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Parametric lifespan models for OLEDs using Design of Experiments (DoE)

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Abstract -- Modeling the lifespan of OLED (Organic Light-Emitting Diode) is a complex task: different factors may impact the lifespan, with possible interactions between them. However, the literature on this subject is still scant. This work proposes new parametric models for the OLED lifespan. For cost and accuracy reasons, the Design of Experiment (DoE) methodology is used for the estimation of model parameters. Different models are computed from thermal and electrical experimental aging tests. These innovative models involve, simultaneously, the current density, the temperature and their interactions, which are rarely taken into account in aging studies. The analysis of the model parameters highlights the prevalence of temperature compared to current density on the OLED luminance performance.

Keywords -- accelerated aging, design of experiments, electrical stress, lifespan prediction, OLED, thermal stress

I. INTRODUCTION

Component and system reliability has become an important issue nowadays. The objective is to understand, model and predict the aging mechanisms that could lead to component and system failure. The effects of the operational constraints on the component degradation must be studied for the lifespan prediction. In the field of electrical engineering, numerous lifespan models have been developed in the literature [1]-[4]. However, these models have some limitations: they depend on the studied material and on its physical properties, they are often restricted to one or two stress factors and they do not integrate interactions that may exist between these factors. Anyway, OLED, together with LEDs, are the future of light sources but have a limited lifespan (30000 h to 40000 h) and an aging mode that is still poorly known. Although this methodology is general and applicable to various components without prior information on their physical properties, it has to take into account the measurement specifications in order to compute a relevant lifespan model.

This paper proposes innovative parametric lifespan models for the very recent light sources OLED whose aging characteristics are still poorly known. The proposed models are inferred from experimental data obtained through accelerated aging tests involving several stress factors. The

proposed models are innovative since they take into account, simultaneously, the effects of the different stress factors and their possible interactions which are rarely taken into account in aging studies. In addition, the number and the configuration of the experiments composing the learning sets are optimized in order to minimize the experimental cost while maximizing the model accuracy. Then a study of the estimated parameters allows to assessing the significance of the considered stress factors. The performance of OLED light sources is impacted by several intrinsic and extrinsic factors [5]. According to [6][7], the temperature is the most important factor contributing to the OLED degradation. High temperatures contribute to the aging of OLEDs during their operation but also, alas, during storage [8]. On the other hand, OLEDs are current-controlled components and their initial luminance is proportional to the applied current level [8]. Current represents an operational electrical stressor whose application to the OLEDs over time contributes to their degradation. Indeed, it has been shown in [9] that, as current flows through OLEDs, their performance gradually decreases over time due to the chemical degradation of organic materials. OLEDs are also sensitive to moisture in the surrounding environment. The penetration of moisture into the electrodes of an OLED creates a high-resistance area around the electrodes and deflects the current flow, degrading its performance [9]. However, this problem has been solved in many applications by different types of encapsulation that protect OLEDs against moisture [8], [9]. Thus, thermal and electrical stresses remain the most critical degradation factors for OLEDs.

For lighting applications, the luminance (measured in cd/m^2) is the most interesting and easy feature to monitor. Thus, the degradation of an OLED is defined by the rate of reduction of its luminance over time [10]. It is assumed that an OLED reaches its end of life when its luminance degrades by 30% to 50%, depending on the application. The corresponding lifetimes are therefore L70 to L50, respectively.

So far, there is no standard measurement method for OLEDs that can be adopted in performance or accelerated aging tests [8], [11]. A US standard published in September 2013 [12]

specifies the general conditions of safety for the use of OLED lighting panels. There is also an international IEC standard published in 2014 [13] that also addresses the safety requirements for OLED lighting panels. However, an international standard IEC 62922 which concerns the evaluation of the performance and reliability of OLEDs is still under development.

As for standards, OLED aging research is still weakly developed. In the OLED aging literature, the studies mainly concern the effects of thermal (temperature) [14], [15] or electrical (current) [10], [16] stresses on the degradation of OLED performance over time. They are based on the monitoring over time of one or more characteristic properties of OLEDs (luminance, efficiency, electrical characteristics, etc.) under the influence of a single stressor (often temperature or electric current). Moreover, in the literature, few studies are interested in the modeling of OLED lifetimes as a function of stress factors in addition to the evaluation over time of their performances (aging). These models use the Arrhenius law to model the effect of temperature [17] and the inverse power law to model the effect of electric current [11]. However, lifespan models that include two or more stressors at once have never been considered for OLEDs in the literature.

The analytical forms of these two factors to be considered in the lifetime models are based on the literature and the classical laws used for these two types of stress. In [11], [17], [18], [19] the developed lifespan models for OLEDs are single stress models that use the classical laws corresponding to the electric stress (inverse power law) or thermal stress (Arrhenius law). In this study, the proposed models include these two main factors. Thus, in OLED lifespan models, a logarithmic transformation of lifetimes, a logarithmic transformation of the current density and an inverse temperature transformation in °K are applied. Under each test condition (current and temperature), only one OLED was tested for cost and time constraints. It should be noted that manufacturers consider their batches of OLED to be very homogeneous, and that in the literature, only a very limited number of samples are generally tested. Our choice is identical, but the dispersion of the characteristics remains to be tested over time, which can constitute a perspective of this work. The Design of Experiment (DoE) methodology has proved its efficiency to tackle these problems in the case of insulation materials [20], [21]. This paper presents an application of this novel methodology on OLED light sources.

II. TESTS PERFORMED ON OLEDs

A. OLED types tested

The proposed methodology is applied on OLED lighting sources. The tested components are commercial OLEDs of the Philips brand "Philips Lumiblade OLED Panel GL55", cf Fig. 1. Table I summarizes their main technical characteristics.

TABLE I
TECHNICAL CHARACTERISTICS OF PHILIPS GL55 OLEDs

Name	Philips Lumiblade OLED Panel GL55
Color	white
Color temperature	3200K
Size	130.2*47.8 mm ² (116.7*35.2 mm ² of luminous surface)
Nominal current	390 mA
Maximal current	450 mA
Minimum voltage	6.9 V
Nominal voltage	7.2 V
Maximal Voltage	7.5 V
Lifespan (L ₅₀) under nominal current	10000h
Rated Luminance	4200 cd/m ²



Fig. 1. Photo of a Philips GL55 OLED

B. Aging factors

According to the literature, which is still scanty in terms of OLED lifespan models, the two main factors that accelerate the degradation of OLEDs are temperature and electric current. The OLEDs will be tested under these two types of stress (pure or combined). However, since there are different forms of OLEDs, it is often common to use the current density instead of the absolute current in order to normalize with respect to the surface of the OLED. Current density (J) and temperature (T) will be used together in our models. The domains of these two factors are chosen in order to accelerate the degradation of OLEDs, without causing sudden failures:

- Current density: the maximum current allowed for normal operation is 450 mA, which corresponds to a current density of 11 mA/cm². To accelerate the degradation, 3 values of current densities are considered: 11.25 mA/cm², 13 mA/cm² and 15 mA / cm² (corresponding to currents of 462, 534 and 616 mA). For values above 15 mA/cm², very fast degradations (of the order of only a few minutes) have been observed,

resulting in black spots, as shown in Fig. 2. Zero-current (no lighting) tests are also considered to study the degradation due solely to temperature, which is equivalent to studying the OLEDs degradation in storage,

- Temperature: one set of OLEDs is tested at room temperature (23°C) and two other sets at 40°C and 60°C respectively. At temperatures above 60 °C, the tested OLEDs do not support acceleration current densities (greater than 11 mA/cm²).



Fig. 2. Photos of a degraded OLED under a strong current (appearance of black spots)

C. Experimental bench

An experimental bench was developed at the LAPLACE laboratory to apply thermal and electrical stresses to the OLED while simultaneously performing in situ electrical and photometric characterizations. OLEDs were subjected to combined electrical and thermal stress but also to pure thermal and electrical stress. To apply the thermal stress, OLEDs are placed in thermal chambers where the temperature can be kept constant at the desired value. The temperature is controlled by a regulator and measured using a thermocouple. Three different temperatures are applied simultaneously in three chambers (23 °C, 40 °C and 60 °C). Each supply can feed up to 4 OLEDs, which can therefore be tested simultaneously at the same temperature. To apply electrical stress, each OLED in its climatic chamber is connected to a DC source except in cases of pure thermal stress. Thus, within the same box, the OLEDs are subjected to the same temperature but to 4 different current densities (zero current, 11.25 mA/cm², 13 mA/cm² and 15 mA/cm²). The boxes are thermally isolated and painted black inside to prevent from light reflection. Finally, each box is equipped with a counter (in hours). The different parts of the experimental bench dedicated to these tests are presented in Fig. 3, 4 and 5.

D. Lifespan measurement method

In order to follow the time evolution of the OLED performance, when subjected to the different stresses, regular measurements of the electrical and photometric characteristics are carried out. The frequency of these measurements varies for the same OLED, according to its degradation state (the rate of degradation is not the same at the beginning of aging tests of an OLED as in the advanced phases) and between OLEDs, depending on the severity of the applied constraints (the

degradation rate of OLEDs subjected to strong constraints is faster than that of OLEDs subjected to lower constraints).



Fig. 3. Climatic chamber



Fig. 4. Temperature controllers and meters (in hours)



Fig. 5. Experimental bench of OLED aging tests

These measurements are made outside the climatic chamber (no thermal and electrical stress) but they last for a very short time compared to the total duration of an aging test. It is assumed that these very short measurements do not affect the lifetime of the OLEDs. It should be noted that these measurements constitute a de facto thermal and electrical cycling whose effects should be studied more precisely in future work. However, this cycling effect will be neglected here given its low frequency and the short duration during which the OLEDs are out of stress. Nevertheless, we consider the study of cycling as an interesting perspective of this work. Among the different characterizations of OLEDs carried out regularly over time, the measurement of luminance is the most interesting to characterize their lifetime. In each experimental

configuration, either for combined or pure stresses, the luminance is measured by applying the nominal current density (9.5 mA/cm^2) to the OLEDs since the luminance measurement is carried out under no stress, as previously explained. The luminance degradation rate expressed in percentage gives the corresponding index of the lifetime: if the luminance reaches $x\%$ of its initial value, the corresponding lifetime is denoted L_x . Thus, each L_x would correspond to a lifespan model as a function of stress factors. This allows us to follow not only the evolution of luminance over time for a given stress, but also the evolution of the effects of stressors (current and temperature) over time.

E. Configuration of tests and measurement results

As partly described in [22], OLEDs have been tested in 12 configurations corresponding to pure or combined stresses. For each configuration, an OLED is tested but different measurements of lifetimes can be recorded for different rates of degradation of the luminance. Fig. 6 and 7 show the evolution over time of the relative luminance (ratio of the luminance measured on the initial luminance) for the different aging tests. The horizontal lines correspond to the percentages 60%, 65%, 70%, 75%, 80% and 85% as aging indices.

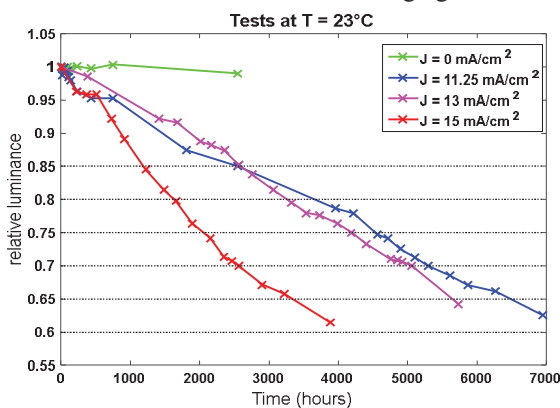


Fig. 6. Test results: relative luminance at $T = 23 \text{ }^\circ\text{C}$ for different current densities

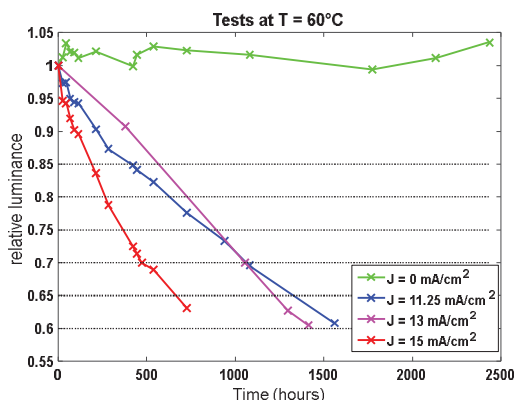


Fig. 7. Test results relative luminance at $T = 60 \text{ }^\circ\text{C}$ for different current densities

From these data it can be noticed that:

- a deterioration of 85% at the highest temperature and current density takes more than one week (187h),

- the temperature alone, up to $60 \text{ }^\circ\text{C}$, cannot degrade the luminance of the tested OLEDs, the tests corresponding to these conditions (curves in green) are thus stopped after 2500h (3 months and a half) since the luminance has not been degraded throughout this period,
- the current alone (at room temperature), on the contrary, can degrade the luminance of OLEDs as displayed in Fig.6,
- at most three points are at constant temperature or current and can therefore be used to validate the forms of the two stress factors, as it will be shown hereafter.

Fig. 8 and 9 present as examples two graphs that validate the respective forms of current and temperature that are considered in the life models from two different indices of duration life. Unfortunately, since only one measurement per test condition is available so far, it is not possible to evaluate statistical properties of the data such as dispersion or distribution. However, for the models, we assume that lifetimes are distributed lognormally.

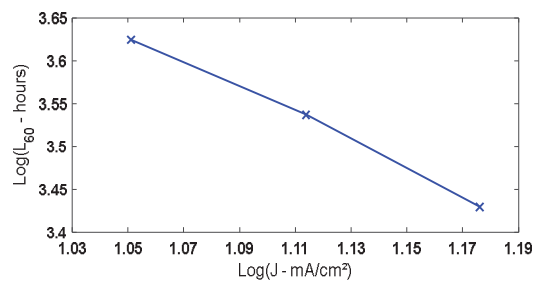


Fig. 8. Linear variation of $\text{Log}(L)$ versus $\text{Log}(J)$ at $T = 40 \text{ }^\circ\text{C}$

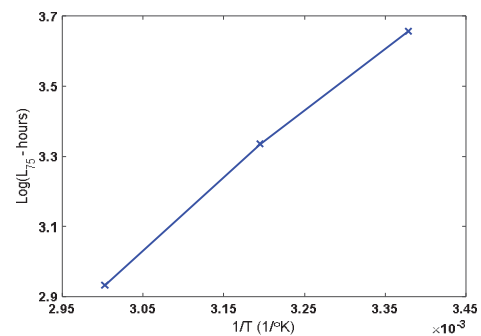


Fig. 9. Linear variation of $\text{Log}(L)$ versus $1/T$ (T in K) at $J = 11.25 \text{ mA / cm}^2$

III. DOE FOR LIFESPAN MODELLING

A. DoE principles

The problem of parametric modeling of a response influenced by a number of factors at a lower experimental cost is based on the Design of Experiments (DoE) method. The DoE method is an experimental planning strategy for studying the effects of factors and their interactions on the response in an efficient and cost-effective manner.

The DoE method was introduced with Fisher's work in 1925 [23] in the field of agronomy. As part of his job at an agricultural research center, Fisher has been seeking experimentation techniques to increase crop yields by combining various types of fertilizers, plant varieties, crop methods, types of soil, etc. Faced with the impossibility of carrying out all the experiments, this led him to propose experimental configurations based on statistical models.

Various researchers have continued Fisher's work to promote and develop the use of experimental planning techniques in fields other than agronomy. But it is certainly the work of G. Taguchi [24] which allowed a wide diffusion of the DoE, in particular in the industrial environment. Traditionally, in experimentation, the tests are carried out sequentially by varying one factor at a time, the others being fixed at an "average" level. If we consider k factors and decide to test m^k points by factor, it will be necessary to perform m^k experiments. In order to reduce the number of tests, there are two solutions: reducing the number of experimental points per factor or reducing the number of factors. In both cases, it is the precision of the model that is diminished. In contrast to the conventional experiment approach, the DoE method consists primarily in varying all factors simultaneously. By this strategy, and with the same number of factors, the number of experimental points is reduced and the accuracy of the model is improved compared to the conventional approach.

The classical method of DoE consists in placing the experimental points at the ends of the experimental plan by involving all the factors at once in each of the experimental points, i.e. in each of the experiments. By this strategy, the number of experimental points per factor is reduced to 2: a point at level -1 (minimum value of the factor) and a point at level +1 (maximum value of the factor). For k factors, the associated DoE is called the factorial plan 2^k since it requires the realization of 2^k experimental points corresponding to the 2^k possible combinations between the levels -1 and +1 of the k factors.

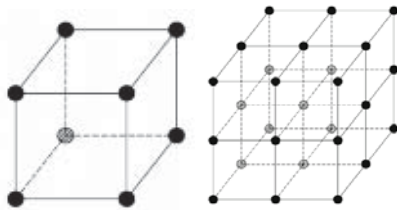


Fig. 10a. Factorial plan 2^3

Fig. 10b. Factorial plan 3^3

There are also factorial plans with m levels ($m > 2$). However, the most used factorial designs are the two-level (2^k) plans since they require a minimum number of experiments while guaranteeing a good quality of the model. Fig. 10 (a and b) illustrate experimental designs associated with three types of factorial designs.

B. Factorial plans at 2 levels

The choice of associating the levels ± 1 with the two extreme values of the factors in a DoE 2^k is the optimal choice in terms of precision of the coefficients of the associated model when $k=1$ [25], [26]. Let's consider the simple example of a factorial plan 2^2 . The response Y is written in expression (1)

$$Y = M + E_1X_1 + E_2X_2 + I_{12}X_1X_2 \quad (1)$$

TABLE II
2² DoE WITH 4 EXPERIMENTAL POINTS

Exp.	M	X ₁	X ₂	X ₁ X ₂	Y
1	1	-1	-1	+1	Y ₁
2	1	-1	+1	-1	Y ₂
3	1	+1	-1	-1	Y ₃
4	1	+1	+1	+1	Y ₄

To estimate the parameters of this model, $2^2=4$ experiments are necessary. Table II summarizes the different configurations of the experimental points to be realized in this case. Parameters of the model (1) can be calculated by the Ordinary Least Square (OLS) method which is equivalent to the solution of the linear system of 4 equations with 4 unknowns and which gives (2):

$$\begin{aligned} M &= \frac{1}{4}(Y_1 + Y_2 + Y_3 + Y_4) \\ E_1 &= \frac{1}{4}(-Y_1 - Y_2 + Y_3 + Y_4) \\ E_2 &= \frac{1}{4}(-Y_1 + Y_2 - Y_3 + Y_4) \\ I_{12} &= \frac{1}{4}(Y_1 - Y_2 - Y_3 + Y_4) \end{aligned} \quad (2)$$

C. Plans for Response Surfaces (RS)

The DoE presented previously allows to obtain a first-order analytical model with respect to each factor with terms of interactions between the factors. These plans are the most used (especially 2-level plans) because they are economic in number of experiments and lead to simple models but often sufficient in terms of accuracy. However, there are many cases where it could be necessary to have a better description of the phenomenon studied and for which second-order mathematical models must be considered, as in the case of our statistical modeling of the lifetime. The response surface plans are then used. These plans make it possible to study the quadratic effects of factors in addition to their main effects and interactions. The associated mathematical model is given in expression (3) [26]:

$$Y = M + \sum_{i=1}^k E_iX_i + \sum_{i=1}^k I_{ii}X_i^2 + \sum_{i=1}^k \sum_{i=1 < j}^k I_{ij}X_iX_j \quad (3)$$

As for the classical DoE, the parameters of this model can be estimated by the OLS method. For k factors, the number of parameters to estimate is:

$$q = \frac{(k+2)!}{k!2!} = \frac{(k+2)(k+1)}{2} \quad (4)$$

At least q experimental points are necessary to be able to estimate these q parameters. It is shown, moreover, that with this model, it is impossible to obtain orthogonal matrices, as in the case of 2^k plans. Several experimental designs with optimal configurations have been proposed in the literature to be able to establish a second-order model with interactions. The 3-level factorial designs present a first possibility to realize a second-order model. If the chosen levels are -1; 0 and 1, the experiment matrix X is an almost orthogonal matrix [26]. However, the number of experiments to be performed increases exponentially with the number of factors.

D. Test configuration and data base for lifespan modeling

This methodological approach is applied to OLEDs. The most influential factors over the life of OLEDs, current density and temperature, will be considered in our aging tests. The variation domain of these two factors is chosen in order to accelerate the aging of the OLEDs without causing sudden failures. The accelerated aging tests for constructing the lifespan models are therefore given in Table III where experiments corresponding to zero current have been removed. Measured (black) and interpolated (red) lifespan for different percentages of the luminance degradation rate are provided. Indeed, if for a given percentage, a measurement has not been made, the corresponding lifetime is calculated by linear interpolation between the two measurements that frame it on both sides in Fig. 6 and 7.

TABLE III

OLED ACCELERATED AGING TEST CONFIGURATIONS (WITHOUT PURE THERMAL TESTS) MEASURED (BLACK) AND INTERPOLATED (RED) LIFETIMES

Exp. Nb.	Constraints		Measured lifespan (in hours)				
	J (mA/cm ²)	T (°C)	L ₈₅	L ₈₀	L ₇₅	L ₇₀	L ₆₅
1	11.25	23	2543	3660	4562	5298	6489
2	13	23	2566	3325	4191	5063	5644
3	15	23	1225	1654	2051	2468	3343
4	11.25	40	1234	1657	2166	2917	3488
5	13	40	860	1192	1517	1955	2702
6	15	40	949	1266	1576	1872	2377
7	11.25	60	423	628	855	1082	1331
8	13	60	567	733	893	1055	1221
9	15	60	187	270	367	471	665

The combined thermal and electrical stress tests have been configured to be able to construct the 1st and 2nd order models with interactions. Experimental points 1 to 9 of Table III form a 3-level experiment plan; indeed, with 2 factors, $3^2=9$ experiments are necessary. These points then make it possible to construct:

- a model of the first order with interactions of the form (1) by using the factorial plan 2^2 with the extreme levels -1 and +1 (exp. 1, 3, 7 and 9), called model L1;
- 4 first-order models with interactions (form (1)) using the 4 factorial 2^2 plans consisting of the levels (-1; 0) and (+1; 0) (note that the levels have to be recalculated each time at (-1; +1) to obtain an orthogonal matrix), called models L21 to L24;
- a first-order model with interactions using the 3-level DoE (exp 1 to 9), called model L3;
- a model of the second order with interactions of the form (3) using the plan formed by the extreme factorial plan 2^2 (exp.1, 3, 7 and 9), the 4 axial points (exp 2, 4, 6 and 8) and the only central point (exp no 5) sufficient to verify the criterion of almost orthogonality in the case of two factors, called model L4.

Because of cost constraints (each tested OLED costs 100€), experimental time constraints (experiments lasted one year), and material availability, only one sample (OLED) per experimental configuration was tested, and no additional configuration could be realized for model testing. Therefore, no statistical analysis of the lifespan models coefficients could be performed. On the other hand, the models are tested, when possible, on organized experimental points that have not been used for their construction and which belong to the same domain as the associated learning set. Table IV summarizes the different transformed real values and the 3 levels associated with each factor in the 3-level factorial design.

TABLE IV
VALUES OF STRESS FACTORS AND ASSOCIATED LEVELS

X_i level	$U_J = \text{Log}(J)$ (mA/cm ²)	$U_T = 1/T$ (°K)
-1	Log(11.25)	1/(23+273.15)
0	Log(13)	1/(40+273.15)
+1	Log(15)	1/(60+273.15)

TABLE V
LEVELS OF THE FACTORS FOR THE DoE AND EXPERIMENTAL RESULTS

Exp. N°	X_J	X_T	L ₈₅ (hr)	L ₈₀ (hr)	L ₇₅ (hr)	L ₇₀ (hr)	L ₆₅ (hr)
1	-1	-1	2543	3660	4562	5298	6489
2	0	-1	2566	3325	4191	5063	5644
3	1	-1	1225	1654	2051	2468	3343
4	-1	0	1234	1657	2166	2917	3488
5	0	0	860	1192	1517	1955	2702
6	1	0	949	1266	1576	1872	2377
7	-1	1	423	628	855	1082	1331
8	0	1	567	733	893	1055	1221
9	1	1	187	270	367	471	665

The different configurations of experiments 1 to 9 after level coding are given in Table V where the levels of the factors are designated by X_J and X_T . In 2D, the configuration of the 9 experimental points is given in Fig. 11.

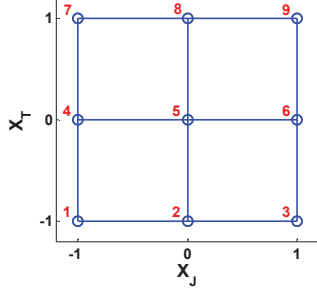


Fig. 11. Experimental points of Table V in 2D space

IV. OLED LIFESPAN PARAMETRIC MODELS

A. First order models with interactions (model L1)

According to the DoE methodology presented in section III and because they are situated at the corners of the square experiments 1, 3, 7 and 9 of Fig. 11 and Table V which are the extreme points, allow the construction of a first-order model with interactions given by expression (4):

$$L1 = \text{Log}(L_{70}) = M + E_J X_J + E_T X_T + I_{JT} X_J X_T \quad (4)$$

where L_{70} denotes the lifespan measured at 70% of the initial luminance in hours, X_J and X_T are the respective levels of $\text{Log}(J)$, and $1/T$ as shown in Table IV. The unknown parameters of this model are the constant M , the coefficients E_J , E_T associated to the effects of the density of the current and the temperature respectively, and the coefficient I_{JT} associated to the effect of their interaction. The coefficients of this model estimated by OLS are given in Table VI. The test base of this model is composed of experiments 2, 4, 5, 6 and 8, all belonging to the experimental field of the learning set of this model. The relative errors on this test basis between measured $\text{Log}(L_{70})$ and those predicted by model L1 are given in Table VII.

TABLE VI
ESTIMATED NORMALIZED COEFFICIENTS OF MODEL L1 BUILT FROM EXTREME POINTS OF THE FIRST ORDER 2 FACTOR DOE

M	3.206
E_J	-0.173
E_T	-0.352
I_{JT}	-0.007

TABLE VII
RELATIVE ERRORS OF MODEL L1 ON ITS TEST BASE

Exp. Nb.	$\text{Log}(L_{70})$ measured	$\text{Log}(L_{70})$ predicted	Relative error
2	3.704	3.558	4.0%
4	3.465	3.379	2.5%
5	3.291	3.206	2.6%
6	3.272	3.033	7.3%
8	3.023	2.854	5.6%

The estimated coefficients of this model show that between levels -1 and +1 of each of the factors ($11.25 \text{ mA/cm}^2 < J < 15 \text{ mA/cm}^2$ and $23 \text{ }^\circ\text{C} < T < 60 \text{ }^\circ\text{C}$), the temperature has a higher effect than current density and the interaction between the two factors is negligible with respect to the main effect. The relative errors calculated on the points that were not used in the construction of the model are generally small (<8%), which validates the considered form of the model and the two factors.

B. Four 1° order models with interactions (L21 to L24)

If the factorial plan of Fig. 11 and Table VI is separated into 4 factorial plans (the 4 inscribed squares of Fig. 11), it is possible to build 4 first order models with interactions from the 4 squares. The learning sets of these 4 models (designated by L21 to L24) are given in Table VIII.

TABLE VIII
LEARNING BASICS OF THE 4 FIRST ORDER DOEs 2°

Model nb.	J levels	T levels	Exp. nb. in the learning base
L21	[-1 ; 0]	[-1 ; 0]	1, 2, 4, 5
L22	[0 ; 1]	[-1 ; 0]	2, 3, 5, 6
L23	[0 ; 1]	[0 ; 1]	5, 6, 8, 9
L24	[-1 ; 0]	[0 ; 1]	4, 5, 7, 8

The 4 DoE models L21 to L24 have the same form as (1) and their coefficients estimated by OLS are given by the diagram of Fig. 12. Note that the levels of J and T are each brought back by changing variables at the levels -1 (for the low level) and +1 (for the high level) when calculating each model.

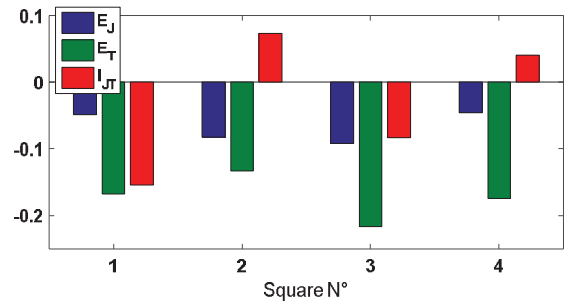


Fig. 12. Estimated coefficients of the four first order model L21 to L24

This diagram first confirms that the effect of the temperature (in green) is higher than that of the current density (in blue), whatever the experimental domain is. In contrast, unlike the extreme DoE model, the interaction between the two factors has a significant effect in each of the four registered DoEs. Finally, the effect of the current density (respectively the temperature) increases when the current levels (respectively the temperature levels) go from $[-1; 0]$ to $[0; 1]$. This phenomenon is observed by comparing, in Fig. 12, E_J between squares 1 and 4, on the one hand, and 2 and 3 on the other hand, and comparing E_T between squares 1 and 2, on the one hand, and 3 and 4 on the other hand.

C. First order model with 3 levels and interactions (model L3)

The decomposition of the 3-level DoE into 4 DoE with 2 levels therefore reveals non-linear effects of the current and temperature density as well as strong interactions between the two factors. In order to confirm these results, a last first-order model is built, based on a 3-level DoE. This model, (expression (5)) has the following form [27]:

$$L3 = \text{Log}(L_{70}) = M + [E_{J_{-1}} \ E_{J_0} \ E_{J_{+1}}][X_J] + [E_{T_{-1}} \ E_{T_0} \ E_{T_{+1}}][X_T] + [X_J]' \begin{bmatrix} I_{J_{-1};T_{-1}} & I_{J_{-1};T_0} & I_{J_{-1};T_{+1}} \\ I_{J_0;T_{-1}} & I_{J_0;T_0} & I_{J_0;T_{+1}} \\ I_{J_{+1};T_{-1}} & I_{J_{+1};T_0} & I_{J_{+1};T_{+1}} \end{bmatrix} [X_T] \quad (5)$$

The different coefficients of this model are calculated using the methods presented in [27] and expression (6) presents some examples. The corresponding coefficients of model L3 are listed in Table IX.

$$\begin{aligned} E_{11} &= \frac{1}{3}(Y_1 + Y_2 + Y_3) - M \\ E_{21} &= \frac{1}{3}(Y_1 + Y_4 + Y_7) - M \\ I_{11;21} &= Y_1 - M - E_{11} - E_{21} \\ I_{12;21} &= Y_4 - M - E_{12} - E_{21} \\ I_{13;21} &= -(I_{11;21} + I_{12;21}) \end{aligned} \quad (6)$$

TABLE IX
COEFFICIENTS OF MODEL L3 FOR A 3² DoE

Main factors	Interactions $X_J X_T$
$M = 3.287$	
$E_{J_0} = 0.053$	$I_{J_0 T_0} = -0.105$
$E_{T_0} = 0.056$	$I_{J_0 T_{+1}} = 0.060$
$E_{J_{+1}} = -0.174$	$I_{J_{+1} T_0} = 0.104$
$E_{J_{-1}} = -0.376$	$I_{J_{+1} T_{+1}} = -0.063$

This model confirms that when the interval $[-1; 1]$ is decomposed into two intervals $[-1; 0]$ and $[0; 1]$, the effects of

X_J and X_T are not the same in these two domains and the effect of the interactions is not negligible.

D. Second order models with interactions based on Surface Response (model L4)

In the case of two factors, the factorial plan with 3 equidistant levels (-1, 0 and 1) also constitutes a new DoE. Experiments 1 to 9 of Table V are used to estimate the 2nd order model with interactions having the form of (7):

$$\begin{aligned} L4 = \text{Log}(L_{70}) &= M + E_J X_J + E_T X_T + I_{JJ} X_J^2 \\ &\quad + I_{TT} X_T^2 + I_{JT} X_J X_T \\ L4 = \text{Log}(L_{70}) &= M + E_J X_J + E_T X_T + I_{JJ} X_J^2 \\ &\quad + I_{TT} X_T^2 + I_{JT} X_J X_T \end{aligned} \quad (7)$$

where I_{JJ} and I_{TT} are the quadratic effects of current density and temperature respectively. The coefficients of this model estimated by OLS are given in Table X.

TABLE X
ESTIMATED COEFFICIENTS FOR MODEL L4

M	3.396
E_J	-0.148
E_T	-0.348
I_{JJ}	-0.079
I_{TT}	-0.084
I_{JT}	-0.007

This model first confirms that the effect of temperature is higher than that of current density. It also shows a large quadratic effect of both factors. Moreover, the values of I_{JT} estimated by models L1 and L4 are the same.

E. Discussion

Comparison between the lifespan models L1 to L4 could be achieved in Fig.13. It can be seen that all the errors remain under 25%.

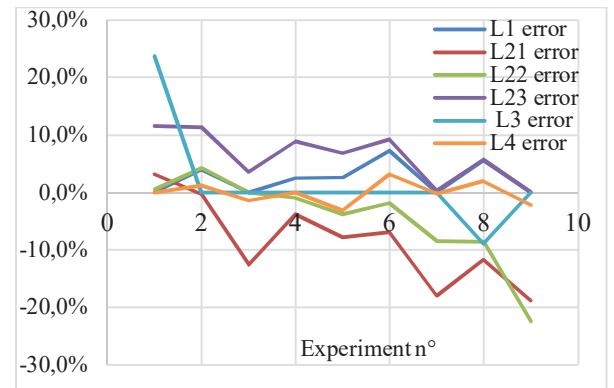


Fig. 13. Percentage of error on lifespan modelling with the 7 models L1, L21 to L24, L3 and L4

These models can be classified with respect to their accuracy, from the worst to the best: $L2x < L1 < L3 < L4$. Among all the proposed models, $L2x$ are obviously the less accurate regarding lifespan errors which remain anyway under 23%. This is certainly due to the relationship between lifespan and the two stress factors, temperature and current density. Consequently, it becomes obvious that models $L3$ (first order 3 levels) or $L4$ (response surface) lead to better results due to their ability to cope with nonlinear phenomena.

V. CONCLUSION AND PERSPECTIVES

This work enriches the previous studies on OLED lifespan thanks to DoE. This method was proven to be very helpful for this purpose. Indeed, the proposed models allow to studying the relative importance of stress factors. The temperature was shown to be predominant, compared with current density and possible interactions. Moreover, the proposed models show good performance for lifespan prediction in the most of the tested cases. Testing a higher number of OLEDs for each experiment would allow to analyzing more deeply the predictive quality of the proposed models and the variability and the statistical significance of models. Randomly configured additional points would also allow to analyze the dispersion and distribution of the lifespan and thus refine the model choice and parameter estimation method. Finally, the models could also be applied to other parameters than luminance such as color rendering index or equivalent electrical model parameters.

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