International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

OP52

FROM MEASUREMENTS TO STANDARDISED MULTI-DOMAIN COMPACT MODELS OF LEDS USING LED E-DATASHEETS

Genevieve Martin et al.

DOI 10.25039/x46.2019.OP52

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

FROM MEASUREMENTS TO STANDARDISED MULTI-DOMAIN COMPACT MODELS OF LEDS USING LED E-DATASHEETS

Martin, G.[1], Marty, C.[5], Bornoff, R[4]., Vaumorin, E.[6], Kleij, A.[1], Onushkin, G.[1], Poppe, A.[2,3]
[1] Signify (ex-Philips Lighting), NETHERLANDS, [2] Budapest University of Technology and Economics, HUNGARY, [3] Mentor, a Siemens business (ex Mentor Graphics), HUNGARY, [4] Mentor, a Siemens business (ex Mentor Graphics), UNITED KINGDOM, [5] Ingelux, France, [6] Magillem, FRANCE

Genevieve.martin@signify.com

DOI 10.25039/x46.2019.OP52

Abstract

In the context of Industry 4.0, the cornerstone for a robust and reliable LED luminaire design is the LED multi-domain compact model also called - LED digital twin. The creation of the multi-domain LED digital twin can be extracted from measured LED characteristics which could be reported in an e-datasheet. Standardised characterised data sets and data reporting are essential. The present paper illustrates the steps of the new LED-based luminaire digital design flow from LED characterisation, LED integration in the luminaire, optimisation through a luminaire design tool till final system.

Keywords: multi-domain compact model, LED, e-datasheet, design flow, LED luminaire design

Nomenclature

LED	Light Emitting Diode
PCB	Printed Circuit Board
MDCM	Multi-domain compact model
SPD	Spectral Power Distribution

1 Introduction

As the LED component is commoditizing, the lighting industry is entering another era with more demanding customers, market acceleration, and integration that extends beyond lighting (e.g. sensors). Industry 4.0 – the fourth industrial revolution that exploits automation and data exchange - favors acceleration and customization. In the current product development, the bottleneck is to get the proper set of data from LED suppliers in order to design first time right reliable product. A way to achieve this is 1- to create awareness among LED suppliers of what set of data is necessary during the design phase, 2- create a multi-domain LED compact model which will mimic the overall working space allowing LED suppliers to keep their confidential information. Besides, the adoption of the first LED digital twin will pave the way towards a digitalized design flow in early phase of development.

In a recent H2020 European wide research project, Delphi4LED [1], (Bornoff et al., 2016),(Marty et al., 2018), extensive studies for generating multi-domain (optical, thermal, electrical) compact LED models based on measurement data was conducted. The primary goal is to be able to elaborate methods and standards to predict, junction and solder temperatures, overall forward voltage, the light output characteristics of LED luminaires under different operating conditions (Poppe et al., 2019). The study covers the most common range of LED families and considers the needs from a luminaire design perspective (Alexeev et al., 2017).

Luminaire maker around the world need proper LED data for designing reliable and robust luminaires in its all functioning range. Current LED datasheet are not always reliable to use for designing luminaire. LEDs are now commodity and having a uniform set of data is not anymore sufficient for design purposes. Therefore, creating International Standard covering a- proper thermal, electrical and photometrical measurement characterization of LEDs and b- standardized reporting of LED specification are necessary.

The paper will present the key parameters required for a robust and reliable luminaire design, the standardised test to carry out to obtain LED characteristics that provide sufficient amount of information needed to set up appropriate models, the ultimate multi-domain compact model (MDCM) of LED packages, and a proposal for standardising data reporting in the form of e-datasheet that can link measurements and modelling.

The objectives of the Delphi4LED project covers: 1) proposing a generic measurement protocol and set of measurements considering the range of LED types available on the market, 2) proposing a method for creation of compact models of LEDs [both on die and package levels], 3) variability analysis, 4) a proposal of an LED e-datasheet.

2 Methodology

The primary step in creating multi-domain LED compact models is the measurement data collection from a physical device. Those collected data are gathered in an electronic datasheet called e-datasheet. The multi-domain LED compact model is extracted from the set of standardised measured data. Finally the LED digital twin can be implemented in a digital design flow.

2.1 Measurement and characterisation

In principle, thermal transient measurements are needed to capture all possible thermal properties of the junction-to-pad heat-flow paths of the LED packages and isothermal* electrical and light outputs characteristics (IVL characteristics). Our recommendation is that absolute spectral power distributions should be measured at such a combination of IF applied steady forward currents and TJ junction temperatures that cover the critical regions of the LED's quantum efficiency surface spanning over the IF-TJ plane, including the peak efficiency, and sufficiently wide regions of the high current and low current regimes.

Physical characterisation LED packages are performed according to JEDEC JESD 51-51, 51-52, JEDEC51-14 standards, considering junction temperature setting and total flux measurement recommendations of the Technical Report CIE 225:2017 Optical Measurements of High-Power LED document. In addition to these measurement standards and recommendations, sets of measurements are defined representing the relevant operating domains of the LED, as mentioned above. A fast measurement protocol is proposed to obtain accurate enough measurement data in a semi-automated way: the best approach is to have a combined thermal transient and radiometric/photometric measurement simultaneously.

Measurements are performed using Laboratory equipment. Those equipments provide RAW data that involve large amount of information, their organisation varies per equipment. Experimental conditions are also described in the RAW file. In Delphi4LED, an automatic extraction is done for all type of RAW files and stored in a simplified and organized way in the file named DET2.0. The data are reported in different sections for electronic data, thermal data, optical data. Figure 1 illustrates the arrangement of data from raw measurement data into a DET2.0 file format.

* Isothermal in terms of the T_J junction temperature.

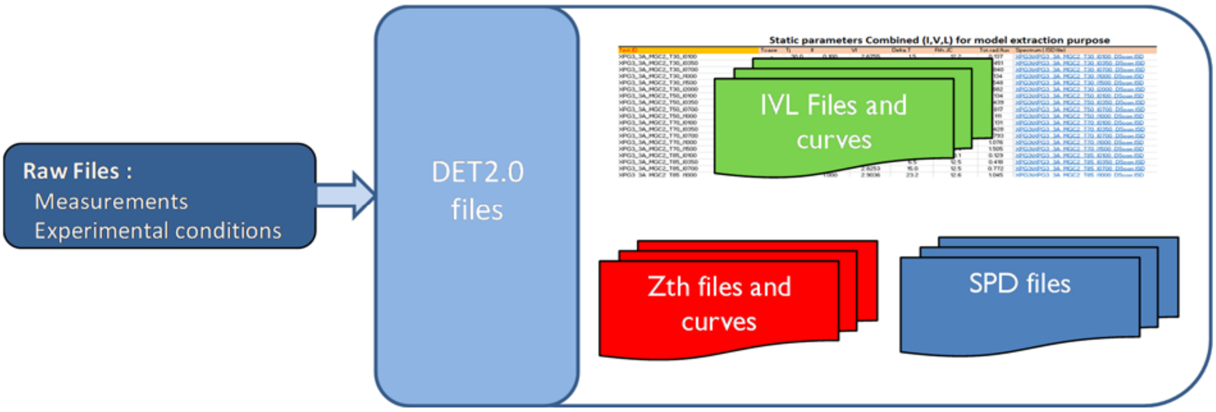


Figure 1 – Example of set of data from measurements to DET2.0 files

In our studies different LED families were characterised at targeted TJ-s between 25 °C up to 110 °C and in wide a range of forward currents, from the mA range up to maximum (e.g. to 1 A). On the contrary to most LED datasheet, a large amount of data is required to represent the full operating space of the LEDs. A minimal number of characterization points is determined by the requirements from model extraction procedure to which measurements will serve as input. Besides, it is important to keep a reasonable balance between accuracy, flexibility and complexity for LED MDCM, then a limited set of characterization results will be sufficient for a successful model extraction.

2.2 Multi-domain LED compact model extraction

The compact model creation is a dual approach at die level and package level. The resulting multi-domain LED compact model can either be used in a Spice-type circuit simulator, with commercially available CFD simulation tools and the multi-domain chip level LED model has also been implemented in spread-sheet based application as quick “luminaire design calculator” tool supporting initial sizing and design option selection.

(Poppe et al., 2019) elaborates in details the LED modelling and the parameters involved in the creation of the LED digital twin. Table 1 presents the set of parameters required for the creation of the compact model at die level. (Bornoff et al., 2017) presents in detail the extraction of the thermal compact model.

Table 1 – List of the parameters of the analytical, quasi black-box model (Poppe et al., 2019)

Input quantities: I_F, T_J			
Output quantities: V_F, P_H, Φ_e, Φ_V			
Model parameters			**Symbol in Spice diode model**
Thermal	T_{ref}, V_T		**TNOM, UT**
Electrical	**entire LED**	**radiative branch only**	
diode internal pn-junctions at T_{ref}	$I_0,\ m$	$I_{0_{rad}},\ m_{rad}$	**IS, N**
resistors at T_{ref}	R_S	R_R	**RS** = 0 to switch of Spice's model of the series resistance
Coefficients of the model of the “ΔV_F generators”	$a_{el},\ b_{el},\ c_{el},\ d_{el},\ e_{el},\ f_{el}$	$a_{rad},\ b_{rad},\ c_{rad},\ d_{rad},\ e_{rad},\ f_{rad}$	-
Coefficients of the efficacy of radiation model	$a_{Kap},\ b_{Kap},\ c_{Kap},\ d_{Kap},\ e_{Kap},\ f_{Kap},\ g_{Kap},\ h_{Kap},\ i_{Kap}$		-

In modelling, variability of model parameters and selection of the nominal device characteristics of a given LED population is an important question, which was also covered in Delphi4LED project, however, this topic extends the limits of this paper therefore it is discussed in a separate publication.

In an “Industry 4.0” context, such multi-domain compact model is called “digital twin”.

Figure 2 illustrates the journey from raw data to extracted data.

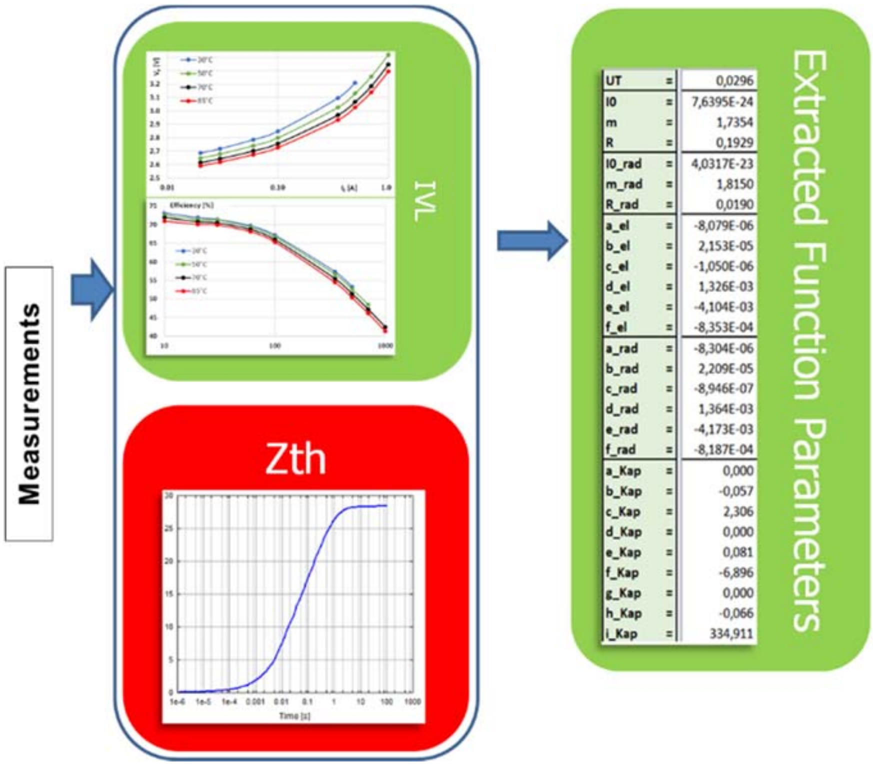


Figure 2 – From Raw data to extracted data into e-datasheet

2.3 E-datasheet proposal

In order to be able to create a multi-domain LED from measurement data, automated and standardised interfaces are key. For an automated model parameter extraction procedure the collected data should be organized and provided in a machine readable format, that we call e-datasheet which is the foundation of an accurate LED compact model destined to product design. In the context of an Industry 4.0 approach this e-datasheet is the starting point of creating the digital twins of the physical devices.

Following the already established standards of the electronics industry for data exchange among electronic design automation tools (see the recent JEDEC JESP 30 standard), an XML schema based approach is suggested. Such a format allows communicating scalar-like quantities such as total flux values, function-like properties such as spectral power distributions or package Zth curves, and matrix like properties like Φe(IF, TJ) or VF(IF, TJ) surfaces in properly structured (tabulated) way, both in a machine and human readable format, close to the present file formats of test equipment manufacturers.

The extracted data can be stored in an electronic datasheet.

The xml-based file format, as presented in Figure 3 will include the minimum set of information necessary for the creation of an LED MDCM. It could also permit the storage of additional information issued from the measurements such as the spectral power distribution (SPD) data or other helpful elements for future additional simulations. Those information could also be stored using external reference. A guideline will be produced for the way to fill-in this type of format.

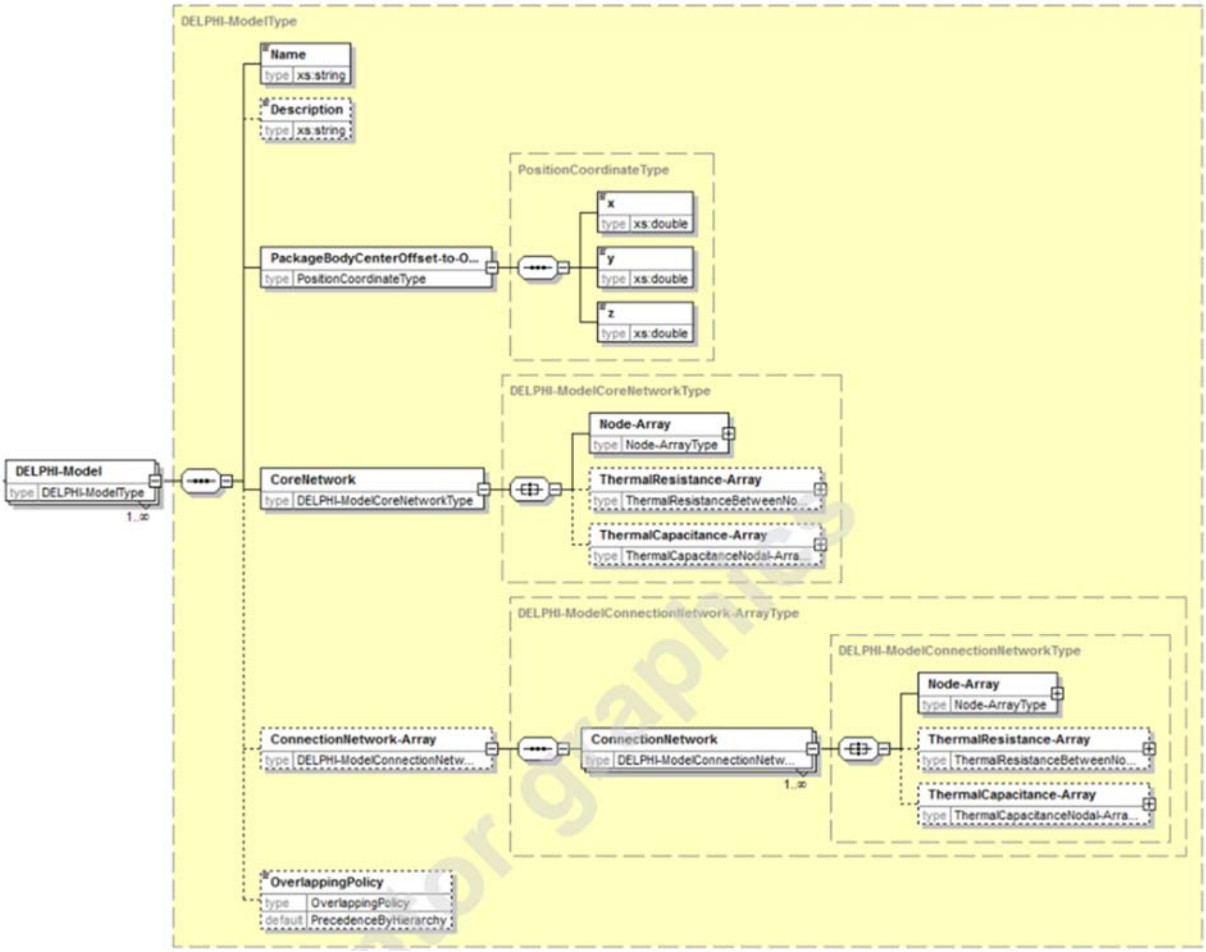


Figure 3 – Proposed e-datasheet

2.4 Implementation of the LED digital twin in an "Industry 4.0" context

The lighting industry contains multiple players. Those players can be split in two categories: small and medium enterprise (SME) and large players (Majors). In the current luminaire design context, the first group usually uses a trials and error using prototyping; the second group possess more knowledge and means for development and has a more extensive use of CFD simulation tools. In both cases, a lot of time and money is spent during the design phase. SME uses prototyping; the second performed reversed engineering of LEDs parts to get the required information for design.

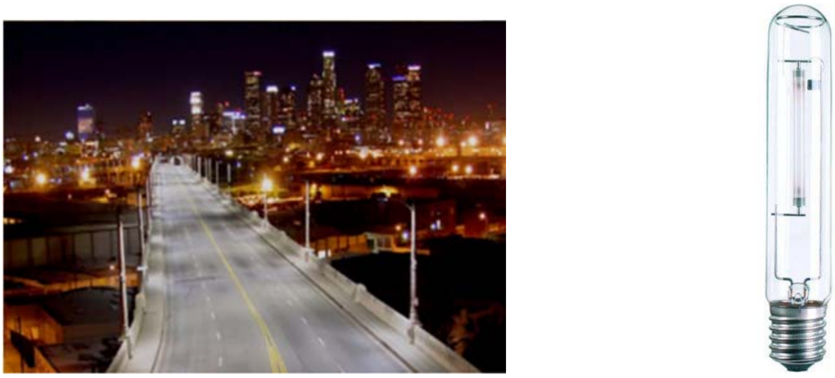
Delphi4LED proposes a new luminaire design flow considering as input: design goals, design constrains. Goal could be minimum emitted total luminous flux. Design constrains could consist in requirements of driver (maximum allowed electrical power, efficiency), lifetime (maximum allowed junction and solder temperatures) and optical (efficiency). (Marty et al., 2018), (Martin, 2019). A luminaire design calculator developed during the project integrates the full system conditions; i.e. LED (chip+package), substrate, luminaire. The design phase consists in varying parameters such as type of LEDs, number of LEDs, type of substrate to obtain a fully optimised design by matching goals and constrains.

The combined chip+package+substrate+luminaire model is the "digital twin" of a foreseen luminaire. This virtual prototype allows computer simulation assisted or computer simulation based optimization of an LED application with reduced time and cost.

2.5 Case study

In an earlier study, the modelling approach was tested with the design of a new LED based product. The design options were compared and design decision made considering product performance achieved, time of development, costs of measurements, and improvement of efficiency of the final product were assessed, compared with a traditional way of designing the same product. (Martin, 2019).

The case under study targets the replacement of an High Intensity Dischage (HID) lamp by an LED lamp dedicated to street application (see Picture 1). In the following, the lamp will be called the system. The system targets a goal of 6000lm and has to fulfil constrains of maximum junction and solder temperatures.



Picture 1 – Example of street application and its current lamp solution (High Intensity Discharge lamp)

3 Results: the case study

The following presents the steps of the design flow through the case study chosen.

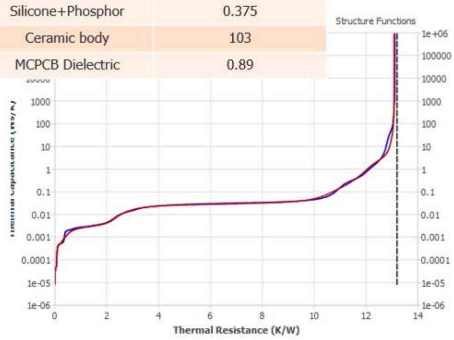
3.1 Characterisation results

Figure 4 presents the data extracted from measurements. Those data can be use for the creation of the multi-domain LED digital twin. It is the intention to report those data in the form of an e-datasheet as presented in Figure 3. Typically LED supplier could provide those e-datasheet.

A	B	C	D	E	F	G	H
15			4				
Sample:			**XPG3_01**	**XPG3_02**	**XPG3_03**	**XPG3_04**	**XPG3_05**
Max Vf error:			0%	1%	0%	0%	0%
Max Fi_e error:			1%	1%	1%	1%	1%
Max Fi_v error:			1%	1%	1%	1%	1%
	UT	=	0,0296	0,0296	0,0296	0,0296	0,0296
	I0	=	7,6395E-24	6,9812E-24	8,1736E-24	7,2375E-24	7,6335E-24
	m	=	1,7354	1,7349	1,7359	1,7353	1,7358
	R	=	0,1929	0,2141	0,197	0,2138	0,1973
	I0_rad	=	4,0317E-23	3,4889E-23	3,4027E-23	3,3826E-23	3,1585E-23
	m_rad	=	1,8150	1,8131	1,8075	1,8107	1,8089
	R_rad	=	0,0190	0,021001	0,020001	0,021001	0,019001
	a_el	=	-8,079E-06	-2,501E-06	-6,348E-06	1,973E-07	-3,155E-06
	b_el	=	2,153E-05	1,209E-05	1,762E-05	7,854E-06	1,475E-05
	c_el	=	-1,050E-06	2,362E-06	-5,003E-08	2,998E-06	-4,546E-07
	d_el	=	1,326E-03	5,207E-04	1,085E-03	1,150E-04	4,845E-04
	e_el	=	-4,104E-03	-2,919E-03	-3,586E-03	-2,243E-03	-2,982E-03
	f_el	=	-8,353E-04	-1,348E-03	-9,861E-04	-1,462E-03	-9,515E-04
	a_rad	=	-8,304E-06	-2,668E-06	-6,589E-06	2,394E-07	-3,053E-06
	b_rad	=	2,209E-05	1,261E-05	1,824E-05	8,137E-06	1,492E-05
	c_rad	=	-8,946E-07	2,563E-06	8,893E-08	3,154E-06	-1,960E-07
	d_rad	=	1,364E-03	5,481E-04	1,127E-03	1,034E-04	4,618E-04
	e_rad	=	-4,173E-03	-2,981E-03	-3,670E-03	-2,259E-03	-2,985E-03
	f_rad	=	-8,187E-04	-1,338E-03	-9,643E-04	-1,449E-03	-9,417E-04
	a_Kap	=	0,000	-0,002	-0,001	-0,002	-0,003
	b_Kap	=	-0,057	0,320	0,123	0,326	0,463
	c_Kap	=	2,306	-12,216	-5,028	-12,613	-17,489
	d_Kap	=	0,000	0,002	0,000	0,002	0,002
	e_Kap	=	0,081	-0,181	-0,028	-0,221	-0,324
	f_Kap	=	-6,896	3,296	-0,971	5,542	8,955
	g_Kap	=	0,000	0,000	0,000	0,000	0,000
	h_Kap	=	-0,066	-0,082	-0,088	-0,055	-0,057
	i_Kap	=	334,911	333,904	333,653	333,397	333,066

a)

Thermal Conductivity	Calibrated value (W/mK)
Solder	36.7
Silicone+Phosphor	0.375
Ceramic body	103
MCPCB Dielectric	0.89



b)

Figure 4 – Example of extracted data for the creation of the LED compact model

3.2 Design flow

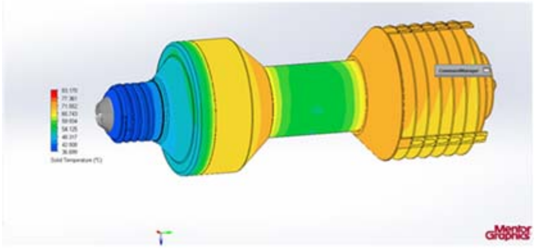
The digital twin is combined with the substrate to form the NETLIST presented in Figure 5-a. The NETLIST can be program in the form of a script into commercially available simulation tool. In short, the system level 3D CAD system is combined with the NETLIST.

```
*XPG3board  Rjs
Rjc1 Junction1    Pos1   3.47
Rjc2 Junction2    Pos2   3.47
Rjc3 Junction3    Pos3   3.47
Rjc4 Junction4    Pos4   3.47
Rjc5 Junction5    Pos5   3.47

*Substrate
RPos1MCPCB_bot Pos1 MCPCB_bot 13.0789793
RPos2MCPCB_bot Pos2 MCPCB_bot 11.4229319
RPos3MCPCB_bot Pos3 MCPCB_bot 10.7096081
RPos4MCPCB_bot Pos4 MCPCB_bot 11.3707428
RPos5MCPCB_bot Pos5 MCPCB_bot 13.043822
RPos1Pos2 Pos1 Pos2 157.222636
RPos2Pos3 Pos2 Pos3 358.358111
RPos3Pos4 Pos3 Pos4 354.782076
RPos4Pos5 Pos4 Pos5 152.092579

*Luminaire to ambient
R_MCPCB_Bot_0    MCPCB_Bot   0   1.99062108
```

a)



b)

Figure 5 – Example of a) a NETLIST of LED+substrate and b) the system digital twin

3.3 Example of results

Table 2 and Table 3 presents simulation results of the system for two different LED types XPG3 and NF2L757DRT-V1. It shows that, in this particular case, XPG3 is fulfilling all the constrains and the target goal of 6000lm. The final decision might take into account commercial aspect like cost.

Table 2– Results for XPG3 4000K CRI 70 high power LEDs on PCB, Tpcb_bottom = 45 °C

Parameter	5 LEDs; 500 mA	22 LEDs; 100 mA
Tsolder [°C]	51.6	46.9
Tjunction [°C]	54.3	47.3
Light output per PCB [lm]	1056	1049
Total Light output [lm]	6336	6294
Efficacy [lm/W]	150	180

Table 3– Results for Nichia NF2L757DRT-V1 4000K CRI 80mid-power LEDs on PCB, Tpcb_bottom = 45 °C

Parameter	5 LEDs; 200 [mA]	22 LEDs ; 60 [mA]
Tsolder [°C]	51.8	47.6
Tjunction [°C]	61.1	49.7
Light output per PCB [lm]	664	1008
Total Light output [lm]	3984	6050
Efficacy [lm/W]	105	136

4 Conclusions

The present paper walk the reader through a case study illustrating the steps of the proposed digital design flow of an LED luminaire. It showed that the combined chip+package, +substrate, +luminaire model is the “digital twin” of a foreseen luminaire. This virtual prototype allows computer simulation assisted or computer simulation based optimization of an LED application coupled to a luminaire design calculator.

In the context of Industry 4.0, a new design flow is proposed. The LED MDCM, also called LED digital twin is key to a robust luminaire design. It is extracted from a defined set of measurement data and simulation, reported in an E-datasheet. The data reported in the form of an e-datasheet is the cornerstone to a sustainable approach within the lighting industry and forms the bridge between luminaire maker and LED suppliers.

References

1. Delphi4LED project website. Available online: https://delphi4led.org (Accessed: 27 March 2019).

ALEXEEV, A., BORNOFF, R., LUNGTEN, S., MARTIN, G., ONUSHKIN, G., POPPE, A., RENCZ, M., YU, J., 2017. Requirements specification for multi-domain LED compact model development in Delphi4LED, *18th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Dresden, Germany, 3-5 April 2017*, DOI: 10.1109/EuroSimE.2017.7926296

BORNOFF, R.; HILDENBRAND, V. ; LUNGTEN, S.; MARTIN, G.; MARTY, C.; POPPE, A.; RENCZ, M.; SCHILDERS, W. ; YU, J. 2016. Delphi4LED - From Measurements to Standardized Multi-Domain Compact Models of LEDs: a New European R&D Project for Predictive and Efficient Multi-domain Modeling and Simulation of LEDs at all Integration Levels Along the SSL Supply Chain., *In: Proceedings of the 22nd International Workshop on THERMal INvestigation of ICs and Systems (THERMINIC'16), Budapest, Hungary 21-23 September 2016*, pp. 174-189, DOI: 10.1109/THERMINIC.2016.7749048

BORNOFF, R. 2019. Extraction of Boundary Condition Independent Dynamic Compact Thermal Models of LEDs – a Delphi4LED Methodology. *Energies*, submitted to the **Special issue on** Thermal and Electro-thermal system simulations

MARTIN, G., POPPE, A., YU, J., ONUSHKIN, G., MARTY C., BORNOFF, R., RENCZ, M. 2019. Luminaire Digital Design Flow with Multi-Domain Digital Twins of LEDs, *Energies*, submitted to the **Special issue on** Thermal and Electro-thermal system simulations

MARTY, C.; YU, J.; MARTIN, G.; BORNOFF, R.; POPPE, A.; FOURNIER, D.; MORARD, E. 2018. Design flow for the development of optimized LED luminaires using multi-domain compact model simulations. *In: Proceedings of the 24th International Workshop on THERMal INvestigation of ICs and Systems (THERMINIC'18), Stockholm, Sweden, 26-28 September 2018*, DOI: 10.1109/THERMINIC.2018.8593318

POPPE, A.; FARKAS, G. ; GAÁL, L.; HANTOS, G.; HEGEDÜS, J.; RENCZ, M. 2019. Multi-domain modelling of LEDs for supporting virtual prototyping of luminaires, *Energies*, submitted to the **Special issue on** Thermal and Electro-thermal system simulations