A MATHEMATICAL MODELLING APPROACH FOR DLED TV PANEL DESIGN

A Thesis

by

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A MATHEMATICAL MODELLING APPROACH FOR DLED TV PANEL DESIGN

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To my family who teaches to overcome all difficulties and to my wife for her strong support…

ABSTRACT

The aim of this study is to increase the luminance performance of direct light emitting diodes (DLED) televisions through case design improvement. We first gather luminance measurements of several regions of active area displays for different DLED models, along with mechanical parameters such as distance to active area from a point of cross section view, lens orientation and a specifically calculated ratio parameter related to the layout. For each area, feature selection and multiple linear regression model selection steps are executed to decide on the most suitable model describing the relationship between parameters and the quantity of interest, luminance of the area under investigation. We then embed the regression equations into optimization models, that aim to find the design maximizing the attained luminance level subject to several design specific constraints. Finally, luminance performance of the design found by the optimization model is compared to that of the previous designs used by the company. The results indicate that design found using the methodology described in this paper is superior to previously used designs, in terms of luminance performance

Keywords: direct led, mechanical design, luminance maximization, uniformity, mathematical model, optic

ÖZETÇE

Bu çalışmanın amacı tasarım iyileştirmeleriyle doğrudan aydınlatmalı televizyonların aydınlatma değerlerini arttırmaktır. İlk olarak, doğrudan aydınlatmalı televizyon modellerinden aktif alanın birkaç bölgesinden aydınlatma değerleri, kesit resimden aktif alana uzaklık gibi mekanik parametreler, lens yerleşimi ve özel olarak hesaplanan lenslerin bölgelerdeki sayısının toplama olan oranı gibi değerler toplandı. Aydınlatma, kalite ve parametreler arası ilişkilere karar verebilmek için her bölgenin özellik seçimleri ve çoklu regresyon adımları uygulandı. Daha sonra regresyon denklemlerini optimizasyon modellerinin içine gömdük. Bunun amacı özel tasarım parametrelerine göre aydınlatma değerlerinin tasarım maksimizasyonunu bulmaktır. Sonucunda elde edilen tasarımı bulunmuş aydınlatma performansları daha önce şirket tarafından üretilen tasarımlarla karşılaştırılır. Sonuç şunu göstermektedir ki, bu yöntem kullanılarak elde edilen tasarım mevcut durumda kullanılanlardan aydınlatma performansı açısından daha iyidir.

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1. INTRODUCTION AND LITERATURE REVIEW

Modern television (TV) systems are empowered by new technologies resulted in advanced features such as HDR, 3D, wireless, etc. LED TVs are more popular than ever, replacing old-fashioned cathode tube TVs. Among many others, illumination level in LED panels is one of the critical attributes and considerably affects the demand for the TV on the market. Because of its effect on sales figures, illumination level of newly designed panels needs to be carefully determined, if possible, using optimization tools that simultaneously consider as many design related issue as possible.

Anandan provides a nice review of basics of LEDs as light sources and their limitations, along with various backlight structures employing LEDs (1). Illumination source of LED TV systems are special and consist of several components such as films with different features and opto-electronic materials form back light unit (2) (3). Light source placement in the back light unit of LED TVs results in edge-type and direct-type systems (4). Edge-type uses light array stationed at the horizontal and/or vertical side of the TV. Additionally, the edge type TVs involve at most two light arrays. At direct-type systems, LED arrays are installed at the rear side of LED unit. The geometry of the panel is basically determined by the light array has comparably slimmer designs that bear more complex and tight organization of back light unit components (5). In addition to the light array, a light guide is required in order to attain a uniform illumination along the display unit.

Design of a TV panel includes mainly includes two main sets of parameters: mechanical parameters and optical parameters. As a matter of course, these parameters cannot be considered in an isolated manner. Relationships of mechanical and optical parameters should also be taken into consideration at the design phase (6) (7). For instance, as direct-type back light array is thicker, TVs using this technology also is thicker than edge-type backlight TVs (8). The LEDs in a direct-type back light unit is also different than edge-type. Moreover, direct-type spreads LEDs with light shaping lenses having wide-spread angles and because of this spreading light into wider areas, more uniform light distribution is achieved (9). All of these designs related aspects need to be carefully taken into consideration while designing LED TV panels.

In this study we first collect data for four main different types DLED TVs. Each main type has different TV models and in total, we consider twenty-three different TV models. For each TV model, twenty-two mechanical and thirteen optical design parameters are taken into consideration. For each design, actual luminance values are attained through lab measurements. Using all mechanical and optical features as regressors and luminance values as response variables, we conduct a selective all subset regression analysis in order to find significant models that best describes the luminance level. These models are then embedded into an optimization model, in which luminance is tried to be maximized subject to several design constraints.

The organization of the thesis study is as follows: In Section 2 we discuss the details of the DLED TV design; Section 3 provides the details of regression and mathematical modelling approaches; Section 4 discusses the results of the numerical analysis; and Section 5 lists the concluding remarks and possible future research directions.

2. DLED TV CONCEPT

DLED panels consist of the following mechanical and optical components: back cover metal (BC BLU), plastic middle frame, front cover (Plastic/Metal optionally), reflector sheet, diffuser plate, optical films (Diffuser & Prism Sheets), Led bars & lenses, and open cell (LCD). A representative layer composition of DLED panel is provided in Figure 1.

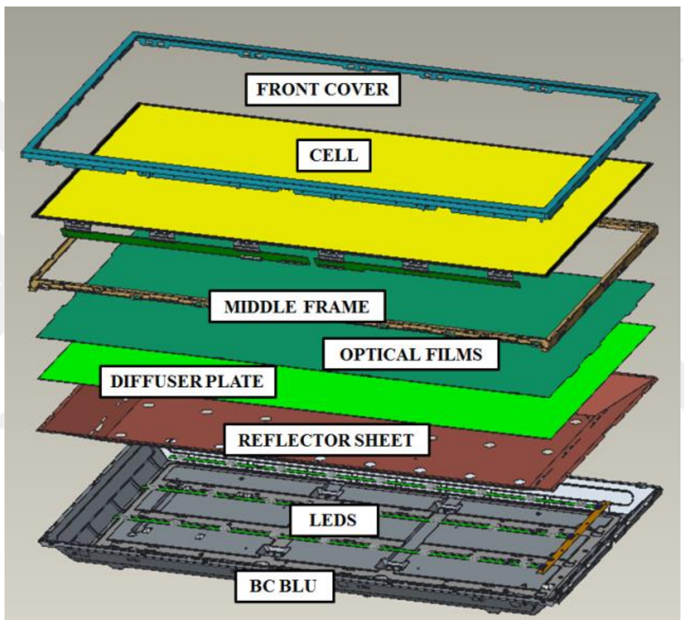


Figure 1 - Layers of DLED panel

DLED TVs have the concept that all led packages are placed as an orientation behind the screen. So, light illuminates directly to the LCD display which the end user watches from the entire back of panel itself. Almost all of the DLED LCDs share this structure. There is no need to process to dim LEDs one by one. By using this technique, attained uniformity becomes much better than edge lit led televisions. Local contrast ratios are also better for DLED backlight systems. Moreover, thickness of DLED backlights are more than the ELED models because they need an optical distance for lighting the screen from back of

LCD. That is why less LEDs are used for this type of backlights covering enough light across the screen. It gives an advantage to spread light with an angle of light gathered by LEDs itself. LED types are also effective on this angular illumination. Furthermore, it is easier to cool the systems in DLED backlights. In addition, DLED backlight models are a bit cheaper than ELED ones because they do not need a light guide plate for directional purpose of light. Mostly manufacturers prefer DLED backlights to reduce production cost. In conventional case, there are also CCFL type backlights but even D-LED structures have an advantage of clarity, brightness, and energy efficiency.

Optic performance of TVs is highly influenced by attained luminance level. Luminance is a photometric measure of the luminous intensity per unit area of light travelling in a given direction. It describes the amount of light that passes through, is emitted or reflected from a particular area, and falls within a given solid angle. The SI unit for luminance is candela per square meter (cd/m^2) (10). Simply, brightness of displays which the power that end user looks from a certain angle is a definition of luminance in the video industry. Target performance is specified by a calculation of uniformity which is described as the ratio of the lowest & highest luminance values. Uniformity is measured on spots which are gathered by dividing panel 4x4 on every edge as shown in Figure 7 in Section 3.2. Current LCD technology has common uniformity problems thoroughly screen results in random figures on medical images. Random figure problems are called mura or noise, like uniformity problem of backlight. The reason for this is typical brightness reduction through display’s corners. Moreover, man-made cells cause non-uniform and continual differences between pixels resulting in variation of brightness and color. Positional voice and cloudy visual problems are occurring as a common result of those malfunctions.

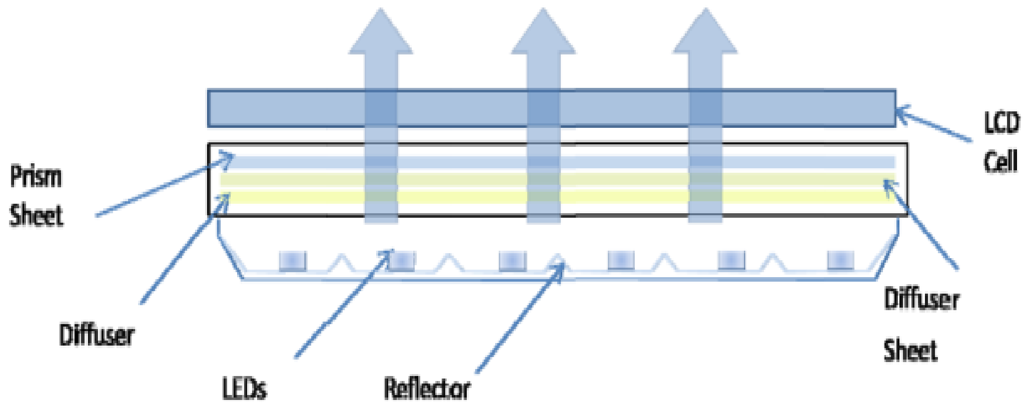


Figure 2 - DLED TV Representation (11)

Optic performance of TV is influenced by gathered luminance.

2.1. OPTICAL COMPONENTS

2.1.1. LIQUID CRYSTAL DISPLAY

Laptops, tablets, televisions and other smaller electronic appliances use displays as called liquid crystal display (LCD). LCD consists of both solid and liquid substance and is produced for all size and shape.

Backlight initiates display for LCD which manages how much light is released behind the screen. In this way it is energy efficient technology compared to other conventional display types like LED and CRT (cathode ray tube). Polarizer is used for both under and top LCD layer and light is controlled of passing through it. By using this type of structure LCD open cell behaves such as stopper on each pixel on the display unit.

Thin film transistor which is beneath and the corner of each pixel orchestrates display by issuing as an active matrix. RGB (red, green, blue) dots in front of the screen are spared in a color filter. And as a matter of fact, there is a white backlight at back so this gives an advantage of gathering full range of colors.

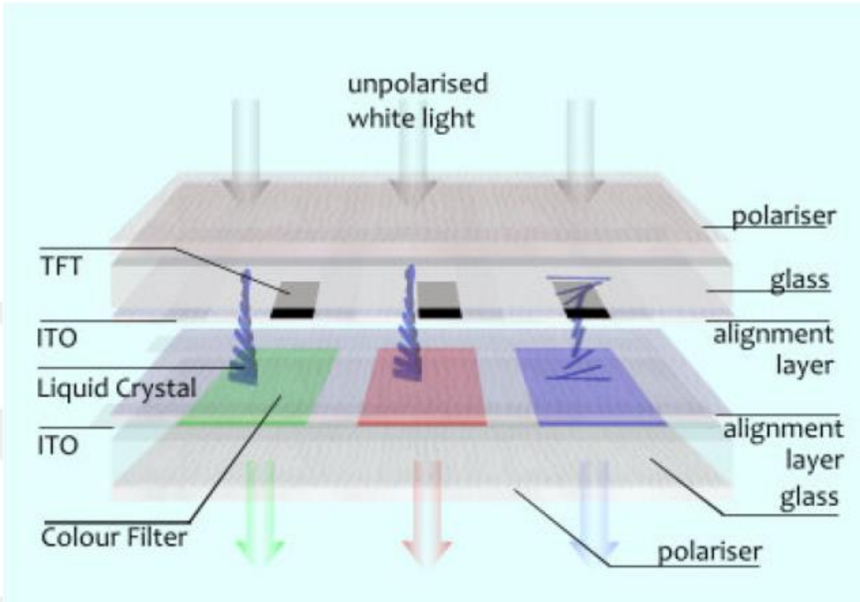


Figure 3 - LCD Structure (11)

2.1.2. LIGHT EMITTING DIODE

Light emitting diode (LED) is basically a semiconducter device that emits light when an electric current is passed through it. Particles inside the semiconducter are loaded with current and make the light occur.

LEDs are called as solid-state devices because light is produced in semiconducter material which is mentioned. In this way, it differs from the resources using heated filaments (photons).

Current is stored within energy bands within the light emitting diodes and decide how much energy is absorbed by them.

Color and wavelength are specified by photon energy. It differs according to semiconducter material such as InGaN, AlGaInP, AlGaAs, GaP.

LEDs have advantage with respect to necessary power, high efficiency, long life, etc.

2.1.3. REFLECTOR SHEET

Reflector sheet is located behind the BLU at the bottom of other films. Purpose of reflector sheet is to provide making the light reflected on the active way. Its critical features are reflecting ratio and variance that the surface affects color.

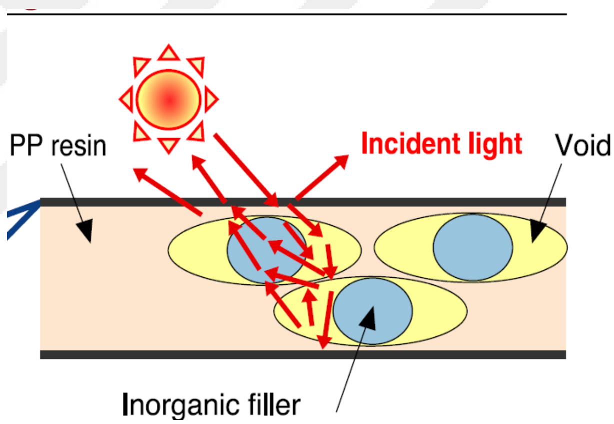


Figure - 4 Reflector Mechanics (12)

2.1.4. DIFFUSER PLATE

Diffuser plate having strong structure ensures that the other films flat. It hides the light source with its high utility of light distribution. Diffuser plate is at the bottom of other more sensitive films accordingly in order to protect them from the high temperature.

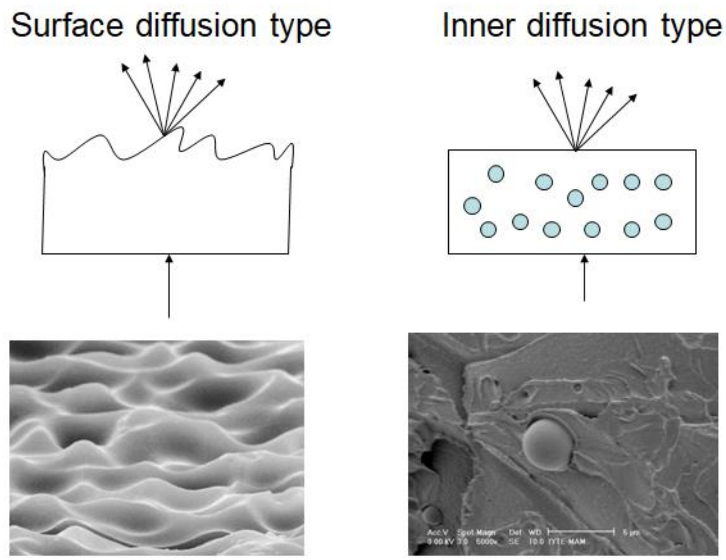


Figure 5 - Diffuser Plate Types (12)

2.1.5. OPTICAL FILMS

Other optical films are diffuser sheets and prism sheets in our current technology.

Diffuser sheet (DS) distributes the light coming from leds. Its transmittance value is directly effective on center luminance. Its haze value has an important role while hiding the errors that are luminance disorder. There is an also upper diffuser sheet (UDS) which provides the same cover-up for those faults. Upper diffuser transparency is higher but, its hiding characteristic is lower than DS. It gives advantage in the situations when the more luminance values are desired.

Prism sheet (PS) is used for brightness enhancement. The reason is explained by directing the light to the end user with its prismatic structure. These films can be found in both vertical and horizontal orientation. Two prisms that are constructed by laminating with different orientation with same thickness and optical performance are called as Prism-on-prism (POP).

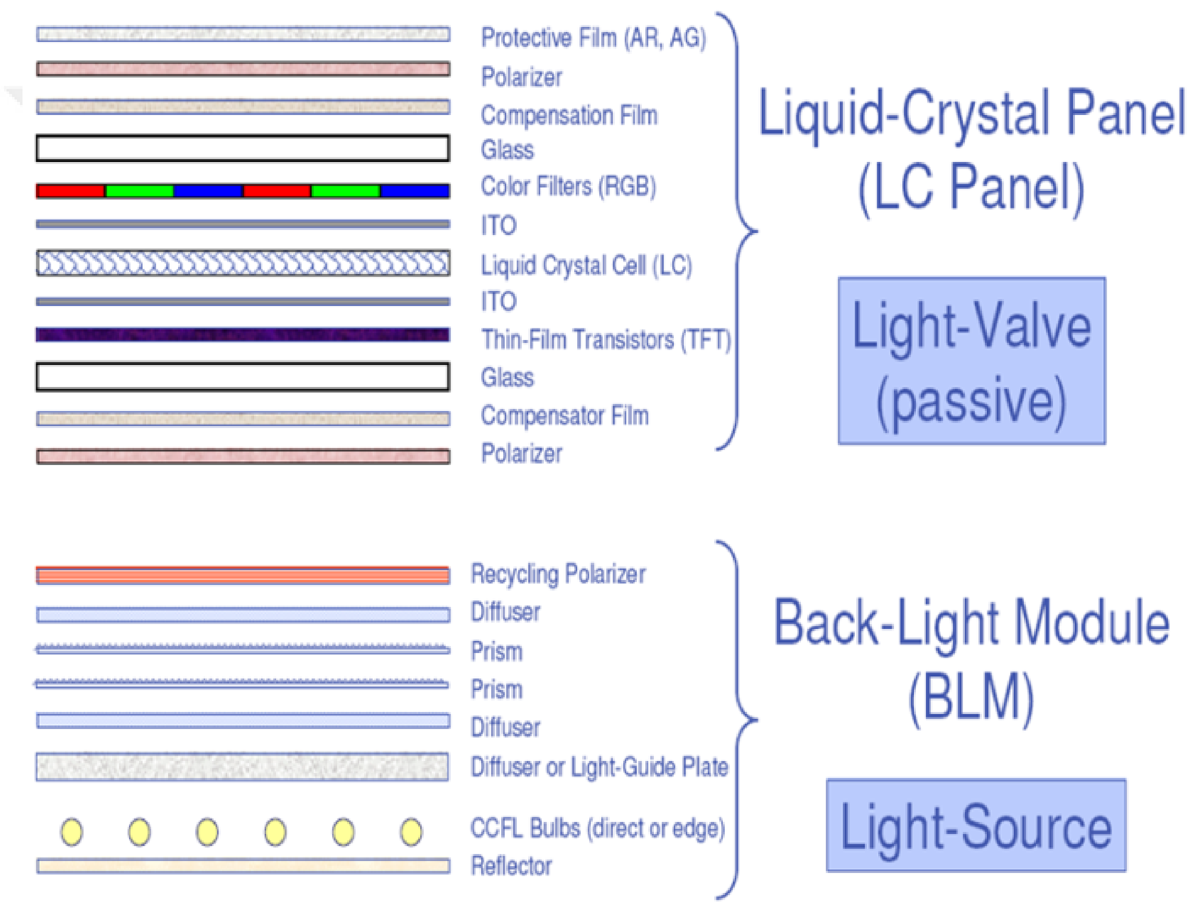


Figure 6 - Backlight Module System (13)

2.2. MECHANICAL PARTS

2.2.1. BACK COVER BACKLIGHT UNIT

Back cover backlight unit (BC BLU) is a mother part of a panel of television. It is made of a metal. As explained in the previous sections, led bars are mounted behind the screen. So, BC BLU provides assembling led bars on it. Depth of metal is an important issue because optical films are put on the BC BLU and the distance from lenses to these films specifies optical distance of that panel. Another function of BC BLU metal is to keep all mechanical and optical components together such as housing strongly rigid for them.

2.2.2. MIDDLE FRAME

Middle frame is a plastic part which is mostly made of PC ABS/GF %15. It covers the optical components, remained like sandwich, inside and mounted to BC BLU. LCD (Cell) the most important and expensive part of the panel is put on the middle frame. Accurate distance can be gathered between optics and cell by means of critical location of middle frame. Physical forces must be avoided in order to protect these optical films and cell that is why middle frame is plastic.

2.2.3. FRONT COVER

Front cover is a cosmetic part which is seen by end user. It can be made of plastic or metal and is assembled to BC BLU or middle frame. Material affects both the physical appearance and the strength of television. As it can be seen from its name, the main mission of this part is to cover the whole panel and hold the cell steady.

3. METHODOLOGY

3.1. REGRESSION ANALYSIS

In this section, details of the conducted regression analysis are provided. The response variable of the analysis selected as the luminance level at different areas of the panel (see Fig. 7). The analysis is restricted to models, which consider twenty-two mechanical and thirteen optical design parameters. As the first step a correlation analysis is conducted and correlated variables are removed (in total eight variables) from the data set. Then, a selective subset regression analysis is conducted to search for the first order models that best describe the relationship between regressors and luminance levels.

The regression analysis is executed for subsets of set *S*, where *S* contains all regressors remained after correlation analysis. Pseudo code of the algorithm used in the analysis is presented below:

input: Set of selected regressors and their interactions, *S*

input: experiment results data matrix, *D*

for *s = 1 ... |S|* **do**

Populate list *K*, that contains all subsets of *S* that has size *s*.

for *k=1 ... |K|* **do**

1. Set *Dk* as the columns of *D*, such that *Dk* contains the regressors in subset *k*.

2. Split the rows of *Dk* into two: *D_traink* and *D_testk.*

3. Fit the linear regression line for *D_traink.*

4. Predict the response variable in *D_testk* using the fitted regression model

5. Record key metrics (list of metrics provided below)

end for

end for

Several metrics, R2, R2-adjusted, AIC, f-statistic, p-values, VIF values, testMAPE, (definitions provided below) are considered to select the best performing model.

- R^2 is a statistical measure of the percentage of variation present in the data explained by the fitted model. It is also known as the coefficient of determination.
- R^2*-adjusted* is a modified version of R^2, where the coefficient of determination is penalized with increasing number of predictors used in the model. R^2*-adjusted* increases with the increasing number of predictors only if the new terms improve the model more than would be expected by chance.
- *AIC* (Akaike information criterion) is an estimator of the relative quality of statistical models for a given set of data. Given a collection of models for the data, AIC estimates the quality of each model, relative to each of the other models.
- *f-statistic* in the context of our analysis refers to the f-statistic value of the analysis of variance (ANOVA) table, that is the f-statistics value of the null hypothesis whether the regression model is significant or not. In other words, the test shows whether the

ratio of the mean variation explained by the model to mean variation not explained by the model is large enough.

- *p-values* show whether the regression coefficients are statistically significant or not
- *VIF* (variance inflation factors) measure how much the variance of the estimated regression coefficients are inflated as compared to when the predictor variables are not linearly related. In other words, it is a measure of multi-colinearity, that is linear dependency among regressors (i.e., used to detect whether there exists correlated regressors).
- *testMAPE measure is used to indicate mean absolute percentage deviation of predicted values with respect to actual values in the holdout (test) data set.*

The best model is the one with high R2-adjusted value, a small AIC value, with all p-values for regressors are significant (i.e., with value smaller than 0.05); VIF values smaller than a threshold (we use ten for VIF threshold) and with minimum possible *testMAPE*. When all metrics are considered, selecting the best model can also be seen as a multi-criteria optimization problem, where some of these metrics conflict with others. In this study, we use a simple rule based prioritization by using metrics in the following order: *R^2-adjusted, AIC, p-values, f-statistic, VIF values, testMAPE* and select the model by inspection.

The models found after the regression analysis are given as follows:

$$LU1 = 3241.29 + 451.09\, ma1y - 5.8\, bq1 - 88.64\, r1 - 17.09\, lensangle$$

$$+ 5414379.04\, lpa\,, \qquad (1)$$

$$LU2 = 4845.39 + 351.66\, ma1y - 9.51\, rq1 - 74.02\, b2 - 9.29\, od$$

$$+17.63\, lensangle\,, \qquad (2)$$

$$LU3 = 3721.37 + 64.42\, k1y - 18.96\, ra2y - 73.33\, k2y - 21.11\, lensangle$$

$$+ 2505152.35\, lpa\,, \qquad (3)$$

$$LU4 = 1368.95 + 82.16\, k1y - 6.24\, rq1 - 81.81\, k2y - 37.74\, b2\,, \qquad (4)$$

$$LU5 = 1200.3 + 101.8\, k1y - 95.99\, k2y - 4.88\, rq2 - 52.76\, b2\,, \qquad (5)$$

$$LU6 = 1016.9 - 40.7\, fa1y - 3.29\, bq1 + 55.26\, b1 - 94.79\, r1\,, \qquad (6)$$

$$LU7 = 3536.63 + 70.22\, k1y - 19.7\, ra2y - 76.49\, k2y - 19.91\, lensangle$$

$$+2358770.57\, lpa\,, \qquad (7)$$

$$LU8 = 4105.87 + 322.26\, ma1y - 10.36\, rq1 - 74.89\, b2 - 7.97\, od$$

$$-12.44\, lensangle\,, \qquad (8)$$

$$LU9 = 3554.93 + 63.65\, k1y - 23.93\, ra2y - 72.11\, k2y - 19.8\, lensangle$$

$$+2239648.33\, lpa\,, \qquad (9)$$

In Section 3.2, mathematical model used to maximize the above equations, i.e. luminance, subject to physical design constraints is provided in details.

3.2. MATHEMATICAL MODEL

The optic performance of a TV comprises of luminance and uniformity those are measured inside the *active area* (AA), i.e.

In this sub-section, we propose the *luminance maximization problem* (LMP) that maximizes the luminance at 9 different regions (or nodes) of the flat TV screen. A representative sketch is provided in Figure 7.

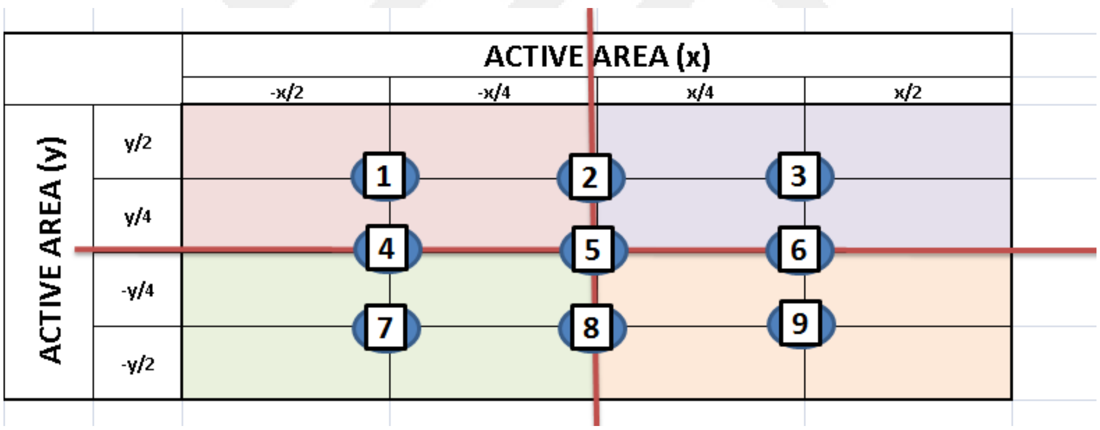


Figure 7 - Uniformity

Structural decision variables (Appendix 7.1) that affect the luminance at different nodes of the TV screen via the *mechanical design* of the TV panel are given as follows:

maiy: distance from middle frame to AA

faiy: distance from optic films to AA line

paiy: distance from diffuser film to AA

raiy: distance from reflector see to AA line

kiy: distance from front cover to AA

bqi: angle of edges of BC BLU

rqi: angle of edges of reflector sheet

bi: distance from folded edge of **BC BLU** to AA

ri: distance from folded edge of reflector sheet to AA,

where $i \in \{1,2,3,4\}$ denotes the index of the edges on the TV screen, namely, bottom, top, right, and left edges; respectively. E.g., "pa1y" denotes the distance of the diffuser film from AA at the bottom edge of the screen.

Optical design variables are given as follows:

od: the depth of the panel

lensangle: the angle of the scattered light

lpa: the ratio of total lenses per mm^2

The section view of AA and associated panel design variables are presented in Figure 8.

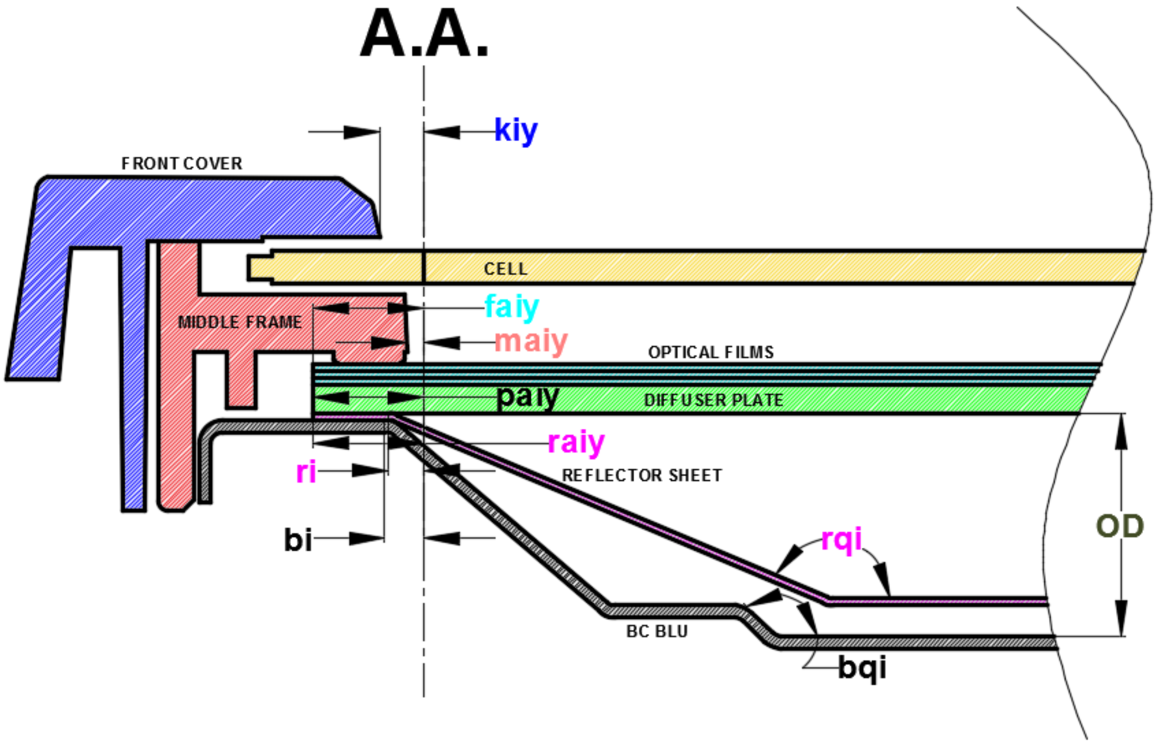


Figure - 8 Section view of TV panel.

Considering Figure 7, it should be noted that luminance at node 5 is the highest among all, because the middle area gathers the light directly to itself. Therefore, in the numerical analysis, we concentrate on the luminance level at node 5.

The mathematical optimization model of LMP for node 5 is given as follows:

LMP:

Maximize $1200.3 + 101.8\, k1y - 95.99\, k2y - 4.88\, rq2 - 52.76\, b2,$

subject to

$0.75\, LU5 \leq LU1,$ (10)

$$0.75\ LU5 \leq LU2, \tag{11}$$

$$0.75\ LU5 \leq LU3, \tag{12}$$

$$0.75\ LU5 \leq LU4, \tag{13}$$

$$0.75\ LU5 \leq LU6, \tag{14}$$

$$0.75\ LU5 \leq LU7, \tag{15}$$

$$0.75\ LU5 \leq LU8, \tag{16}$$

$$0.75\ LU5 \leq LU9, \tag{17}$$

$$0.80 \leq k1y \leq 3.70, \tag{18}$$

$$0.80 \leq k2y \leq 4.20, \tag{19}$$

$$144.40 \leq rq1 \leq 169.50, \tag{20}$$

$$144.40 \leq rq2 \leq 169.50, \tag{21}$$

$$-0.70 \leq b1 \leq 3.20, \tag{22}$$

$$-0.80 \leq b2 \leq 3.05, \tag{23}$$

$$0.30 \leq ma1y \leq 0.80, \tag{24}$$

$$105.00 \leq bq1 \leq 150.00, \tag{25}$$

$$-1.20 \leq r1 \leq 1.80, \tag{26}$$

$$3.70 \leq ra2y \leq 8.70, \tag{27}$$

$$4.00 \leq fa1y \leq 7.40, \quad (28)$$

$$160 \leq lensangle \leq 172, \quad (29)$$

$$0.00005 \leq lpa \leq 0.00009, \quad (30)$$

$$20 \leq od \leq 50, \quad (31)$$

$$bq - rq1 \leq 0, \quad (32)$$

$$ma1y - k1y \leq 0, \quad (33)$$

$$ma1y - fa1y \leq 0, \quad (34)$$

$$ma1y - ra1y \leq 0, \quad (35)$$

$$fa1y - ra1y \leq 0, \quad (36)$$

The objective of the problem is to maximize the luminance at the center (LU5) of the screen that coincides with node five. Notice that the luminance performance of the center of a TV screen is one of the most important indicators of a high quality optical performance. Nevertheless, if one only focuses on improving the luminance at node five, the resulting design may yield low performance at other nodes of the screen. To keep the uniformity of the luminance, constraints (10) through (17) ensure that the luminance measurements at other nodes must be at least 75% of the luminance at node five. Upper and lower bounds of the optical and mechanical decision variables of the TV panel are given at constraints (18) through (31). Finally, constraint from (32) to (36) ensure that certain physical requirements are met; also see Figure 8

4. NUMERICAL ANALYSIS

4.1. DETERMINISTIC STUDY

Notice that LMP is a linear programming problem that can be efficiently solved by commercial solvers such as CPLEX. We use CPLEX version 12.6.1 in this study.

The optimal design setting LMP is provided in Table 1, where first column provides the name of the parameters decided by the R&D engineers and the second column presents the optimal design values.

Table 1 - Optimal design setting of LMP for deterministic study

Parameter	Value
b1	3.2
b2	0
bq1	105
bq2	120
fa1y	4
fa2y	3.7
k1y	3.7
k2y	0.8
lensangle	160
lpa	0.00010405
ma1y	0.30037
od	15
pa1y	7.4
pa2y	2.4

r1	0
ra1y	7.7
ra2y	37
rq1	144.4
rq2	144.4

The luminance (LU) estimations of the nine nodes with respect to the "optimal" TV design settings that are presented in Table 1 are given below in Table 2.

Table 2 - Luminance estimations for the nine nodes for deterministic study

Lıminance	Value
LU1	596.733
LU2	617.623
LU3	713.961
LU4	706.438
LU5	795.644
LU6	685.482
LU7	722.184
LU8	596.733
LU9	709.234

It may be easy to see that the associated design performs significantly better than the current physical designs that are manufactured by the company (compare the numerical results in Table 2 with that of the Appendix 7.2). Nevertheless, it requires further physical prototype and tests before it used in mass-production.

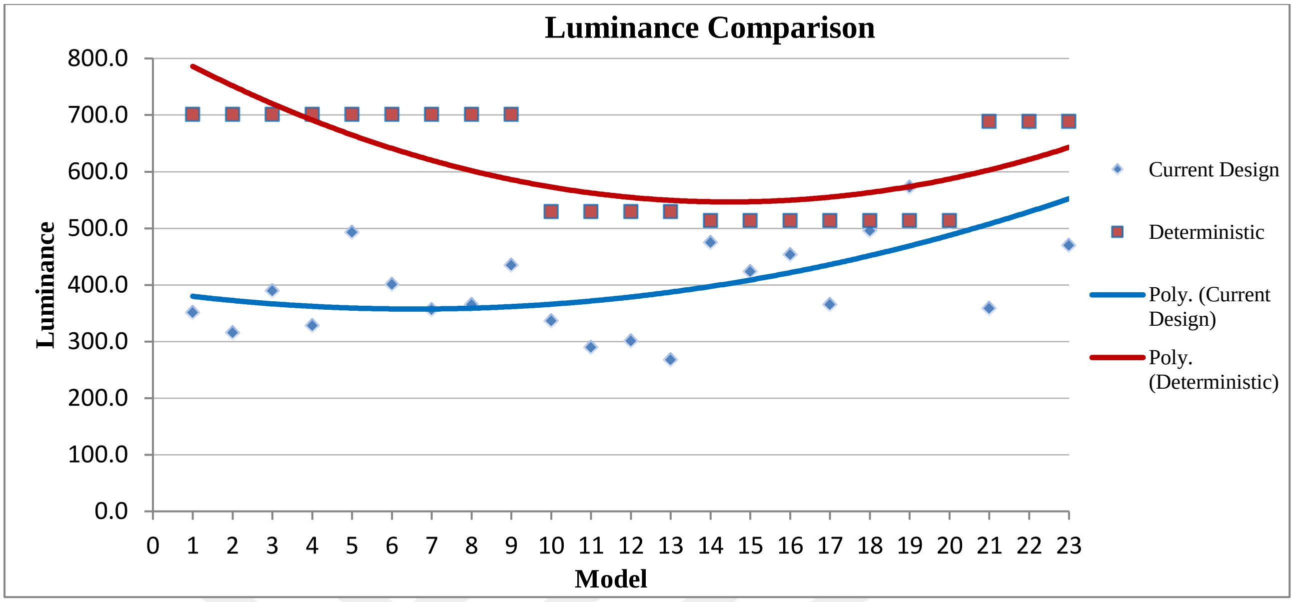
Next, we focus on the four TV families that are currently manufactured by the company. While some variables of a TV panel can be optimized, certain variables are design specific and they are fixed to certain values in a given family. Appendix 7.3 shows the family specific decision variables. In the second experiment, we fix these variables to their family specific values and optimize the remaining variables; notice that this can be easily done by adding additional constraints to LMP. Consequently, we run the mathematical model for all twenty-three TV models and record the resulting luminance levels for all nine nodes. To compare the performance of our approach to the previous designs' performance a set paired of paired t-test is executed. It is found that, for eight nodes (except node 2), the luminance values obtained from the mathematical model is statistically better at a significant level of 0.05. As mentioned earlier, our main focus is on node 5. Therefore, we present the luminance results attained for node 5 in all twenty-three TV models in Table 3, where column titled "previous design" shows the luminance values attained for the company's previous design, column "our design" lists the corresponding luminance values for the optimal design found by the mathematical model. The "difference" column shows the difference between two luminance vectors, indicating a huge difference in favor of the optimal designs (with a single exception, model 19).

Table - 3 Performance comparison for luminance of node 5 for deterministic study

Model ID	**Previous Design**	**Our Design**	**Difference**
1	351.1	701.2	350.1
2	315.4	701.2	385.8
3	389.8	701.2	311.5
4	327.8	701.2	373.4

5	493.0	701.2	208.3
6	401.2	701.2	300.1
7	356.5	701.2	344.7
8	365.0	701.2	336.2
9	435.0	701.2	266.2
10	336.4	529.7	193.4
11	289.8	529.7	239.9
12	301.2	529.7	228.5
13	267.8	529.7	261.9
14	474.8	513.7	38.8
15	423.6	513.7	90.1
16	453.2	513.7	60.4
17	365.0	513.7	148.6
18	496.0	513.7	17.7
19	572.5	513.7	-58.9
20	510.5	513.7	3.1
21	358.6	689.2	330.7
22	686.2	689.2	3.0
23	469.8	689.2	219.4
Avg.	**410.5**	**612.7**	

In addition to comparison table, graphical demonstration is also given below. In conclusion, deterministic model is better than the current luminance values. It is an expected result that there is 49% improvement we gathered.



4.2. ROBUST OPTIMIZATION

Optimization for the worst case value of parameters within a set is known as "robust optimization". It is useful for both static and dynamic problems with indefinite information and applicable for wide range of area. Our aim is to find the best design we gather despite the uncertainties in the regression model. So, conventional decision making methods under uncertainty can be improved by robustness.

In real life problems such as this study, light robustness is mostly used for comparing results with the ones from deterministic analysis, and provides solutions with a simple formulation.

In addition, there can be estimation errors in the regression coefficients and this situation leads to suboptimal design decisions which could be ignored in the mathematical optimization.

Moreover, current approach does not give information about how uncertainties affect the problem. So, we have to adapt robust optimization in order to find variances of the constraints which are effective on the objective function. For further details, we refer the reader to Yanıkoğlu (2017) that gives an easy to read robust optimization guideline (14).

The purpose of using robust optimization is that we do not have probabilistic distributional information. That is why this approach is diifered from stochastic modelling.

In luminance optimization case, the uncertainty in the vector of regression coefficients β can be defined as follows;

$$\beta_i'(\xi_i) = \beta_i + \alpha\, \beta_i\, \xi_i \qquad\qquad \forall i \in I,$$

where $\xi_i \in [-1, 1]$ represents the primary uncertainty parameter and $\alpha \in [0, 1]$ represents a scaling parameter (α = 0,04 is used in the numerical experiments). The most famous uncertainty sets are box and ellipsoidal sets. In this study, primary uncertainty parameters are assumed to be in a given box uncertainty set such as;

$$U = \{\xi \in R\ |I| :\ \left||\xi|\right|_\infty \leq\ 1\ \}$$

Adopting the previous notation, uncertain regression model of the luminance is given as follows:

(uRM): $1200.3 + 101.8\, k1y - 95.99\, k2y - 4.88\, rq2 -\ 52.76\, b2$

$-\alpha\ (1200.3\, \xi_0\ + 101.8\ \ \xi_1\, k1y\ +\ 95.99\, \xi_2\, k2y\ \ +\ 4.88\, \xi_3\, rq2\ +\ 52.76\, \xi_4\, tb2\ ),$

where β_0 = 1200.3, β_1 = 101.8, β_2 = 95.99, β_3 = 4.88, β_4 = 52.76 and $\xi \in$ U

Hence, robust construction of LMP (RLMP) becomes as written below;

$$\max_{X} \min_{\xi \in U} \sum_{i \in I} \beta_i'(\xi_i)\, X_i$$

s.t. (10) - (36).

where vector β denotes the regression coefficients, X is the design setting of regression parameters given abovementioned and U denotes box uncertainty set.

Purpose of robust reformulation is to maximize the worst case luminance values. maximin structure creates a complexity in robust optimization case so objective function is minimized inside to gather equation as given;

$$\max_{X} \sum_{i \in I} \beta_i\, X_i - \alpha\, |\beta_i\, X_i| \tag{37}$$

s.t. (10) - (36).

The form of linear constraints in our problem is;

$$|\beta_i\, X_i\,| \leq maximum$$

$$|\beta_i\, X_i\,| \geq minimum$$

where minimum and maximum values are constant. In this study, we have adapted absolute values methodology to our design case. Absolute values method aims a special case for the problems to be converted from nonlinearity. Absolute value functions which are not differentiable, linear are hard to be performed for standard optimization procedures but easy manipulations can be applied to overcome these difficulties by using linear programming.

By looking at given representation, It is "$\beta_i X_i$" if "$\beta_i X_i$"is positive or 0 and it is "$-\beta_i X_i$" if "$\beta_i X_i$" is negative.

The minimum should always be bigger than zero. Then, if "$\beta_i X_i$" is positive, the restriction becomes,

"$\beta_i X_i$" $\geq minimum$

If "$\beta_i X_i$" is negative, the restriction becomes:

$-$"$\beta_i X_i$" $\geq minimum$

However, this restriction discontinues and must be converted into a set of linear equations. Integer variables are a useful method to overcome discontiunity. We used a binary variable B, which can be either 0 or 1;

$\beta_i X_i + M B \geq minimum$

$-\beta_i X_i + M (1 - B) \geq minimum$

where M is a large enough constant. In each case for both constraints are fulfilled. It is important to choose a realistic value of M here. If we can assume how big "$\beta_i X_i$" can be, we can select M according to this. This method is applied to parameters "b1", "b2", "r1" which can get both positive and negative values in our problem.

As an example, for the parameter "b1" the equations are shown below;

$$b1 + 10\, bb1 \geq tb1,$$

$$10 - b1 - 10\, bb1 \geq tb1,$$

$$tb1 + b1 \geq 0,$$

$$tb1 - b1 \geq 0,$$

In this way of procedure, problem can be solved by using CPLEX.

In both LMP and RLMP case, results are the same when "$\alpha = 0$". Then this is what we want to see the results gathered while changing the uncertainty variance "α" in desired percentages.

In order to improve optimization results where luminance values are the maximum but the minimum by the effect of uncertainties, robust case is considered. Then the final robust reformulation is given as;

RLMP:

Maximize $1200.3 + 101.8\, k1y - 95.99\, k2y - 4.88\, rq2 - 52.76\, b2$

$$- \alpha\, (1200.3 + 101.84\, k1y + 95.99\, k2y + 4.88\, rq2 + 52.76\, tb2),$$

$$LU1 = 3241.29 + 451.09\, ma1y - 5.8\, bq1 - 88.64\, r1 - 17.09\, lensangle$$
$$+ 5414379.04\, lpa - \alpha\, (3421.29 + 451.09\, ma1y + 5.8\, bq1 + 88.64\, r1 +$$
$$7.09\, lensangle + 5414379.04\, lpa), \tag{38}$$

$$LU2 = 4845.39 + 351.66\, ma1y - 9.51\, rq1 - 74.02\, b2 - 9.29\, od$$
$$+17.63\, lensangle - \alpha\, (4845.39 + 351.66\, ma1y + 9.51\, rq1 + 74.02\, tb2 +$$
$$9.29\, od + 17.63\, lensangle), \tag{39}$$

$$LU3 = 3721.37 + 64.42\, k1y - 18.96\, ra2y - 73.33\, k2y - 21.11\, lensangle$$

$$+ 2505152.35\, lpa \,-\, \alpha\,(3721.37 \,+ 64.42\, k1y \,+\, 18.96\, ra2y \,+\, 73.33\, k2y \,+$$

$$21.11\, lensangle + 2505152.35\, lpa), \tag{40}$$

$$LU4 = 1368.95 + 82.16\, k1y - 6.24\, rq1 - 81.81\, k2y - \ 37.74\, b2 \,-\, \alpha\,(1368.95 \,+$$

$$82.16\, k1y \,+\, 6.24\, rq1 \,+\, 81.81\, k2y + \ 37.74\, tb2), \tag{41}$$

$$LU6 = 1016.9 - 40.7\, fa1y - 3.29\, bq1 + 55.26\, b1 - 94.79\, r1 \,-\, \alpha\,(1016.9 \,+$$

$$40.7\, fa1y \,+\, 3.29\, bq1 \,+\, 55.26\, b1 \,+\, 94.79\, r1)\,, \tag{42}$$

$$LU7 = 3536.63 + 70.22\, k1y - 19.7\, ra2y - 76.49\, k2y \,- 19.91\, lensangle$$

$$+ 2358770.57\, lpa \,-\, \alpha\,(3536.63 \,+ 70.22\, k1y \,+\, 19.7\, ra2y \,+\, 76.49\, k2y \,+$$

$$19.91\, lensangle), \tag{43}$$

$$LU8 = 4105.87 + 322.26\, ma1y - 10.36\, rq1 - 74.89\, b2 - 7.97\, od$$

$$-12.44\, lensangle \,-\, \alpha\,(4105.87 \,+ 322.26\, ma1y \,+\, 10.36\, rq1 \,+\, 74.89\, b2 \,+$$

$$7.97\, od + 12.44\, lensangle), \tag{44}$$

$$LU9 = 3554.93 + 63.65\, k1y - 23.93\, ra2y - 72.11\, k2y - 19.8\, lensangle$$

$$+2239648.33\, lpa \,-\, \alpha\,(3554.93 \,+ 63.65\, k1y \,+\, 23.93\, ra2y \,+\, 72.11\, k2y \,+$$

$$19.8\, lensangle), \tag{45}$$

Such that (10) - (36)

$ttb1 \geq b1$ (46)

$ttb1 \geq -b1$ (47)

$ttb2 \geq b2$ (48)

$ttb2 \geq -b2$ (49)

$ttr1 \geq r1$ (50)

$ttr1 \geq -r1$ (51)

Constraint (46-51) provides the worst case of maximization and all the other constraints stay the same as in the deterministic model explained before.

Then, robust solution luminance seems to be less than the deterministic one. When we increase α, luminance values is getting worse. Compared to luminance value at node 5 gathered from deterministic model in table 2, the variations of robust model values are given below in table 4;

Table 4 - Optimal design setting of RLMP

α	**LU5**
0.01	772.06
0.02	748.47
0.03	724.89
0.04	643.92

As stated in the table 4, scaling parameter "α" leads to fast decrease in luminance values. While we increase uncertainty percentage, our solution starts to seem to be infeasible. Actually, this situation shows us our data is not highly uncertain. To apply robust optimization, we stopped at 4% uncertainty level. Moreover, in order to overcome infeasible solution we stretched uniformity constraints given from 10 to 17 by getting 60% luminance ratio instead of 75%.

The optimal design setting RLMP according to 4% uncertainty percentage is provided in Table 5, where first column provides the name of the parameters decided by the R&D engineers and the second column presents the optimal design values.

Table 5 - Optimal design setting of RLMP

Parameter	Value
b1	0
b2	0
bq1	105
bq2	120
fa1y	4
fa2y	3.7
k1y	3.2418
k2y	0.8
lensangle	160
lpa	0.00012
ma1y	0.8
od	15
pa1y	7.7
pa2y	2.4
r1	0
ra1y	7.7
ra2y	3.7
rq1	144.4
rq2	146.88

According to robust optimization the luminance (LU) estimations of the nine nodes with respect to the related design settings that are presented in Table 5 are given below in Table 6.

Table 6 - Luminance estimations for the nine nodes for RLMP

Luminance	Value
LU1	604.675
LU2	414.919
LU3	414.919
LU4	564.720
LU5	643.918
LU6	415.000
LU7	432.959
LU8	438.959
LU9	422.029

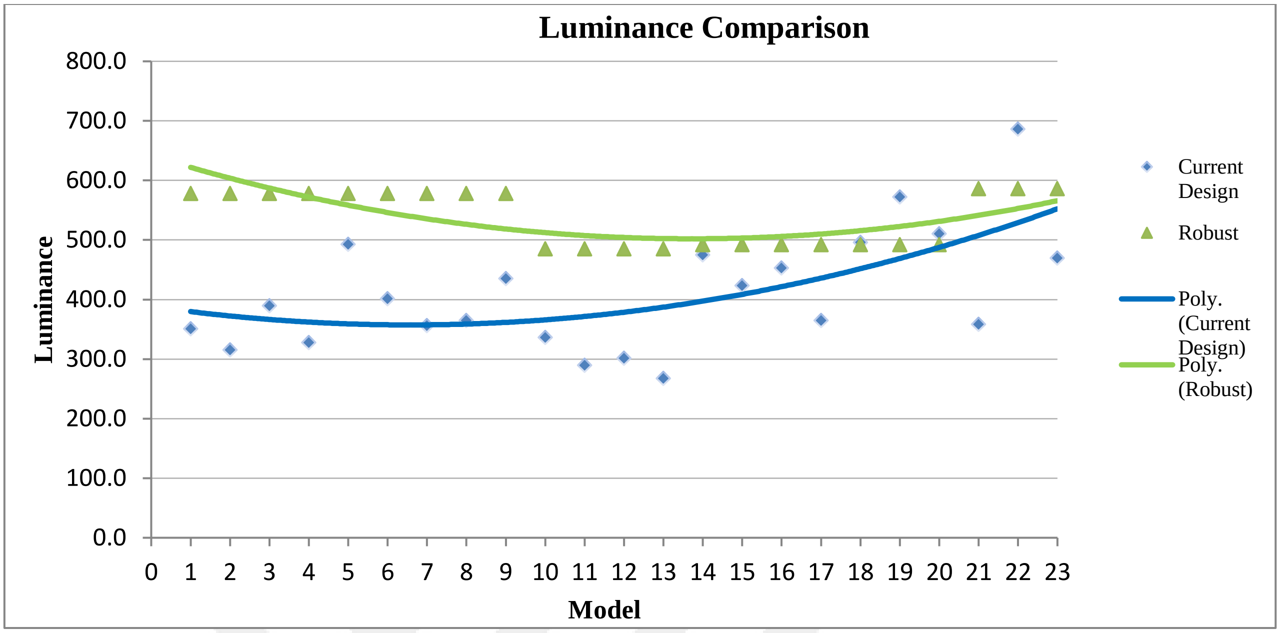
Now we have both deterministic and robust solutions available. In addition to comparison done in deterministic model, here is the table 7 for comparison of all optimization cases and the measured available values of luminance.

Table - 7 Performance comparison for luminance of node 5 for all

Model ID	Previous Design	Robust
1	351.1	578.1
2	315.4	578.1
3	389.8	578.1
4	327.8	578.1

5	493.0	578.1
6	401.2	578.1
7	356.5	578.1
8	365.0	578.1
9	435.0	578.1
10	336.4	485.0
11	289.8	485.0
12	301.2	485.0
13	267.8	485.0
14	474.8	492.2
15	423.6	492.2
16	453.2	492.2
17	365.0	492.2
18	496.0	492.2
19	572.5	492.2
20	510.5	492.2
21	358.6	586.4
22	686.2	586.4
23	469.8	586.4
Avg.	**410.5**	**536.9**

Hence, previous design luminance and corresponding luminance values for optimal design as deterministic and robust found by mathematical model are presented for given television models. With exception of 4 out of 23 models given, still robust outcomes are better than the real life examples.



Graph above shows means of available and calculated luminance. It is as expected robust result is far better than the current design values with 30% in robust model improvement either.

5. CONCLUSION

Mathematical modelling which is both deterministic and robust is an effective method in order to optimize luminance of DLED televisions.

In this study, we obtain valid regression models to estimate the luminance measurements in the nine nodes of the TV screen by adopting a detailed regression analysis. We also propose a mathematical modelling approach to optimize the design features of the DLED TV panel using the associated regression models and the given design constraints. Two numerical experiments are held, the results show that our approach is valid, and it significantly improves the luminance measurements of the designs at hand.

In addition, we considered possible uncertainties that may be caused by implementation errors or data scarcity; we adopted robust optimization paradigm to yield robust reformulations of LMP. This approach provides more accurate and better results for luminance.

In conclusion, the outcomes show that values found for the design optimization model can be used in mass production in the future. It can be helpful for estimating the findings are good design guide to start new project.

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7. APPENDIX

7.1.VARIABLES DATA

Model ID	ma1y	fa1y	pa1y	ra1y	k1y	bq1	rq1	ma2y	f2y	pa2y	ra2y	k2y	bq2	rq2	b1	b2	b3	b4	r1	r2	r3	r4	od	lensangle	lpa
1	0.7	6	6.9	7	3.7	135	144.5	0.7	6	5.5	7	4	125	144.5	3.2	3.1	2.9	2.9	1.4	1.5	1.5	1.5	40	160	0.000080
2	0.7	4	5.3	4.8	1.8	120	154.5	0.7	4.3	3.9	8.7	3	120	154.5	0	1.8	1.7	1.7	1.8	1.4	1.5	1.5	40	160	0.000063
3	0.7	6	7.4	7.4	3.7	120	147.2	0.7	5.5	6.13	6	4	135	147.2	2.5	2	2	2	1.6	1.5	1.2	1.2	40	160	0.000052
4	0.7	4.2	6.4	6.3	1	120	149	0.7	5.7	5.3	5.7	1	135	147.2	1	1.5	1.5	1.5	1.6	1.8	1.8	1.8	40	160	0.000052
5	0.7	6	4.7	6	2.2	105	144.4	0.7	3.7	3.7	3.7	2	135	144.4	1.5	1.5	1.5	1.5	1.3	1.3	1.3	1.3	40	160	0.000056
6	0.7	7.4	6.7	7.4	2.3	120	152.8	0.7	6.5	4.7	6.5	2	135	152.8	1.5	1.5	1.5	1.5	0.5	0.5	0.5	0.5	40	160	0.000048
7	0.7	7.4	6.7	7.4	2.3	120	151.2	0.7	6.4	4.6	6.4	2	135	151.2	1.6	1.5	1.5	1.5	0.5	0.5	0.5	0.5	40	160	0.000046
8	0.7	7.2	6.5	7.2	1.8	120	154.1	0.7	6.6	4.8	6.6	2	135	154.1	1.7	1.8	1.8	1.8	0.5	0.5	0.5	0.5	40	160	0.000044
9	0.8	7.1	7.1	7.7	1.8	120	149	0.8	6.6	5.1	6.6	2	120	149	2	2	2	2	0.5	0.5	0.5	0.5	40	160	0.000051
10	0.7	5.1	5.1	5.1	3.3	150	163.1	0.7	4.6	4.6	4.6	4	150	163.1	1.5	1.5	1.5	1.5	1.2	1.2	1.2	1.2	15	172	0.000113
11	0.7	6	4.7	6	2.6	150	169.5	0.7	3.7	3.7	3.7	3	150	169.5	0.9	0.9	0.9	0.9	1	1	1	1	15	172	0.000100
12	0.7	6.6	5.1	6.6	3.5	150	161.5	0.7	4.3	4.3	4.3	4	150	161.5	1.5	1.5	1.5	1.5	1.2	1.2	1.2	1.2	15	172	0.000109
13	0.8	6.6	5.6	6.2	3	155	161.5	0.8	4.7	4.7	5.2	4	150	161.5	1.5	1.5	1.5	1.5	1.3	1.2	1.2	1.2	15	172	0.000102
14	0.3	6.8	5.3	6.8	3.6	120	147.2	0.3	4.8	3.35	4.8	4	120	147.2	-0.5	-0.5	-0.5	-0.5	-1	-1	-1	-1	40	160	0.000061
15	0.3	6.1	4.4	6.1	2.6	120	144.4	0.3	3.8	2.4	3.8	3	120	144.4	-0.5	-0.5	-0.5	-0.5	-1	-1	-1	-1	40	160	0.000068
16	0.3	5.7	4.2	5.9	2.2	120	151.2	0.3	4.1	2.7	4.1	3	120	151.2	-0.7	-0.7	-0.7	-0.7	-1	-1.2	-1.2	-1.2	40	160	0.000065
17	0.3	6.9	5.4	6.9	1.7	120	151.2	0.3	5.3	3.3	5.3	3	120	151.2	-0.5	-0.5	-0.5	-0.5	-1	-1	-1	-1	40	160	0.000062
18	0.3	7	5.5	7	3	120	149	0.3	5.4	3.3	5.4	4	120	149	-0.5	-0.5	-0.5	-0.5	-1	-1	-1	-1	40	160	0.000063
19	0.5	7	5.6	7	0.8	130	151.7	0.5	5.2	3.2	5.2	1	135	151.6	1.3	-0.8	-0.8	-0.8	-1	-1.3	-1.3	-1.3	30	160	0.000068
20	0.5	6.9	5.3	6.9	1	135	150.7	0.5	4.2	3.2	4.2	1	135	150.7	1.3	-0.5	-0.5	-0.5	-1	-1	-1	-1	30	160	0.000076
21	0.3	6.1	4.4	6.1	1.5	120	152.7	0.3	3.8	2.4	3.8	2	120	152.7	-0.5	-0.5	-0.5	-0.5	-1	-1	-1	-1	25	160	0.000072
22	0.3	5.7	4.2	5.7	2.5	120	152.1	0.3	4.1	2.7	4.1	1	120	152.1	-0.7	-0.7	-0.7	-0.7	-1	-1.2	-1.2	-1.2	25	160	0.000074
23	0.3	7	5.5	7	3	130	158.2	0.3	5.4	3.3	5.4	3	135	158.2	-0.5	-0.5	-0.5	-0.5	-1	-1	-1	-1	25	160	0.000066

7.2. LUMINANCE DATA

Model ID	LU1	LU2	LU3	LU4	LU5	LU6	LU7	LU8	LU9
1	326	324	326	369	351	362	332	321	320
2	287	293	276	305	315	287	277	276	264
3	319	358	321	377	390	378	325	355	324
4	274	297	283	316	328	319	288	301	297
5	431	457	425	461	493	451	438	455	435
6	338	361	344	363	401	371	351	371	348
7	322	319	322	345	357	355	317	319	332
8	312	325	302	331	365	333	304	306	301
9	357	378	349	394	435	383	349	370	330
10	255	293	251	294	336	283	256	296	258
11	218	255	232	249	290	260	239	272	249
12	210	224	207	233	301	220	224	236	217
13	234	250	234	265	268	262	234	247	234
14	352	397	350	413	475	382	360	399	345

15	359	384	357	382	424	382	372	402	368
16	356	379	378	420	453	445	362	397	389
17	312	325	302	331	365	333	304	306	301
18	376	412	383	428	496	434	368	410	385
19	501	560	497	508	573	499	485	530	485
20	437	505	442	448	511	453	431	506	440
21	329	335	309	342	359	338	316	339	326
22	584	651	575	613	686	601	575	622	579
23	364	429	372	404	470	397	359	409	370

7.3.FAMILY SPECIFIC VALUES

Model ID	ma1y	bq1	ma2y	od	lensangle
1	1	120	1	40	160
2	1	120	1	40	160
3	1	120	1	40	160
4	1	120	1	40	160
5	1	120	1	40	160
6	1	120	1	40	160
7	1	120	1	40	160
8	1	120	1	40	160
9	1	120	1	40	160
10	1	150	1	15	172
11	1	150	1	15	172
12	1	150	1	15	172
13	1	150	1	15	172
14	0	120	0	40	160
15	0	120	0	40	160
16	0	120	0	40	160
17	0	120	0	40	160
18	0	120	0	40	160
19	0	120	0	40	160
20	0	120	0	40	160
21	0	120	0	25	160
22	0	120	0	25	160
23	0	120	0	25	160

7.4.REGRESSION CODE

```
install.packages("car")

library(car)


wdPath =
"C:/Users/lenovo/Desktop/Important/Ozyegin/Thesis/Prep/R_Data&Results/Total_Lens_Per_Area"

setwd(wdPath)


mydata = read.table("finalper.txt", header = TRUE)

#mydataXs = mydata[,1:35]

#mydataYs = mydata[,45:53]

#cor(cbind(mydataYs,mydataXs))

#mydataXs = mydataXs[,-c(8,17,18,20,21,22,25,29,32,33,34,35)] # remove dependent columns
manually, after running and anlyzing cor(cbind(mydataYs,mydataXs))

mydataXs = cbind(mydata[,1:24],mydata[,c(61)])


mydataYs = mydata[,45:53]

mydataXs = mydataXs[,-c(8,17,18,20,21,22)]

noofYs = dim(mydataYs)[2]

noofXs = dim(mydataXs)[2]


#AllResults = cbind(t(rep(1,19)))

#AllResultsStrs = cbind(t(rep(1,2)))


minSubsetSize = 2

maxSubsetSize = 5

minYs = 1
```

```
maxYs = noofYs

NoofAllsubsets = 0
for(k in minSubsetSize:maxSubsetSize)
{
 allSubsetsofsize_k <- combn(1:noofXs, k, simplify = FALSE)
 NoofAllsubsets <- NoofAllsubsets + length(allSubsetsofsize_k)
}

AllResults = matrix(ncol= 19, nrow = NoofAllsubsets*(maxYs-minYs+1))
AllResultsStrs = matrix(ncol= 2, nrow = NoofAllsubsets*(maxYs-minYs+1))

rowCounter = 1
for(i in minYs:maxYs) # loop over response variables
{
 for(k in minSubsetSize:maxSubsetSize) # loop over subsets of size 2,3,4, and 5
 {
  allSubsetsofsize_k <- combn(1:noofXs, k, simplify = FALSE)
  noofSubsetsofsize_k = length(allSubsetsofsize_k)
  for(s in 1:noofSubsetsofsize_k) # loop over all subsets of cardinality = k, where k={2,3,4,5}
  {
   #select the data for the related subset
   columnIdx = c(unlist(allSubsetsofsize_k[s]))
   modelData = cbind(mydataYs[,i],mydataXs[,columnIdx])
   responseVarName = paste("y_LU", i, sep="")
   colnames(modelData)[1] <- responseVarName
   # split into train and test sets
   dataRowCount <- dim(modelData)[1]
```

```
trainRowLimit = as.integer(dataRowCount*0.9)
trainset <- modelData[-c(6,13,17),]
testset <- modelData[c(6,13,17),]
#build and run regression model
theTarget <- responseVarName
theFormula <- as.formula(paste(theTarget," ~ ."))
fit <- lm(theFormula,data=trainset)
#record formula
myFormula = as.formula(
  paste0(paste(theTarget," ~ "), round(coefficients(fit)[1],2), "",
        paste(sprintf(" %+.2f*%s ",
                coefficients(fit)[-1],
                names(coefficients(fit)[-1])),
            collapse="")
  )
)
###record KPIs
##train and test MAPE performance
#predict train and test data
train_pred <- predict(fit, trainset)
test_pred <- predict(fit, testset)
#Calculate accuracy
m <- as.matrix(abs(train_pred - trainset[,1]) / abs(trainset[,1]))
m <- m[!rowSums(!is.finite(m)),]
train_Acc_lm <- mean(m)
m <- as.matrix(abs(test_pred - testset[,1]) / abs(testset[,1]))
m <- m[!rowSums(!is.finite(m)),]
test_Acc_lm <- mean(m)
```

```
    Model_fstat_pvalue = pf(summary(fit)$fstatistic[1],
summary(fit)$fstatistic[2],summary(fit)$fstatistic[3], lower.tail = FALSE)

    modelAllKPIs =
cbind(k,AIC(fit),Model_fstat_pvalue,summary(fit)$r.squared,summary(fit)$adj.r.squared,rbind(summary
(summary(fit)$coefficients[,4])),rbind(summary(vif(fit))),train_Acc_lm,test_Acc_lm)

    #AllResults = rbind(AllResults,modelAllKPIs)

    AllResults[rowCounter,] = modelAllKPIs

    strs = cbind(paste(deparse(myFormula,width.cutoff = 500),":"),responseVarName)

    #AllResultsStrs = rbind(AllResultsStrs,strs)

    AllResultsStrs[rowCounter,] = strs

    rowCounter = rowCounter + 1

   }

  }

}

#AllResults = AllResults[-c(1),]

#AllResultsStrs = AllResultsStrs[-c(1),]


output <- data.frame (AllResults)

colnames(output) <- c("SubsetSize", "AIC",

                "ANOVA_pvalue", "RSquare",

                "Adj_RSquare", "coef_pvals_Min", "coef_pvals_1stQ",

                "coef_pvals_Median", "coef_pvals_Mean","coef_pvals_3rdQ","coef_pvals_Max","VIF_Min",
"VIF_1stQ",

                "VIF_Median", "VIF_Mean","VIF_3rdQ","VIF_Max","Train_MAPE","Test_MAPE")


is.num <- sapply(output, is.numeric)

output[is.num] <- lapply(output[is.num], round, 3)

write.table(output ,file =
"C:/Users/lenovo/Desktop/Important/Ozyegin/Thesis/Prep/R_Data&Results/Total_Lens_Per_Area/Valu
es.csv",row.names=FALSE)
```

write.table(output ,file = "C:/Users/lenovo/Desktop/Important/Ozyegin/Thesis/Prep/R_Data&Results/Total_Lens_Per_Area/Values.txt",row.names=FALSE)

outputstr <- data.frame (AllResultsStrs)

colnames(outputstr) <- c("ModelFormula","ResponseVariableName")

write.table(outputstr ,file = "C:/Users/lenovo/Desktop/Important/Ozyegin/Thesis/Prep/R_Data&Results/Total_Lens_Per_Area/Ids.csv",row.names=FALSE)

write.table(outputstr ,file = "C:/Users/lenovo/Desktop/Important/Ozyegin/Thesis/Prep/R_Data&Results/Total_Lens_Per_Area/Ids.txt",row.names=FALSE)

7.5. CPLEX CODE FOR DETERMINISTIC MODEL

```
range I=1..9;//#of luminance region

//decisionvariables
dvar float+ LU[I];
dvar float fa1y;//distance from optical films to active area
dvar float fa2y; // distance from optical films to active area
dvar float pa1y;//distance from diffuser plate to active area
dvar float pa2y;    // distance from diffuser plate to active area
dvar float rq1;//distance from folding edge of reflector sheet to active area
dvar float rq2;     // distance from folded edge of reflector sheet to active area
dvar float ra1y;  // distance from reflector sheet to active area
dvar float ra2y;//distance from reflector sheet to active area
dvar float bq1;// distance from folded edge of backlight unit to active area
dvar float bq2;// distance from folded edge of backlight unit to active area
dvar float k1y;// distance from front cover to active area
dvar float k2y;// distance from front cover to active area
dvar float+ b1;    // angle of backlight unit
dvar float+ b2;      // angle of backlight unit
dvar float ma1y;    // distance from middle frame to active area
dvar float+ r1;// angle of reflector sheet
dvar float+ od;// depth of panel
dvar float+ lensangle;      // angle of scattered light
dvar float+ lpa;      // total lens per area

//objectivefunction
maximize  LU[5];//luminance of middle node

//constraints
subject to{
bq1-rq1<=0;//folding edge of backlight unit vs folding edge of reflector sheet
```

```
ma1y-k1y<=0;//middle frame vs front cover
ma1y-fa1y<=0;//optical films vs middle frame
ma1y-pa1y<=0;//diffuser plate vs middle frame
ma1y-ra1y<=0;//reflector sheet vs middle frame
fa1y-ra1y<=0;//optical films vs reflector sheet
fa2y-ra2y<=0;

ma1y>=0.3;//boundary for distance from middle frame to active area
ma1y<=0.8;
fa1y>=4;//boundary for distance from optical films to active area
fa1y<=7.4;
fa2y>=3.7;
fa2y<=6.6;
pa1y>=4.2;//boundary for distance from diffuser plate to active area
pa1y<=7.4;
pa2y>=2.4;
pa2y<=6.13;
ra1y>=4.8;//boundary for distance from reflector sheet to active area
ra1y<=7.7;
ra2y>=3.7;
ra2y<=8.7;
k1y>=0.8;//boundary for distance from front cover to active area
k1y<=3.7;
k2y>=0.8;
k2y<=4.2;
bq1>=105;//boundary for angle of backlight unit
bq1<=150;
bq2>=120;
bq2<=150;
rq1>=144.4;//boundary for angle of reflector sheet
rq1<=169.5;
rq2>=144.4;
rq2<=169.5;
b1>=-0.7;//boundary for distance from folding edge of backlight unit to active area
b1<=3.2;
b2>=-0.8;
b2<=3.05;
r1>=-1.2;//boundary for distance from folding edge of reflector sheet to active area
r1<=1.8;
od>=15;//boundary for panel depth
od<=50;
lensangle>=160;//boundary for lens angle
lensangle<=172;
lpa>=0.00004;//boundary for lens per area
lpa<=0.00012;

forall (i in I:i!=5){
LU[i]>=0.75*LU[5];
LU[i]<=LU[5];

}
LU[1]==(3241.29 + 451.09 * ma1y - 5.8 * bq1 - 88.64 * r1 - 17.09 * lensangle +
5414379.04 *lpa);
LU[2]==(4845.39 + 351.66 * ma1y - 9.51 * rq1 - 74.02 * b2 - 9.29 * od - 17.63 *
lensangle);
```

```
LU[3]==(3721.37 + 64.42 * k1y - 18.96 * ra2y - 73.33 * k2y - 21.11 * lensangle +
2505152.35 *lpa);
LU[4]==(1368.95 + 82.16 * k1y - 6.24 * rq1 - 81.81 * k2y - 37.74 * b2);
LU[5]==(1200.3 + 101.84 * k1y - 95.99 * k2y - 4.88 * rq2 - 52.76 * b2);
LU[6]==(1016.9 - 40.7 * fa1y - 3.29 * bq1 + 55.26 * b1 - 94.79 * r1);
LU[7]==(3536.63 + 70.22 * k1y - 19.7 * ra2y - 76.49 * k2y - 19.91 * lensangle +
2358770.57 *lpa);
LU[8]==(4105.87 + 322.26 * ma1y - 10.36 * rq1 - 74.89 * b2 - 7.97 * od - 12.44 *
lensangle);
LU[9]==(3554.93 + 63.65 * k1y - 23.93 * ra2y - 72.11 * k2y - 19.8 * lensangle +
2239648.33 *lpa);
```

7.6. CPLEX CODE FOR ROBUST MODEL

```
range I=1..9;     //#of luminance region

 //decisionvariables

dvar float LU[I];
dvar float bLU[I];
dvar float fa1y;//distance from optical films to active area
dvar float fa2y; // distance from optical films to active area
dvar float pa1y;//distance from diffuser plate to active area
dvar float pa2y;// distance from diffuser plate to active area
dvar float rq1;//distance from folding edge of reflector sheet to active area
dvar float rq2;// distance from folded edge of reflector sheet to active area
dvar float ra1y;// distance from reflector sheet to active area
dvar float ra2y;//distance from reflector sheet to active area
dvar float bq1;// angle of backlight unit
dvar float bq2;// angle of backlight unit
dvar float k1y;// distance from front cover to active area
dvar float k2y;// distance from front cover to active area
dvar float+ b1;// distance from folded edge of backlight unit to active area
dvar float+ b2;// distance from folded edge of backlight unit to active area
dvar float ma1y;// distance from middle frame to active area
dvar float+ r1;// angle of reflector sheet
dvar float+ od;// depth of panel
dvar float+ lensangle;// angle of scattered light
dvar float+ lpa;// total lens per area

dvar float tb1;
dvar float ttb1;
dvar float tb2;
dvar float ttb2;
dvar float tr1;
dvar float ttr1;

//dvar boolean bb1;
dvar boolean bb2;
//dvar boolean br1;

float a = 0.04;
```

```
float bet = 0.5;

//objectivefunction
maximize LU[5];
//minimize -LU[5];

//constraints

subject to{
bq1-rq1<=0;//folding edge of backlight unit vs folding edge of reflector sheet
ma1y-k1y<=0;//middle frame vs front cover
ma1y-fa1y<=0;//optical films vs middle frame
ma1y-pa1y<=0;//diffuser plate vs middle frame
ma1y-ra1y<=0;//reflector sheet vs middle frame
fa1y-ra1y<=0;//optical films vs reflector sheet
fa2y-ra2y<=0;

ma1y>=0.3;//boundary for distance from middle frame to active area
ma1y<=0.8;
fa1y>=4;//boundary for distance from optical films to active area
fa1y<=7.4;
fa2y>=3.7;
fa2y<=6.6;
pa1y>=4.2;//boundary for distance from diffuser plate to active area
pa1y<=7.4;
pa2y>=2.4;
pa2y<=6.13;
ra1y>=4.8;//boundary for distance from reflector sheet to active area
ra1y<=7.7;
ra2y>=3.7;
ra2y<=8.7;
k1y>=0.8;//boundary for distance from front cover to active area
k1y<=3.7;
k2y>=0.8;
k2y<=4.2;
bq1>=105;//boundary for angle of backlight unit
bq1<=150;
bq2>=120;
bq2<=150;
rq1>=144.4;//boundary for angle of reflector sheet
rq1<=169.5;
rq2>=144.4;
rq2<=169.5;
b1>=-0.7;//boundary for distance from folding edge of backlight unit to active area
b1<=3.2;
b2>=-0.8;
b2<=3.05;
r1>=-1.2;//boundary for distance from folding edge of reflector sheet to active area
r1<=1.8;
od>=15;//boundary for panel depth
od<=50;
lensangle>=160;//boundary for lens angle
lensangle<=172;
lpa>=0.00004;//boundary for lens per area
lpa<=0.00012;
```

```
// b1
//b1 + 10 * bb1 >= tb1;
//10 - b1 - 10 * bb1 >= tb1;
//tb1 + b1>=0;
//tb1 - b1>=0;
//
ttb1 >= b1;
ttb1 >= -b1;

// b2
b2 + 10 * bb2 >= tb2;
10 - b2 - 10 * bb2 >= tb2;
tb2 + b2>=0;
tb2 - b2>=0;
ttb2 >= b2;
ttb2 >= -b2;

// r1
//r1 + 10 * br1 >= tr1;
//10 - r1 - 10 * br1 >= tr1;
//tr1 + r1>=0;
//tr1 - r1>=0;
ttr1 >= r1;
ttr1 >= -r1;

LU[1]>=bet*bLU[5];
LU[2]>=bet*bLU[5];
LU[3]>=bet*bLU[5];
LU[4]>=bet*bLU[5];
LU[6]>=bet*bLU[5];
LU[7]>=bet*bLU[5];
LU[8]>=bet*bLU[5];
LU[9]>=bet*bLU[5];

//LU[1] == 3241.29 + 451.09 * ma1y - 5.8 * bq1 - 88.64 * r1 - 17.09 * lensangle +
5414379.04 *lpa;
LU[1] == 3241.29 + 451.09 * ma1y - 5.8 * bq1 - 88.64 * r1 - 17.09 * lensangle +
5414379.04 *lpa - a*(3241.29 + 451.09 * ma1y + 5.8 * bq1 + 88.64 * ttr1 + 17.09 *
lensangle + 5414379.04 *lpa);
//LU[2]==4845.39 + 351.66 * ma1y - 9.51 * rq1 - 74.02 * b2 - 9.29 * od - 17.63 *
lensangle;
LU[2] == 4845.39 + 351.66 * ma1y - 9.51 * rq1 - 74.02 * b2 - 9.29 * od - 17.63 *
lensangle - a*(4845.39 + 351.66 * ma1y + 9.51 * rq1 + 74.02 * ttb2 + 9.29 * od +
17.63 * lensangle);
//LU[3]==3721.37 + 64.42 * k1y - 18.96 * ra2y - 73.33 * k2y - 21.11 * lensangle +
2505152.35 *lpa;
LU[3] == 3721.37 + 64.42 * k1y - 18.96 * ra2y - 73.33 * k2y - 21.11 * lensangle +
2505152.35 *lpa -a*(3721.37 + 64.42 * k1y + 18.96 * ra2y + 73.33 * k2y + 21.11 *
lensangle + 2505152.35 *lpa);
//LU[4]==1368.95 + 82.16 * k1y - 6.24 * rq1 - 81.81 * k2y - 37.74 * b2;
LU[4] == 1368.95 + 82.16 * k1y - 6.24 * rq1 - 81.81 * k2y - 37.74 * b2 - a*(1368.95 +
82.16 * k1y + 6.24 * rq1 + 81.81 * k2y + 37.74 * tb2);
//LU[6]==1016.9 - 40.7 * fa1y - 3.29 * bq1 + 55.26 * b1 - 94.79 * r1;
```

```
LU[6] == 1016.9 - 40.7 * fa1y - 3.29 * bq1 + 55.26 * b1 - 94.79 * r1 -a*(1016.9 +
40.7 * fa1y + 3.29 * bq1 + 55.26 * tb1 + 94.79 * tr1);
//LU[7]==3536.63 + 70.22 * k1y - 19.7 * ra2y - 76.49 * k2y - 19.91 * lensangle +
2358770.57 *lpa;
LU[7] == 3536.63 + 70.22 * k1y - 19.7 * ra2y - 76.49 * k2y - 19.91 * lensangle +
2358770.57 *lpa - a*(3536.63 + 70.22 * k1y + 19.7 * ra2y + 76.49 * k2y + 19.91 *
lensangle + 2358770.57 *lpa);
//LU[8]==4105.87 + 322.26 * ma1y - 10.36 * rq1 - 74.89 * b2 - 7.97 * od - 12.44 *
lensangle;
LU[8] == 4105.87 + 322.26 * ma1y - 10.36 * rq1 - 74.89 * b2 - 7.97 * od - 12.44 *
lensangle -a*(4105.87 + 322.26 * ma1y + 10.36 * rq1 + 74.89 * tb2 + 7.97 * od + 12.44
* lensangle);
//LU[9]==3554.93 + 63.65 * k1y - 23.93 * ra2y - 72.11 * k2y - 19.8 * lensangle +
2239648.33 *lpa;
LU[9] == 3554.93 + 63.65 * k1y - 23.93 * ra2y - 72.11 * k2y - 19.8 * lensangle +
2239648.33 *lpa -a*(3554.93 + 63.65 * k1y + 23.93 * ra2y  + 72.11 * k2y + 19.8 *
lensangle + 2239648.33 *lpa);

//LU[5]==1*(1200.3 + 101.84 * k1y-a*101.84*tk1y5 - 95.99 * k2y-a*95.99*tk2y5 - 4.88 *
rq2-a*4.88*trq25 - 52.76 * b2-a*52.76*tb25);
LU[5]  ==  1200.3 + 101.84*k1y - 95.99*k2y - 4.88*rq2 - 52.76*b2 - a*(1200.3
+101.84*k1y + 95.99*k2y + 4.88*rq2 + 52.76*tb2);
bLU[5] ==  1200.3 + 101.84 * k1y - 95.99 * k2y - 4.88 * rq2 - 52.76 * b2 + a*(1200.3
+101.84 * k1y + 95.99 * k2y + 4.88 * rq2 + 52.76 * ttb2);
```

8. VITA

Mr. Olkan Kurt completed bachelor's degree of mechanical engineering in Middle East Technical University. He started his first job in Vestel Electronics Corp. as a mechanical design engineer. During three years of time period, he promoted to Sr. Mechanical Design Specialist. In addition, he started to study master degree in industrial engineering at Ozyegin University. Advisors of the graduate project are Assistant Professor Ihsan Yanikoglu and Assistant Professor Erinc Albey. After Vestel career, he left to work for Innolux Europe BV. in Netherlands as a Sr. Mechanical Engineer. Currently, he works for Philips in Eindhoven.