27 : Interaction between the Blended AO (X_1) and the OBA (X_2).

Properties	Models in the form of response surface equation	
MFR	1st pass	$MFR = 0.13341+0.737X_1+125.2X_2-6.3333X_1^2-72800.0X_2^2$
	3rd pass	$MFR = 0.14093+1.725X_1+170.6X_2-1080.0X_1X_2-12.0333X_1^2-67680.0X_2^2$
	5th pass	$MFR = 0.23783+1.12178X_1+39.8667X_2-797.333X_1X_2-10.1778X_1^2$
Lightness Index	1st pass	$L_c = 63.82-75.93X_1+50428.0X_2-333.33X_1^2-2.656\times10^7X_2^2$
	3rd pass	$L_c = 74.64-93.87X_1+12480.0X_2$
	5th pass	$L_c = 73.98-123.0X_1+9148.0X_2$
OIT	1st pass	$OIT = 152.76-1360.4X_1-1.19\times10^5X_2+2.38\times10^6X_1X_2$
	3rd pass	$OIT = 75.30-363.2X_1-28062.7X_2+1.0433\times10^6X_1X_2$
	5th pass	$OIT = 69.94-501.34X_1+8154.44X_1^2$

Table 5.28 : Interaction between the PATHP (X_1), DLTDP (X_2) and the OBA (X_3).

Properties	Models in the form of response surface equation	
MFR	1st pass	$MFR = 0.21834-1.3304X_1+0.1553X_2-0.6256X_3+10.3778X_1^2+6.2556X_3^2$
	3rd pass	$MFR = 0.2528-0.6609X_1+0.1020X_2-0.40X_3+4.6889X_1^2+4.0X_3^2$
	5th pass	$MFR = 0.33094-2.0681X_1-0.7389X_3+15.3444X_1^2+7.3889X_3^2$
Lightness index	1st pass	$L_c = 81.28-429.73X_1+208.44X_2+8597.6X_3+1673.11X_1^2-2084.44X_2^2$
	3rd pass	$L_c = 75.97-367.98X_1+208.44X_2+8152.0X_3+1254.44X_1^2-2084.44X_2^2$
	5th pass	$L_c = 70.31-233.97X_1+147.22X_2+8004.0X_3-1472.22X_2^2$
OIT	1st pass	$OIT = 102.09-197.71X_1-1026.17X_2-577.33X_3+5517.78X_1^2+6126.67X_2^2$ $+5773.33X_3^2$
	3rd pass	$OIT = 90.78+222.67X_1-1543.49X_2-304.89X_3+2440.0X_1^2+12005.56X_2^2$ $+3048.89X_3^2$
	5th pass	$OIT = 62.53+891.17X_1-926.67X_2-572.44X_3-7583.33X_1X_2+9397.78X_2^2$ $+5724.44X_3^2$

Table 5.29 : Interaction between the PATHP (X_1), DSTDP (X_2) and the OBA (X_3).

Properties	Models in the form of response surface equation	
MFR	1st pass	$MFR = 0.19113-0.46733X_1-0.04277X_2-8.2111X_1X_2+6.7889X_1^2+4.5333X_2^2$
	3rd pass	$MFR = 0.23557-0.40611X_1-0.78389X_2+20.04167X_3-6.4333X_1X_3+7.2778X_1^2+6.2222X_2^2$
	5th pass	$MFR = 0.30961-1.45922X_1+10.72889X_1^2$
Lightness Index	1st pass	$L_c = 80.47-23.03X_1+60.83X_2+4624.0X_3-1216.67X_1X_2-1530.0X_1^2$
	3rd pass	$L_c = 82.32-49.18X_1-1752.22X_1^2$
	5th pass	$L_c = 72.54+29.06X_1+202.89X_2-2415.56X_1^2-2028.89X_2^2$
OIT	1st pass	$OIT = 78.46+887.15X_1-924.88X_2-588.23X_3-6958.89X_1X_2+11764.44X_2X_3+3643.33X_2^2$
	3rd pass	$OIT = 86.42-75.16X_1-1126.67X_2+5355.56X_1^2+6003.33X_2^2$
	5th pass	$OIT = 82.22+405.10X_1-1524.72X_2+10498.89X_2^2$

Table 5.30 : Interaction between the ODHP (X_1), DLTDP (X_2) and the OBA (X_3).

Properties	Models in the form of response surface equation	
MFR	1st pass	$MFR = 0.14941+0.82556X_2+0.82556X_3-16.51111X_2X_3$
	3rd pass	$MFR = 0.20224+0.8189X_2+0.76779X_3-27.5556X_2X_3+5.8889X_2^2+6.10X_3^2$
	5th pass	$MFR = 0.25541+0.49945X_2+0.3739X_3-23.9889X_2X_3+7.0X_2^2+8.2556X_3^2$
Lightness Index	1st pass	$L_c = 84.03-106.73X_1+5480.0X_3$
	3rd pass	$L_c = 76.72-106.10X_1+7302.56X_3-905.56X_3^2$
	5th pass	$L_c = 75.32-105.07X_1+8016.0X_3$
OIT	1st pass	$OIT = 55.22+905.01X_1-179.47X_2-13583.89X_3-7677.78X_1^2-5281.11X_3^2$
	3rd pass	$OIT = 38.59+735.49X_1-195.9X_2+528.11X_3-5172.22X_1^2-5281.11X_3^2$
	5th pass	$OIT = 45.25+547.58X_1-309.2X_2+343.781X_3-6875.56X_1X_3$

Table 5.31 : Interaction between the ODHP (X_1), DSTDP (X_2) and the OBA (X_3).

Properties	Models in the form of response surface equation	
MFR	1^{st} pass	$MFR = 0.17276+0.33611X_1+0.60034X_2-17.930X_3-6.7222X_1X_3$
		$-8.0333X_2X_3+3.87778X_3^2$
	3^{rd} pass	$MFR = 0.22168+0.19722X_1+0.76556X_2+27.40389X_3-3.9444X_1X_3$
		$-7.6556X_2^2+7.9333X_3^2$
	5^{th} pass	$MFR = 0.30071-0.666X_1+0.98778X_2-9.8778X_2^2$
Lightness Index	1^{st} pass	$L_c = 87.23-177.91X_1+6810.22X_3+1795.56X_1X_3$
	3^{rd} pass	$L_c = 79.47-32.37X_1+6842.83X_3+1698.89X_1X_3-1317.78X_1^2+82.22X_3^2$
	5^{th} pass	$L_c = 70.77+179.57X_1+7002.44X_3+1711.11X_1X_3-3375.56X_1^2$
OIT	1^{st} pass	$OIT = -1.10+1713.97X_1+384.37X_2+17728.06X_3-5403.33X_1X_2$
		$-9681.11X_1X_3-7931.11X_1^2-4690.0X_2^2$
	3^{rd} pass	$OIT = 43.31+958.78X_1-355.23X_2+325.0X_3-6500.0X_1X_3-5177.78X_1^2$
	5^{th} pass	$OIT = 35.37+1067.45X_1+220.82X_2+241.0X_3-4820.0X_1X_3-8264.44X_1^2$
		$-5435.56X_2^2$

Table 5.32 : Interaction between the DAT (X_1), DLTDP (X_2) and the OBA (X_3).

Properties	Models in the form of response surface equation	
MFR	1^{st} pass	$MFR = 0.2559-1.779X_1-1.090X_2-1.1444X_3+14.8333X_1^2+10.90X_2^2$
	3^{rd} pass	$+11.4444X_3^2$
		$MFR = 0.25074-1.61944X_1-0.21555X_2-0.50222X_3-10.4889X_2X_3$
	5^{th} pass	$+13.3111X_1^2+7.40X_2^2+10.2667X_3^2$
		$MFR = 0.29656-2.45633X_1-0.9889X_3+20.4667X_1^2+9.8889X_3^2$
Lightness Index	1^{st} pass	$L_c = 78.68-290.23X_1+261.33X_3-2613.33X_3^2$
	3^{rd} pass	$L_c = 69.32-169.93X_1+151.33X_2-3026.67X_1X_2$
	5^{th} pass	$L_c = 59.69-104.64X_1+202.56X_2-4051.11X_1X_2$
OIT	1^{st} pass	$OIT = 58.41+466.93X_1-185.83X_2+15716.0X_3$
	3^{rd} pass	$OIT = 70.97+1331.58X_1-767.98X_2-404.0X_3-6514.44X_1X_2-6055.56X_1^2$
		$+8086.67X_2^2+4040.0X_3^2$
	5^{th} pass	$OIT = 81.38+1324.58X_1-1328.06X_2-425.0X_3+8500.0X_2X_3-8387.78X_1^2$
		$+6775.56X_2^2$

Table 5.33 : Interaction between the DAT (X_1), DSTDP (X_2) and the OBA (X_3).

Properties	Models in the form of response surface equation	
MFR	1st pass	$MFR = 0.18804-0.20233X_1-0.19222X_2-0.19222X_3+3.8444X_2X_3$
	3rd pass	$MFR = 0.20337-0.16489X_1-3.89667X_3-2.0667X_1X_3+1.3222X_1^2$
	5th pass	$MFR = 0.23869-1.08156X_1+0.44333X_3+7.5556X_1^2-4.4333X_2^2$
Lightness Index	1st pass	$L_c = 87.88-487.93X_1+2096.67X_1^2$
	3rd pass	$L_c = 79.09-531.52X_1+6956.0X_3+1872.22X_1^2$
	5th pass	$L_c = 75.80-351.60X_1$
OIT	1st pass	$OIT = 68.89+1525.06X_1-707.64X_2-11612.22X_1^2+5161.11X_2^2$
	3rd pass	$OIT = 57.96+1011.31X_1-162.13X_2-5451.11X_1^2$
	5th pass	$OIT = 71.05+430.77X_1-251.73X_2$