DIGITAL SYSTEM DESIGN APPLICATION – EHB 436E

Project I

Muhammed Velihan Bağcı

040170093

Yiğit Bektaş Gürsoy

040180063

Class Lecturer: Sıddıka Berna Örs Yalçın

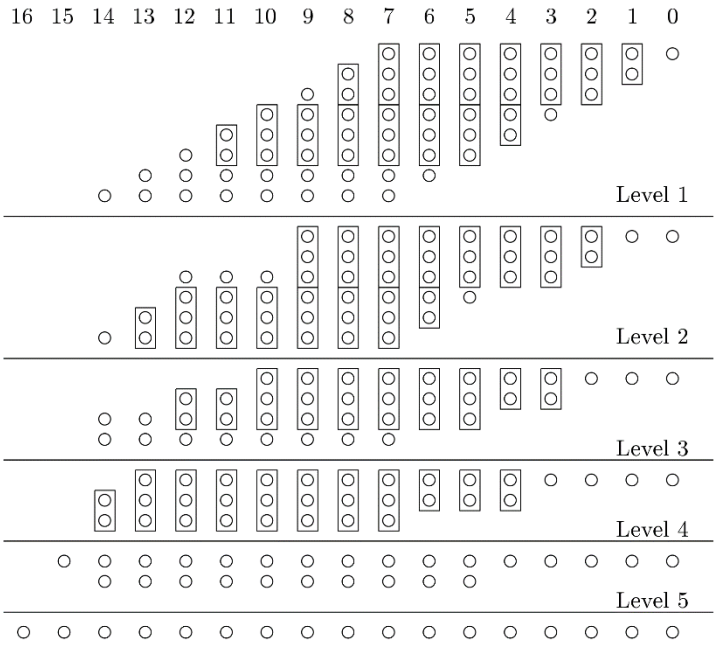
Class Assistant:
Serdar Duran
Yasin Fırat Kula
Mehmet Onur Demirtürk

Muhammed Velihan BAĞCI
040170093
Yiğit Bektaş GÜRSOY
040180063

1. Wallace Tree Multiplier

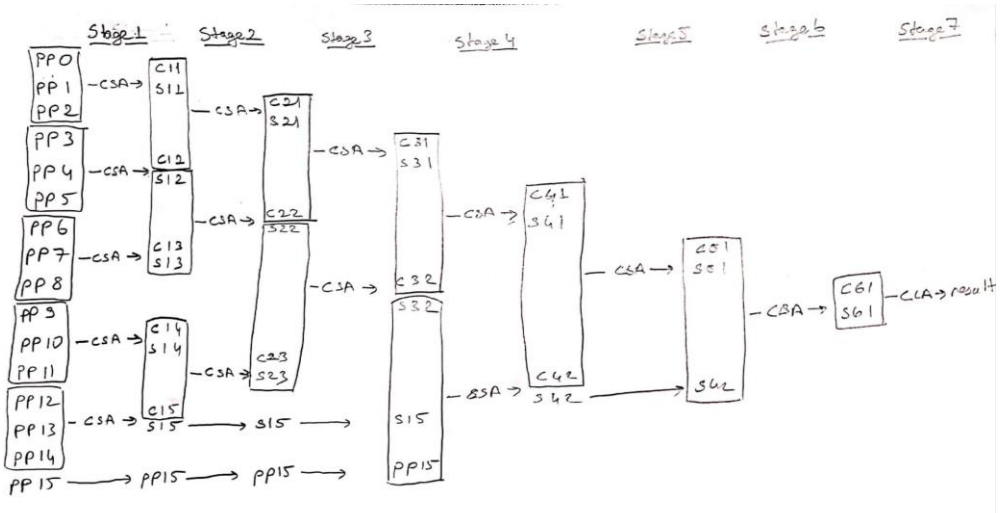
The wallace tree multiplier is an algorithm that performs multiplication for two binary numbers.

First, partial products are calculated. Partial products are the offset of the first number. The translation is done by looking at the second number. The first number is shifted to the left by the numeric value for each bit of the '1' value of the second number. In the '0' bits of the second number, the partial products get '0'.



The partial products obtained are collected in threes with the Carry save adder. As a result of this operation, 32-bit carry and sum numbers are obtained. The process is repeated in the same way for the subsequent results.

At the end of the transactions, the two results from a single CSA are combined with the CLA and the result is obtained.



2. Verilog Code

```
(* DONT_TOUCH = "TRUE" *)
module Wallace_Tree_Mult(
    input [15:0]A,
    input [15:0]B,
    output [31:0]C,
    output carry
    );
    wire  [31:0] pp [15:0];
    PP partial_products(
        A,
        B,
        pp[0][31:0],
        pp[1][31:0],
        pp[2][31:0],
        pp[3][31:0],
        pp[4][31:0],
        pp[5][31:0],
        pp[6][31:0],
        pp[7][31:0],
        pp[8][31:0],
        pp[9][31:0],
        pp[10][31:0],
        pp[11][31:0],
        pp[12][31:0],
        pp[13][31:0],
        pp[14][31:0],
        pp[15][31:0]
        );

    // STAGE1
    wire [31:0] sum_s11, carry_s11, sum_s12, carry_s12, sum_s13, carry_s13, sum_s14, carry_s14,
sum_s15, carry_s15;
    CSA s11 (pp[0][31:0], pp[1][31:0], pp[2][31:0], sum_s11[31:0], carry_s11[31:0]);
    CSA s12 (pp[3][31:0], pp[4][31:0], pp[5][31:0], sum_s12[31:0], carry_s12[31:0]);
    CSA s13 (pp[6][31:0], pp[7][31:0], pp[8][31:0], sum_s13[31:0], carry_s13[31:0]);
    CSA s14 (pp[9][31:0], pp[10][31:0], pp[11][31:0], sum_s14[31:0], carry_s14[31:0]);
    CSA s15 (pp[12][31:0], pp[13][31:0], pp[14][31:0], sum_s15[31:0], carry_s15[31:0]);

    //STAGE2
    wire [31:0] sum_s21, carry_s21, sum_s22, carry_s22, sum_s23, carry_s23;
    CSA s21 (sum_s11[31:0], carry_s11[31:0], sum_s12[31:0], sum_s21[31:0], carry_s21[31:0]);
    CSA s22 (carry_s12[31:0], sum_s13[31:0], carry_s13[31:0], sum_s22[31:0], carry_s22[31:0]);
    CSA s23 (sum_s14[31:0], carry_s14[31:0], sum_s15[31:0], sum_s23[31:0], carry_s23[31:0]);
    //STAGE3

    wire [31:0] sum_s31, carry_s31, sum_s32, carry_s32;
    CSA s31 (sum_s21[31:0], carry_s21[31:0], sum_s22[31:0], sum_s31[31:0], carry_s31[31:0]);
    CSA s32 (carry_s22[31:0], sum_s23[31:0], carry_s23[31:0], sum_s32[31:0], carry_s32[31:0]);

    //STAGE4
    wire [31:0] sum_s41, carry_s41, sum_s42, carry_s42;
    CSA s41 (sum_s31[31:0], carry_s31[31:0], sum_s32[31:0], sum_s41[31:0], carry_s41[31:0]);
    CSA s42 (carry_s32[31:0], carry_s15[31:0], pp[15][31:0], sum_s42[31:0], carry_s42[31:0]);

    //STAGE5
    wire [31:0] sum_s51, carry_s51;
    CSA s51 (sum_s41[31:0], carry_s41[31:0], sum_s42[31:0], sum_s51[31:0], carry_s51[31:0]);

    //STAGE6
    wire [31:0] sum_s61, carry_s61;
    CSA s61 (sum s51[31:0], carry s51[31:0], carry s42[31:0], sum s61[31:0], carry s61[31:0]);

    CLA Carry_Lookahead_Adder(
        .A(sum_s61),
        .B(carry_s61),
        .CIN(1'b0),
        .COUT(carry),
        .SUM(C)
        );

endmodule
```

3. Code Algorithm Explanation

In the above code, first partial products are calculated and PP module is used for this process. The obtained partial product values are collected using CSA modules and the two 32-bit outputs are sent to the next stage. Stages may have unprocessed inputs and these inputs are transferred directly to the next stage. At each stage, the outputs of the previous stages and the values that have not been processed before are added to the CSA process. In this way, at the end of 6 stages, 2 32-bit numbers are obtained. The obtained numbers are added to the addition process with the help of CLA.

Although carry output is added in this circuit, it always gives '0' output. This is because the product of two 16-bit numbers cannot exceed 32-bit. However, the carry output is connected to the carry output of the CLA and it has been observed that it always gives '0' as a result of the simulations.

4. Random Number Generated with Python

With the python code specified below, 2 random integers are generated, each of which is 100. Since the circuit in the project is a multiplication circuit, the numbers produced separately are multiplied with each other and written as result, then all of these results are written to the random_numbers.txt file. These generated numbers were generated for use in simulation.

```
import random

# Open the file for writing
with open('random_numbers.txt', 'w') as f:
    # Generate 100 random pairs of integers
    for i in range(100):
        a = random.randint(0, 65535)
        b = random.randint(0, 65535)
        result = a * b
        # Write the result to the file
        f.write(str(a) + " " + str(b)+ " " +str(result) + '\n')
```

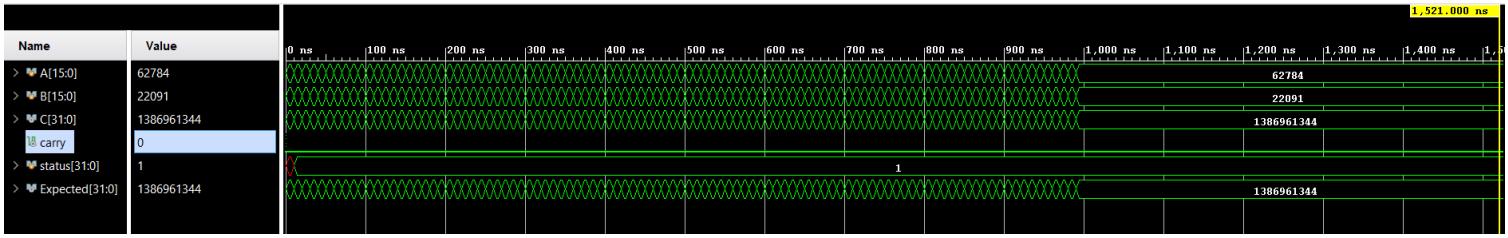
Muhammed Velihan BAĞCI
040170093
Yiğit Bektaş GÜRSOY
040180063

5. Test Bench Code

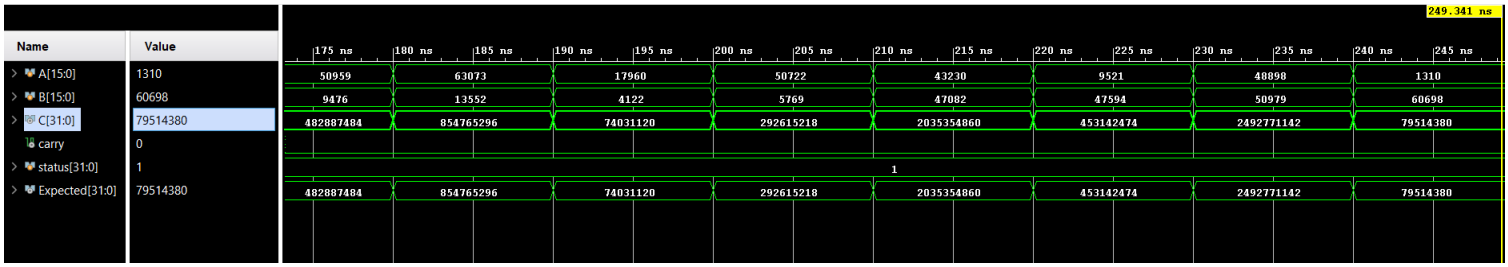
```
`timescale 1ns / 1ps
module Wallace_tb();

    reg [15:0] A;
    reg [15:0] B;
    wire [31:0] C;
    wire carry;

    integer status;
    wire [31:0]Expected;
    integer fin_ptr, fout_ptr;

    Wallace_Tree_Mult UUT (
        .A(A),
        .B(B),
        .C(C),
        .carry(carry)
        );

    initial begin
        fin_ptr = $fopen("C:/Users/yigit/Desktop/random_numbers.txt","r");
        fout_ptr = $fopen("C:/Users/yigit/Desktop/output.txt","w");

        while(!$feof(fin_ptr))
            begin
            $fscanf(fin_ptr,"%d %d %d\n", A, B, Expected); #10;
            $display("A=%b, %d / B=%b, %d / Expected=%b, %d", A, A, B, B, Expected, Expected);
            $display("Result=%b, %d / carry=%b || Expected Result=%b, %d || Status = %d \n ", C, C, carry,
Expected, Expected, status );
            assign status = C === Expected ? 1'b1 : 1'b0;
            $fwrite(fout_ptr,"Result=%b, %d / carry=%b || Expected Result=%b, %d || Status= %d \n", C, C,
carry, Expected, Expected, status);
        end
        $finish();
    end

endmodule
```

6. Behavioral Simulation Results

Two simulation results are shown below. A and B values are numbers that can take a maximum of 2^{16}-1 values drawn in the random_numbers.txt file and randomly generated on python. The C value is the value that represents the A multiplied by the B value. The value called Expected was written to a .txt file to be verified from Python, and then transferred to the simulation via Vivado for accuracy comparison. It is written in the testbench code to give the value "TRUE" when the status value is 1 and "FALSE" when it is 0. This can be seen in the testbench code above. The carry value represents the COUT value from the CLA.



Şekil 1



Şekil 2

7. TCL Console

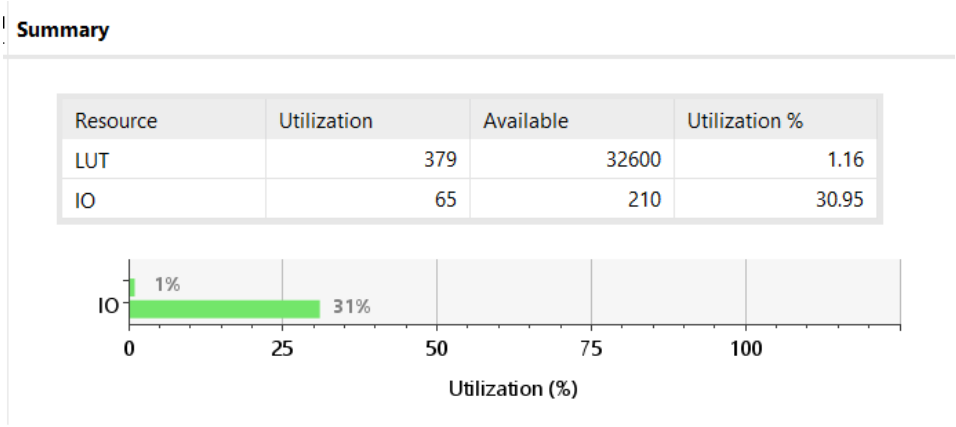
```
A=0000101101010000,  2896 / B=1010000000111111, 41023 / Expected=00000111000101001100100010110000,  118802608
Result=00000111000101001100100010110000,  118802608 / carry=0 || Expected Result=00000111000101001100100010110000,  118802608 || Status =          1

A=1110011011011011, 59099 / B=0110101101010011, 27475 / Expected=01100000110010000110001000000001, 1623745025
Result=01100000110010000110001000000001, 1623745025 / carry=0 || Expected Result=01100000110010000110001000000001, 1623745025 || Status =          1

A=0010001001110101,  8821 / B=1001110111010000, 40400 / Expected=00010101001111011100000000010000,  356368400
Result=00010101001111011100000000010000,  356368400 / carry=0 || Expected Result=00010101001111011100000000010000,  356368400 || Status =          1

A=0001000000011111,  4127 / B=1001111010011010, 40602 / Expected=00001001111111001101010010100110,  167564454
Result=00001001111111001101010010100110,  167564454 / carry=0 || Expected Result=00001001111111001101010010100110,  167564454 || Status =          1

A=0101111011011101, 24285 / B=0011010001010010, 13394 / Expected=00010011011000110100011011001010,  325273290
Result=00010011011000110100011011001010,  325273290 / carry=0 || Expected Result=00010011011000110100011011001010,  325273290 || Status =          1

A=0111011010010011, 30355 / B=0111111111101111, 32751 / Expected=00111011010000011010000000111101,  994156605
Result=00111011010000011010000000111101,  994156605 / carry=0 || Expected Result=00111011010000011010000000111101,  994156605 || Status =          1

A=1110001000011001, 57881 / B=1111001110111011, 62395 / Expected=11010111010000101110001101000011, 3611484995
Result=11010111010000101110001101000011, 3611484995 / carry=0 || Expected Result=11010111010000101110001101000011, 3611484995 || Status =          1

A=1010110110010011, 44435 / B=0001100110011111,  6559 / Expected=00010001010111110010100101001101,  291449165
Result=00010001010111110010100101001101,  291449165 / carry=0 || Expected Result=00010001010111110010100101001101,  291449165 || Status =          1

A=0100001000110111, 16951 / B=0000000110011110,   414 / Expected=00000000011010110001010011110010,    7017714
Result=00000000011010110001010011110010,    7017714 / carry=0 || Expected Result=00000000011010110001010011110010,    7017714 || Status =          1

A=0000001100001111,   783 / B=1111100111000011, 63939 / Expected=00000010111110111110101101101101,   50064237
Result=00000010111110111110101101101101,   50064237 / carry=0 || Expected Result=00000010111110111110101101101101,   50064237 || Status =          1

A=1101101100101100, 56108 / B=1000110100101001, 36137 / Expected=01111000110110100101011000001100, 2027574796
Result=01111000110110100101011000001100, 2027574796 / carry=0 || Expected Result=01111000110110100101011000001100, 2027574796 || Status =          1
```

```
Result=00011011000000100110011111001010,  453142474 / carry=0 || Expected Result=00011011000000100110011111001010,  453142474 || Status =          1

A=1011111100000010, 48898 / B=1100011100100011, 50979 / Expected=10010100100101001010101101000110, 2492771142
Result=10010100100101001010101101000110, 2492771142 / carry=0 || Expected Result=10010100100101001010101101000110, 2492771142 || Status =          1

A=0000010100011110,  1310 / B=1110110100011010, 60698 / Expected=00000100101111010100101100001100,   79514380
Result=00000100101111010100101100001100,   79514380 / carry=0 || Expected Result=00000100101111010100101100001100,   79514380 || Status =          1

A=1011111110110111, 49079 / B=0000110110100100,  3492 / Expected=00001010001101110001110000111100,  171383868
Result=00001010001101110001110000111100,  171383868 / carry=0 || Expected Result=00001010001101110001110000111100,  171383868 || Status =          1

A=0101101010100101, 23205 / B=1110011000110000, 58928 / Expected=01010001100000010011110011110000, 1367424240
Result=01010001100000010011110011110000, 1367424240 / carry=0 || Expected Result=01010001100000010011110011110000, 1367424240 || Status =          1

A=1010011100110100, 42804 / B=0010000101110100,  8564 / Expected=00010101110110010111011110010000,  366573456
Result=00010101110110010111011110010000,  366573456 / carry=0 || Expected Result=00010101110110010111011110010000,  366573456 || Status =          1

A=1001100001000101, 38981 / B=0110110010110010, 27834 / Expected=01000000101010111011111000100010, 1084997154
Result=01000000101010111011111000100010, 1084997154 / carry=0 || Expected Result=01000000101010111011111000100010, 1084997154 || Status =          1

A=1011101000111101, 47677 / B=1000110010101111, 36015 / Expected=01100110010110001010101110110011, 1717087155
Result=01100110010110001010101110110011, 1717087155 / carry=0 || Expected Result=01100110010110001010101110110011, 1717087155 || Status =          1

A=0100100101010001, 18769 / B=0000110101111100,  3452 / Expected=00000011110111001010000000111100,   64790588
Result=00000011110111001010000000111100,   64790588 / carry=0 || Expected Result=00000011110111001010000000111100,   64790588 || Status =          1

A=0010110111011111, 11743 / B=1001100011011011, 39131 / Expected=00011011011000111010010111000101,  459515333
Result=00011011011000111010010111000101,  459515333 / carry=0 || Expected Result=00011011011000111010010111000101,  459515333 || Status =          1

A=1011001000000100, 45572 / B=0111001001100011, 29283 / Expected=01001111100010101001111110001100, 1334484876
Result=01001111100010101001111110001100, 1334484876 / carry=0 || Expected Result=01001111100010101001111110001100, 1334484876 || Status =          1

A=0111001100010111, 29463 / B=1011101110101111, 48047 / Expected=01010100011000000111100110111001, 1415608761
```

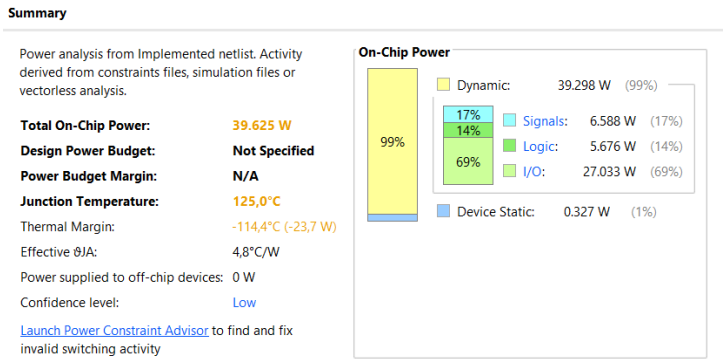
```
Result=01111000011000010101110011000000, 2019646656 / carry=0 || Expected Result=01111000011000010101110011000000, 2019646656 || Status =          1

A=0010011110110000, 10160 / B=0001010111010111,  5591 / Expected=00000011011000101100010011010000,   56804560
Result=00000011011000101100010011010000,   56804560 / carry=0 || Expected Result=00000011011000101100010011010000,   56804560 || Status =          1

A=1111100101111110, 63870 / B=0111010101111100, 30396 / Expected=01110011101101110100110010001000, 1941392520
Result=01110011101101110100110010001000, 1941392520 / carry=0 || Expected Result=01110011101101110100110010001000, 1941392520 || Status =          1

A=1100000011010100, 49364 / B=0011100001000000, 14400 / Expected=00101010010111010010101000000000,  710841600
Result=00101010010111010010101000000000,  710841600 / carry=0 || Expected Result=00101010010111010010101000000000,  710841600 || Status =          1

A=1111111000010100, 65044 / B=1100000010110011, 49331 / Expected=10111111010000001010011111111100, 3208685564
Result=10111111010000001010011111111100, 3208685564 / carry=0 || Expected Result=10111111010000001010011111111100, 3208685564 || Status =          1

A=0100110111001001, 19913 / B=0001011101001110,  5966 / Expected=00000111000101001100001000111110,  118800958
Result=00000111000101001100001000111110,  118800958 / carry=0 || Expected Result=00000111000101001100001000111110,  118800958 || Status =          1

A=0110000001011011, 24667 / B=0100011101011110, 18270 / Expected=00011010110111001001111001101010,  450666090
Result=00011010110111001001111001101010,  450666090 / carry=0 || Expected Result=00011010110111001001111001101010,  450666090 || Status =          1

A=1101110101011101, 56669 / B=0010110100111100, 11580 / Expected=00100111000111010011101011001100,  656227020
Result=00100111000111010011101011001100,  656227020 / carry=0 || Expected Result=00100111000111010011101011001100,  656227020 || Status =          1

A=0101110110001010, 23946 / B=1010101100101111, 43823 / Expected=00111110100011000101101001010110, 1049385558
Result=00111110100011000101101001010110, 1049385558 / carry=0 || Expected Result=00111110100011000101101001010110, 1049385558 || Status =          1

A=0100101110000000, 19328 / B=0111111111101111, 32751 / Expected=00100101101110101111110010000000,  633011328
Result=00100101101110101111110010000000,  633011328 / carry=0 || Expected Result=00100101101110101111110010000000,  633011328 || Status =          1

A=0111101010111000, 31416 / B=1110100101100100, 59748 / Expected=01101111111000010110011111100000, 1877043168
Result=01101111111000010110011111100000, 1877043168 / carry=0 || Expected Result=01101111111000010110011111100000, 1877043168 || Status =          1

A=1100010110101110, 50606 / B=0010010000111000,  9272 / Expected=00011011111101111101101000010000,  469218832
```

8. Circuit Analysis Summary

As seen in the circuit, 379 LUTs are used. It is seen that the I/O value is too high. In the partial product process, we saw that due to the version we use, Vivado does not allow the codes made in the experiments and we cannot use it in the top module. As a solution to this, we tried to find a solution by defining these values separately as output.



As seen below, the total chip on power value is 39,625W. The individual power consumptions are indicated on the right. Most of the power consumption is due to the high I/O rating. Although signal and logic consume approximately 20% power, I/O value accounts for most of the power consumption with 69% value.



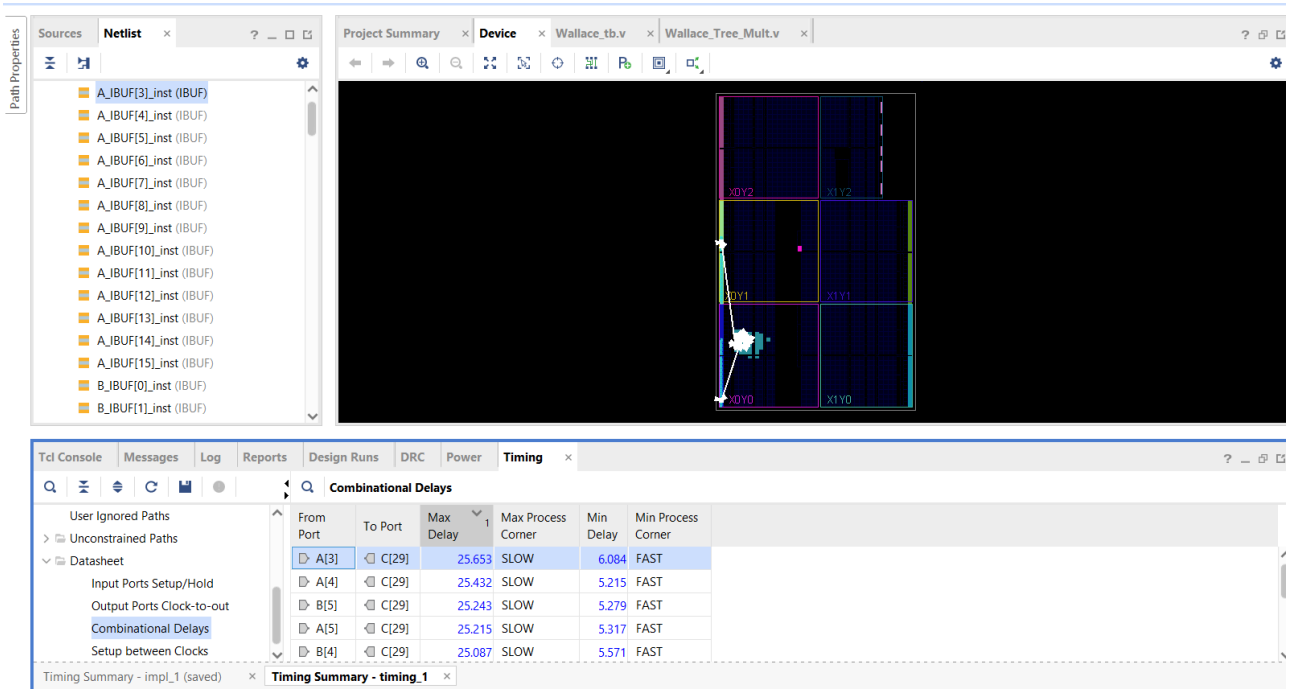
We have listed the combinational delays data values after the implementation of the circuit. After sorting the delay values from the largest to the smallest, we saw that our maximum delay value is 26.563ns. If we convert this to frequency with the formula f=1/T, we can see that the maximum clock frequency is 37.646 Mhz. This value means that we cannot go above this value while we are simulating and tells us that we should simulate accordingly.

Combinational Delays

From Port	To Port	Max Delay	Max Process Corner	Min Delay	Min Process Corner
A[3]	C[29]	25.653	SLOW	6.084	FAST
A[4]	C[29]	25.432	SLOW	5.215	FAST
B[5]	C[29]	25.243	SLOW	5.279	FAST
A[5]	C[29]	25.215	SLOW	5.317	FAST
B[4]	C[29]	25.087	SLOW	5.571	FAST
A[3]	C[28]	24.842	SLOW	5.711	FAST
A[0]	C[29]	24.702	SLOW	7.049	FAST
A[2]	C[29]	24.661	SLOW	6.085	FAST
A[4]	C[28]	24.621	SLOW	4.843	FAST
A[1]	C[29]	24.523	SLOW	6.421	FAST
B[5]	C[28]	24.432	SLOW	4.906	FAST
A[5]	C[28]	24.404	SLOW	4.944	FAST
A[9]	C[29]	24.335	SLOW	4.677	FAST
B[4]	C[28]	24.276	SLOW	5.198	FAST
A[6]	C[29]	24.104	SLOW	4.875	FAST
B[1...	C[29]	24.004	SLOW	4.567	FAST
B[8]	C[29]	23.921	SLOW	4.793	FAST
B[1]	C[29]	23.905	SLOW	6.121	FAST
A[0]	C[28]	23.891	SLOW	6.676	FAST
A[2]	C[28]	23.850	SLOW	5.712	FAST
A[1...	C[29]	23.749	SLOW	4.335	FAST
A[3]	C[30]	23.734	SLOW	5.219	FAST

9. Critical Path

The critical path is the path between A[3] and C[29] with the longest delay value. As seen in the photo above, the max delay is 25.563ns. The critical path is specified in the device below.



10.References

B. Parhami, Computer arithmetic - algorithms and hardware designs, Oxford University Press, (2010)

11.Work Package

NAME SURNAME	Assignment Research	Verilog Code	Python Code	Report	Vivado Outputs
Yiğit Bektaş GÜRSOY	X	Wallace_Tree.v CSA.v PP.v Wallace_tb.v	Random_number.py	X	X
Muhammed Velihan BAĞCI	X	Wallace_Tree.v CSA.v CLA.v Wallace_tb.v		X	