SCEE 2022

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Creating new multi-domain digital twins of LEDs with an attempt to describe their ageing for predictive maintenace schemes

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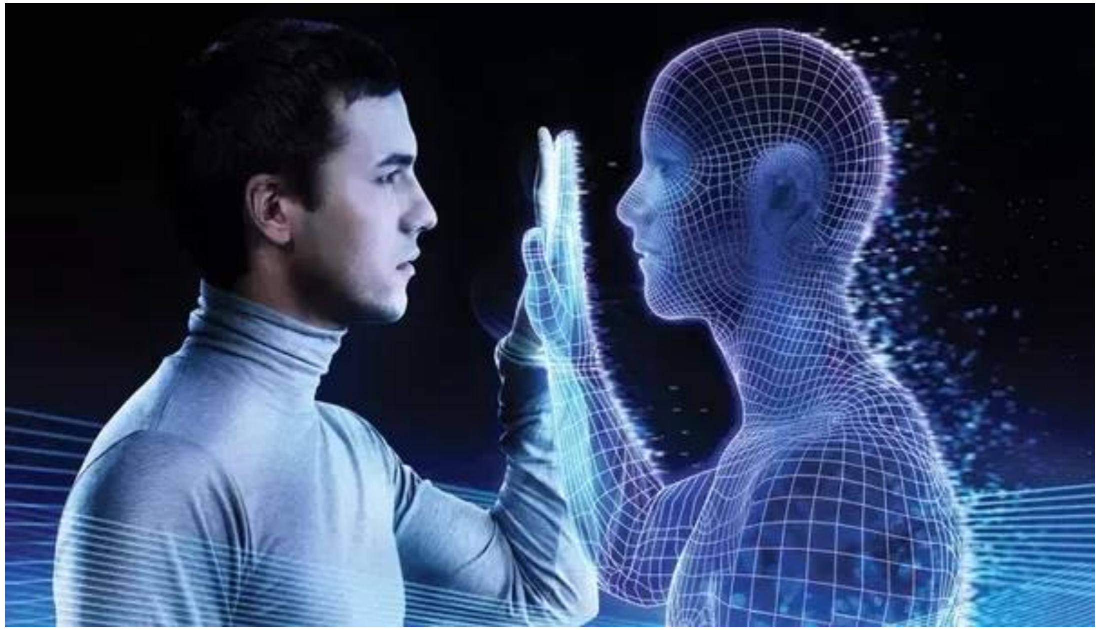
What are the digital twins (DT-s)?

"**Digital twin** refers to a **digital replica of physical assets, processes and systems** that can be used for various purposes. The digital representation provides both the elements and the dynamics of how an IoT device, equipment, or machine operates and lives throughout its life cycle.“

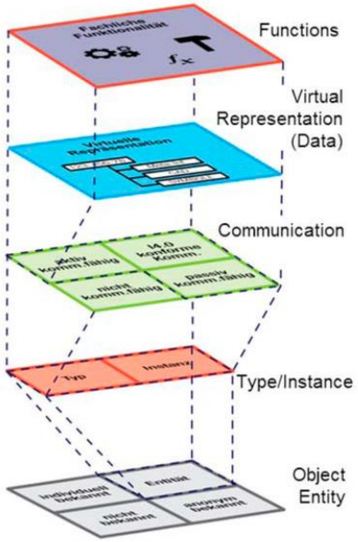
https://niotek.net/digital-twin/



https://niotek.net/digital-twin/

With the help digital twins:

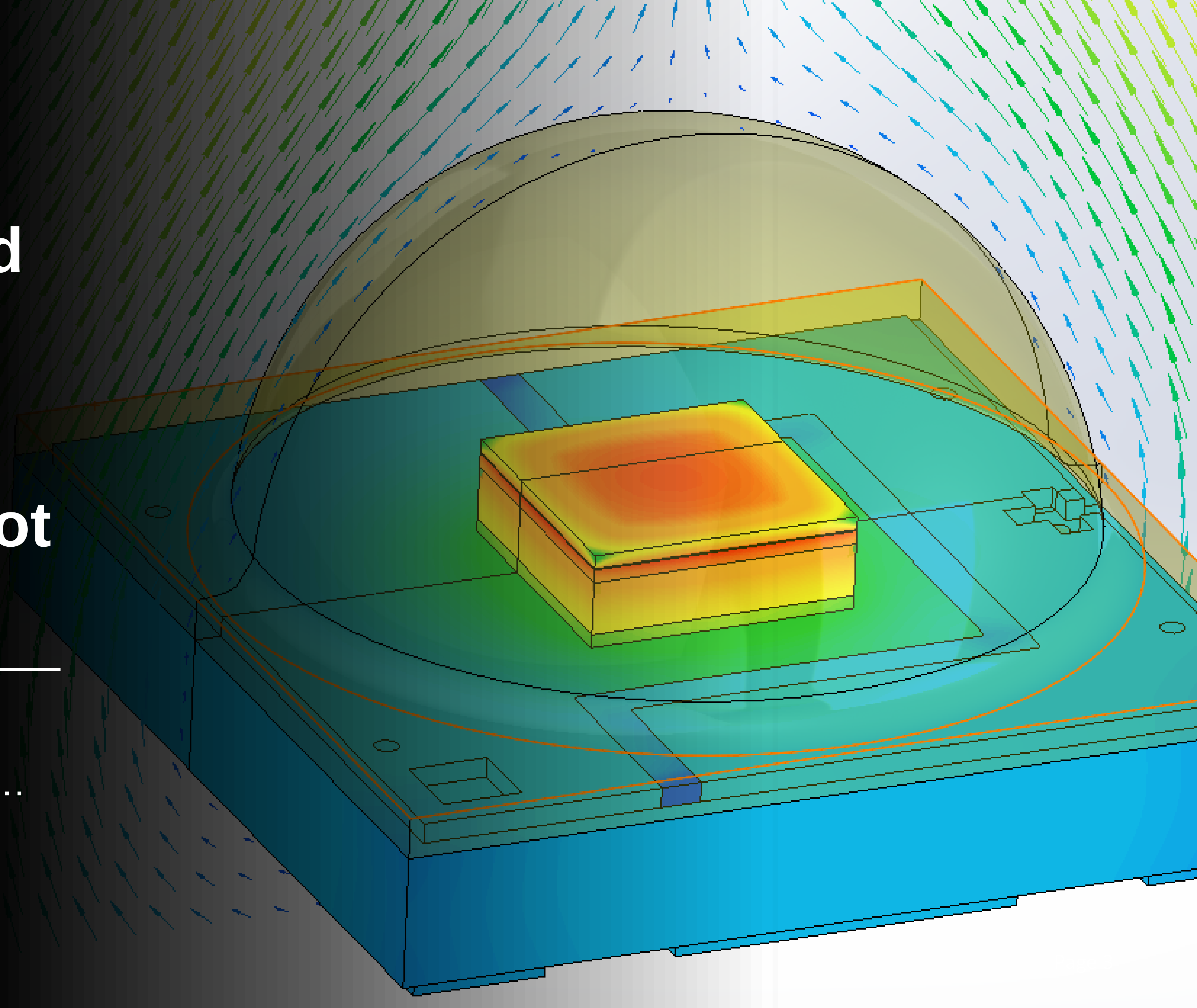
- **Product design/development can be speeded up** and development costs can be reduced by avoiding iteration cycles that traditionally involve building and testing physical prototypes ➔ **virtual prototyping**
  - Complex optimization
- **During lifetime**, monitoring, diagnostics, prognostics, optimization of operation (performance, utilization) can be achieved by a DT



Schluse, M.; Rossmann, J. From simulation to experimentable digital twins: Simulation-based development and operation of complex technical systems, https://dx.doi.org/10.1109/SysEng.2016.7753162

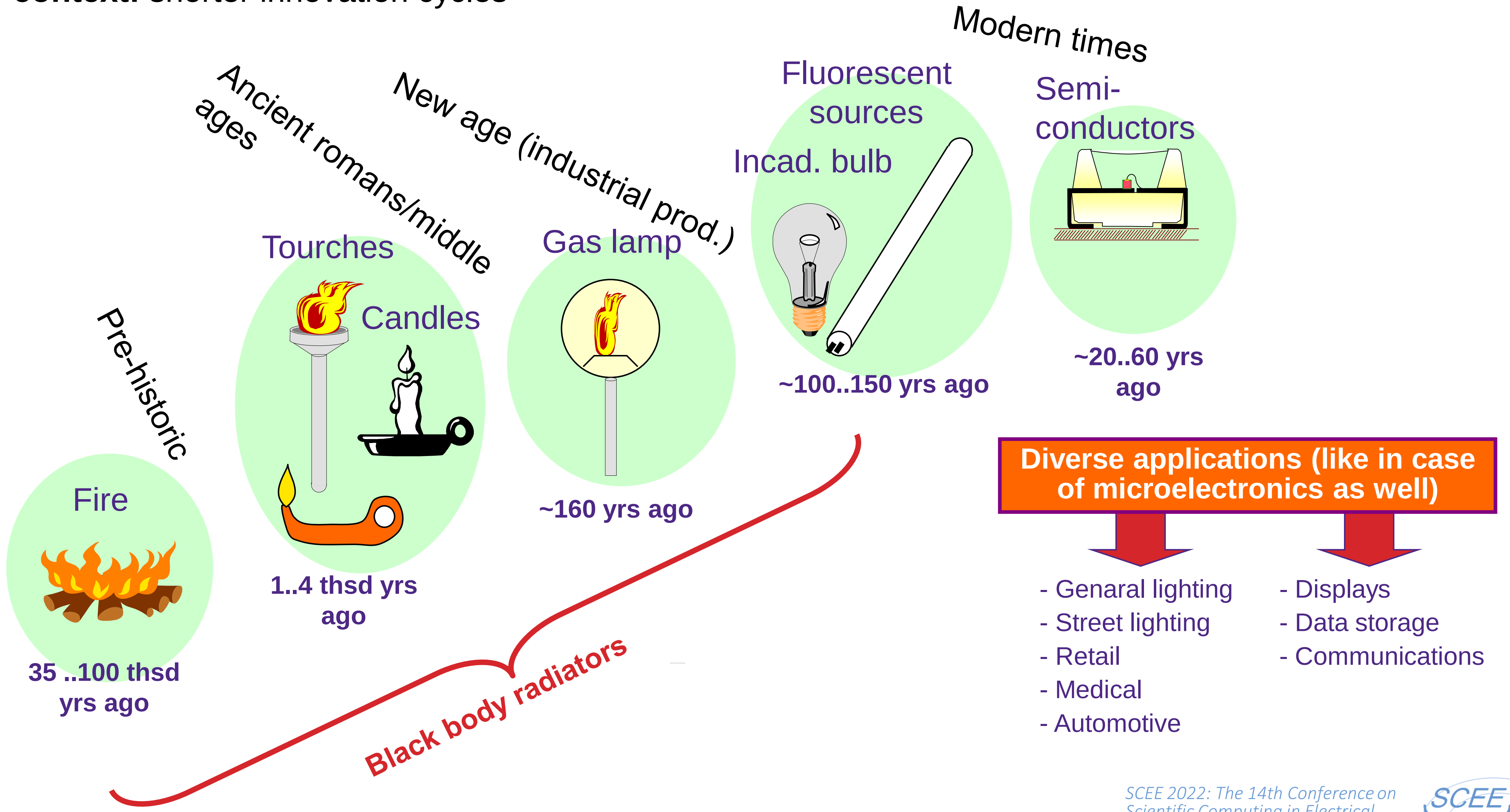
Why do we need digital twins of LEDs and LED luminaieres? Why now and not earlier?

A wider context in terms of history, trends, LED behaviour…



Why to deal with digital twins of LEDs?

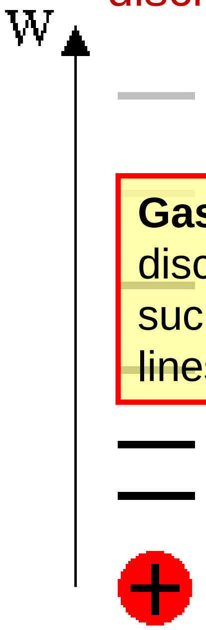
The wider context: shorter innovation cycles



Why to deal with digital twins of LEDs?

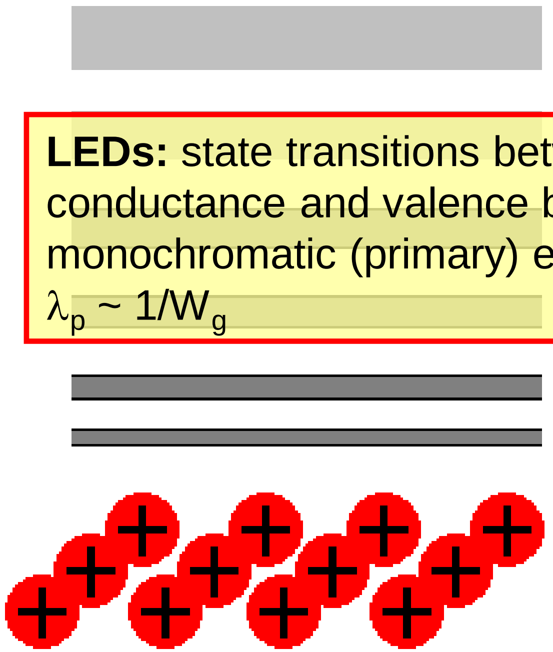
The wider context: vacuum technology replaced by **semiconductor technology** and electronics assembly

discrete energy levels of electrons



Gas discharge lamps / CFLs: discrete state transitions among such niveous ➔ discrete spectrum lines

in the semiconductor crystal, the single niveous split into bands



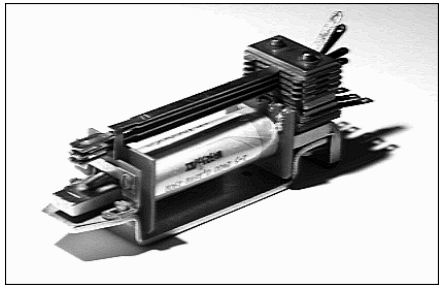
LEDs: state transitions between the conductance and valence bands ➔ almost monochromatic (primary) emission, $\lambda_p \sim 1/W_g$

classical light sources	**solid-state light sources**
electron tubes	semiconductor diodes / transistors
vacuum technology	**semiconductor technology**
Heating needed / helps the operation	**Cooling is required for the proper operation**

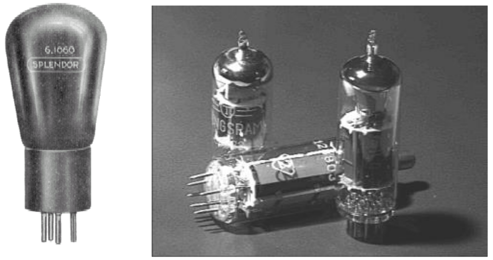
Why to deal with digital twins of LEDs?

The wider context: electric lighting has a similar development path as electronics, catching up in speed…

1837 Morse: telegraph (electro mechanical)

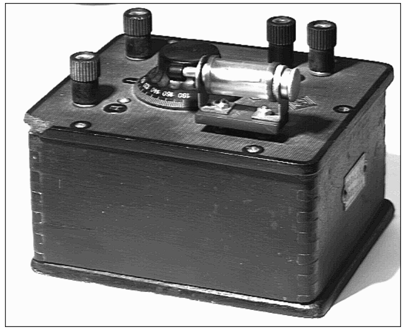


Electron tubes (rectifiers, amplifiers)

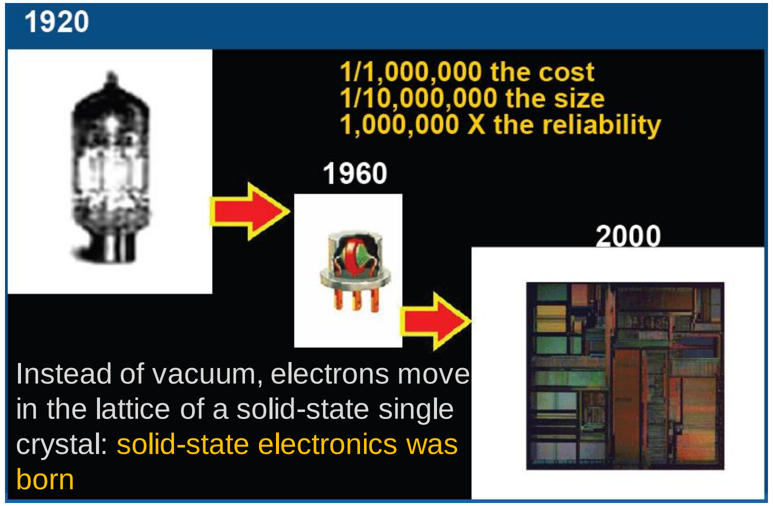


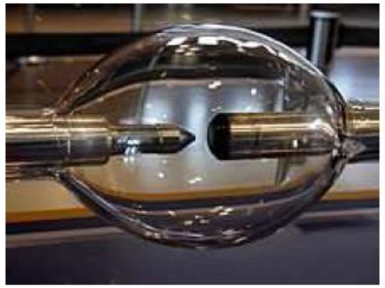
Electron devices

All electric radio



Based on electron devices electronics was born





Arc lamp: 1841

Edisons light bulb: 1879

Fluorescent lamp: 1926

First LEDs (red): 1962

1989: GaN homo-junction LED
1993: High efficiency blue LED
2014: Nobel Prize for Physics

The high-efficiency "L-prize" bulb, August 2011 (60W incandescent replacement)

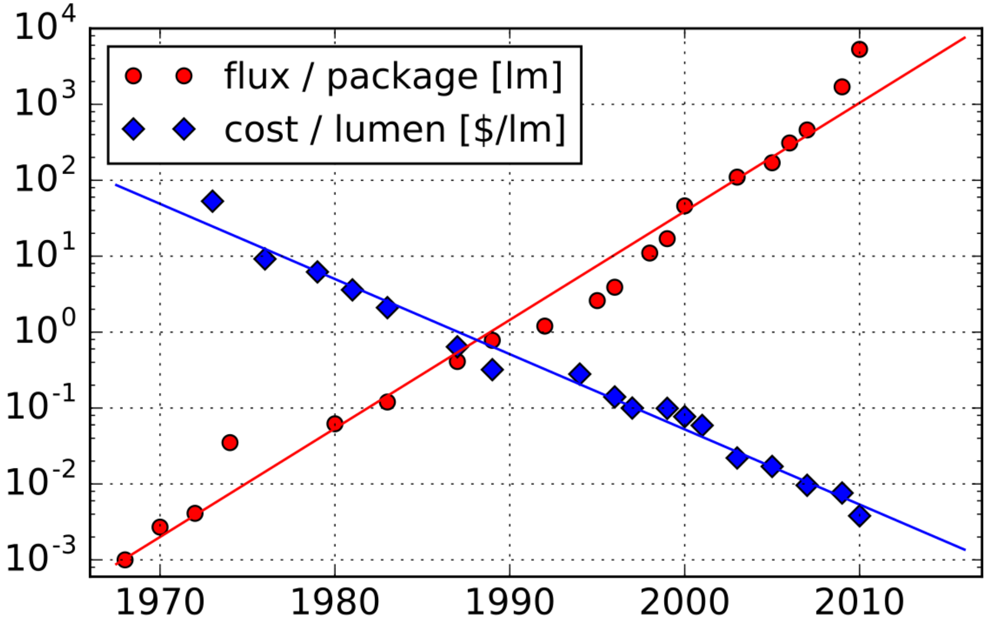
LED lamps: ~1998

Philips' 70W HPS replacement, 2018

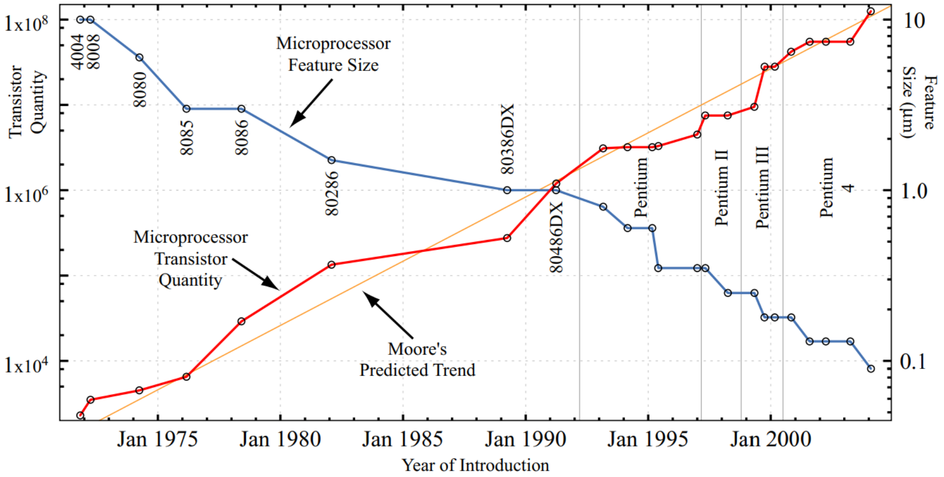
Philips' Hue bulbs with integrated smart control + communications, October 2012, for Iphone

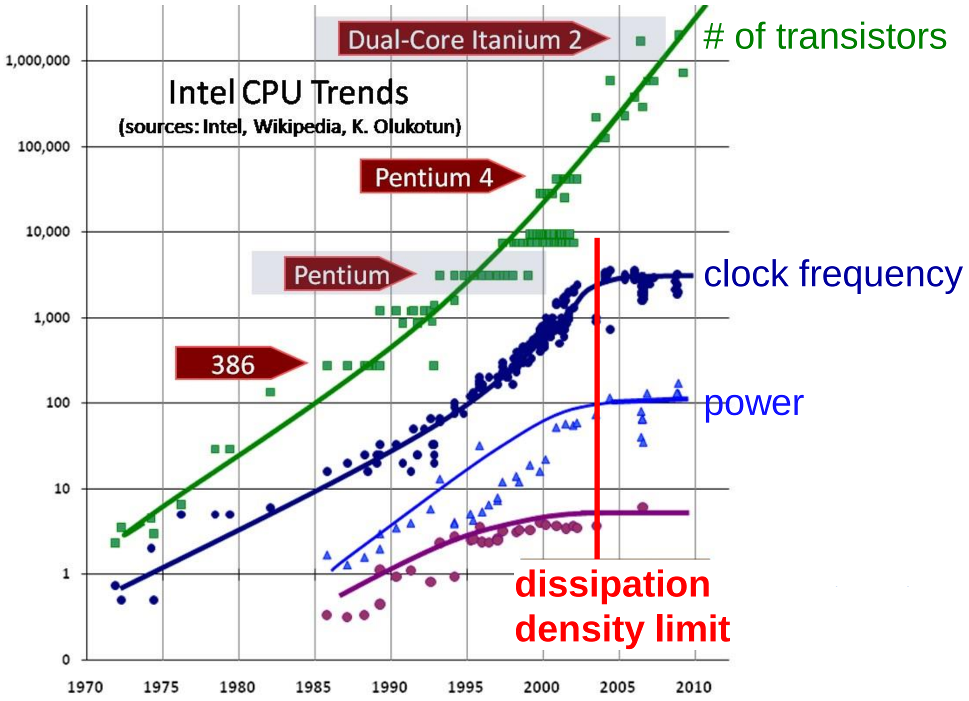
Why to deal with digital twins of LEDs?

The wider context: solid-state lighting has similar development trends as microelectronics:
Haitz's law is the Moore's law of SSL



https://www.researchgate.net/publication/224704395_Evolvable_Hardware_a_Fundamental_Technology_for_Homeostasis





There are fundamental limits of development…

An important practical limit though, both in microelectronics and SSL, is the manageable heat dissipation density…

The (solid-state) lighting industry became a special part of the electronics industry

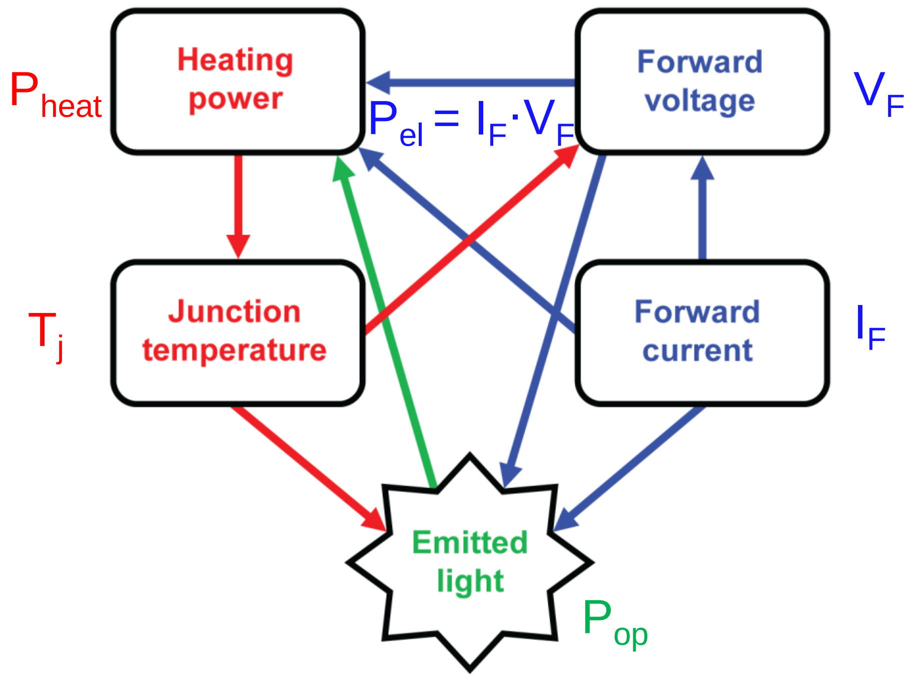
- **Success in LEDification ➔ classical light sources disappear** (as well as their manufacturers)
  - Selling incandescent bulbs banned in the EU, CFLs begin to phase out now
  - LED retrofit HPS replacement on the market

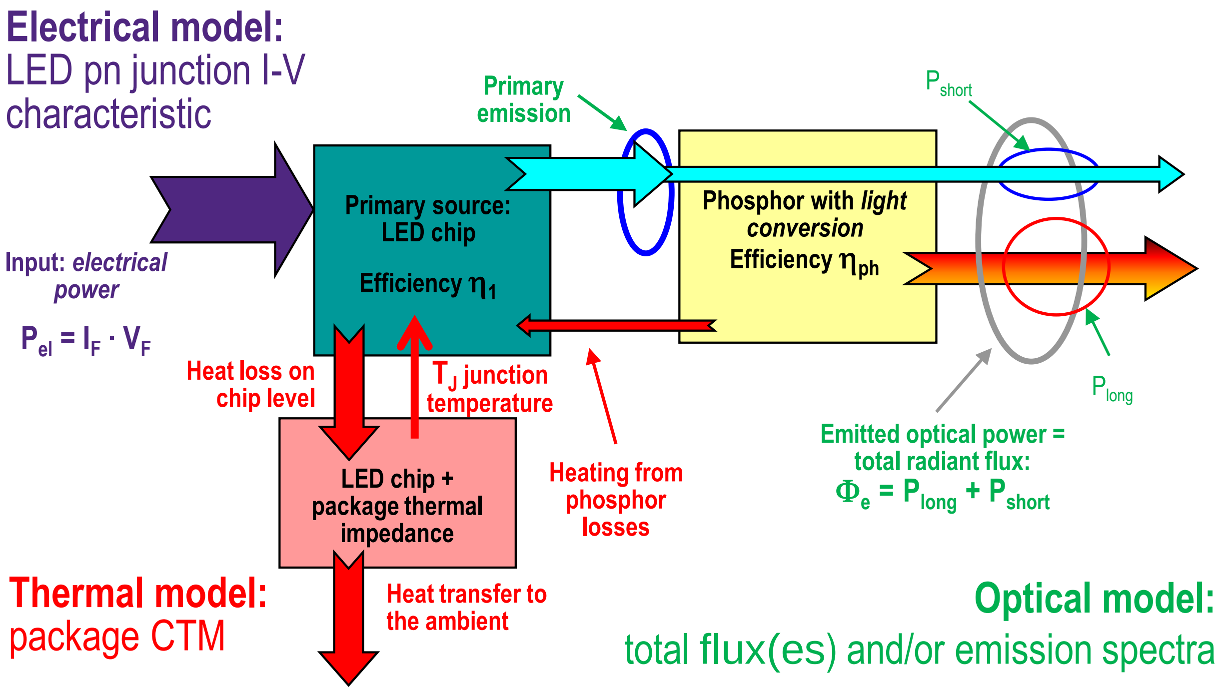
  On top of the above, ***today's high energy prices*** (gas, electricity) represent further ***drives for rapid changes***
    - Glass-based solutions are becoming too expensive to produce due to the high energy need of manufacturing (glass factories for bulb manufacturing are in trouble). *Is manufacturing of filament LED bulbs in danger?*
    - Energy cost reduction is getting even more urgent than a few years ago…
- **LEDs are semiconductor devices**
  - Characteristics of the semiconductor industry apply…, e.g. computerized, simulation-based design: wide use of TCAD and EDA tools
- **LED modules are produced by electronics assembly processes**
  - PCB design and manufacturing
- **LED luminaires are complex electronic systems** (classical ones were just lamp fixtures & holders of optics)
  - LED luminaires include delicate electronics (LED drivers, smart controls, diagnostics, communications)
  - LEDs need proper cooling, thus, luminaires have to provide delicate thermal management solutions as well

Until recently, using EDA tools has not been a common practice at luminaire makers, electrical, mechanical and optical design teams are de-coupled

Why to deal with digital twins of LEDs?

The wider context: complex operation in 3 closely coupled operating domains…



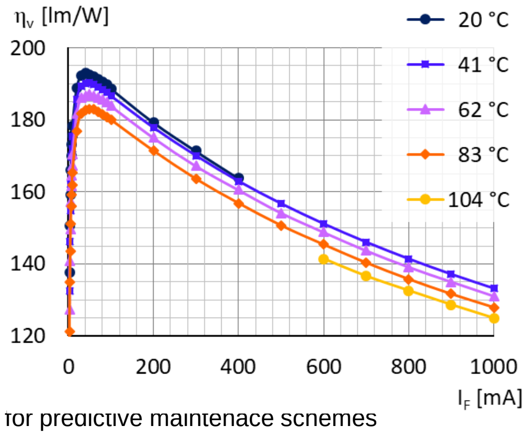


LEDs' electric operating point determines its light output but also gives rise to self-heating.

$$P_{opt} = P_{el} - P_{heat}$$

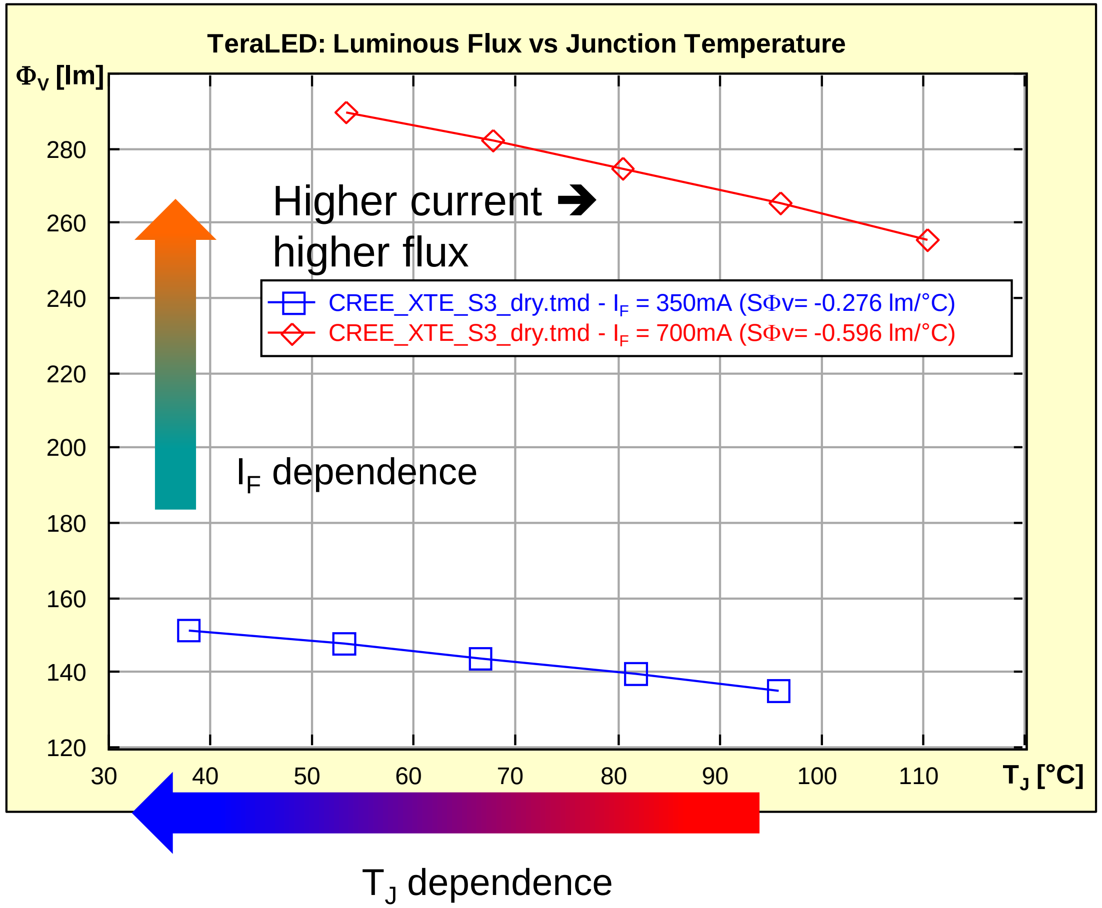
More heat results in higher junction temperature

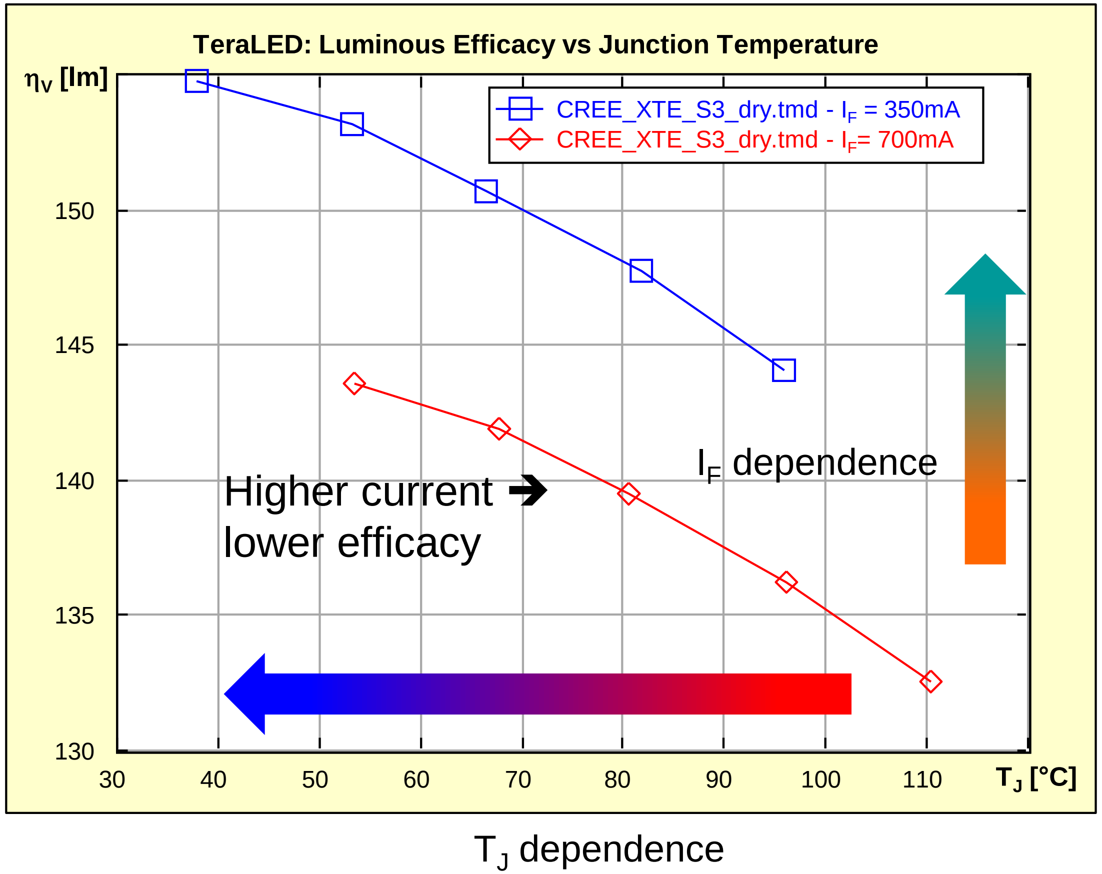
Higher junction temperature results in reduction of efficiency and shorter lifetime…



Why to deal with digital twins of LEDs?

The wider context: LED operating point has to be optimized that needs careful design based on simulations





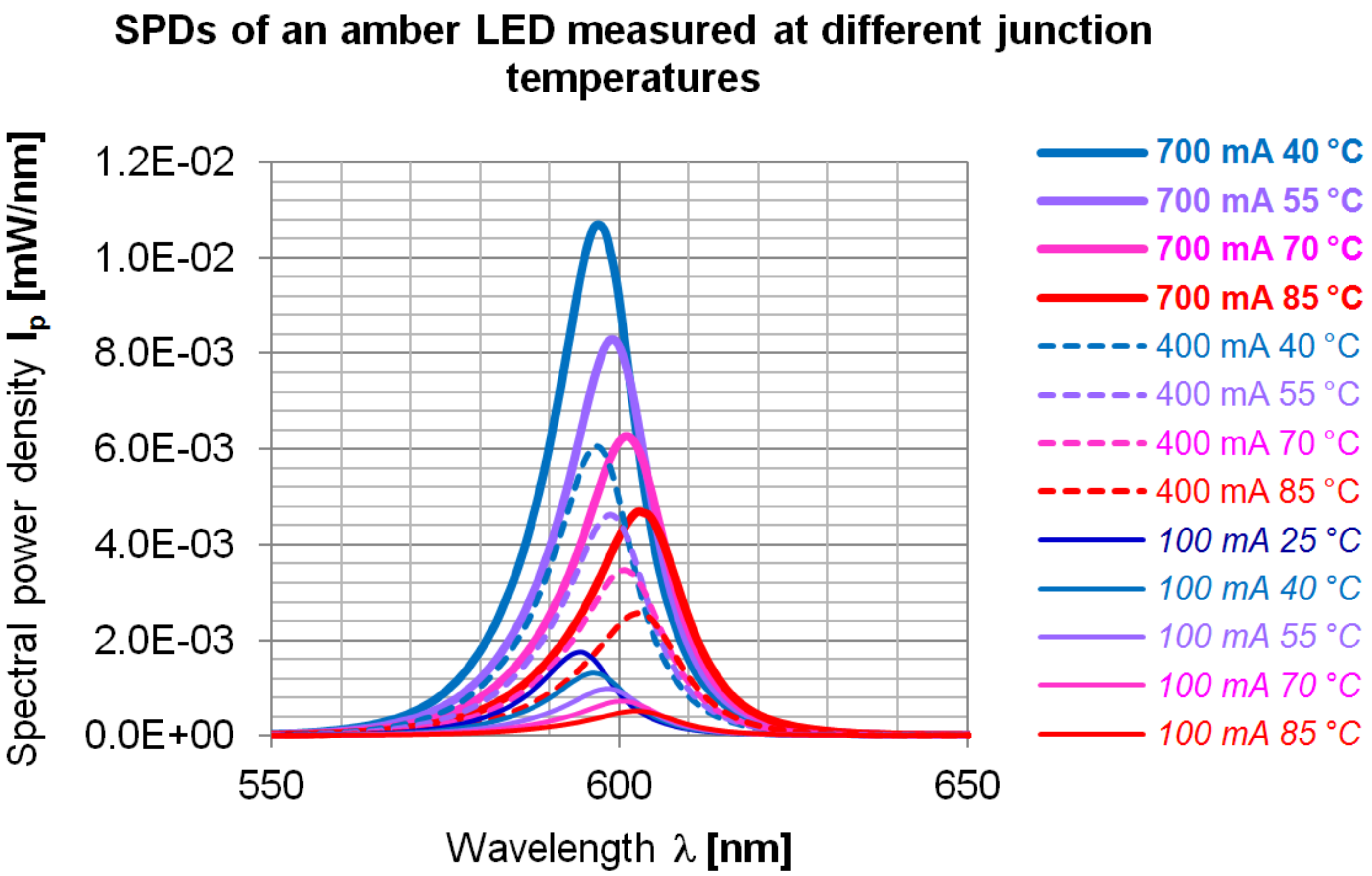
At higher current more light is generated but less efficiently. How to find good trade-offs?

Why to deal with digital twins of LEDs?

The wider context: some other aspects of the LEDs' complex operation

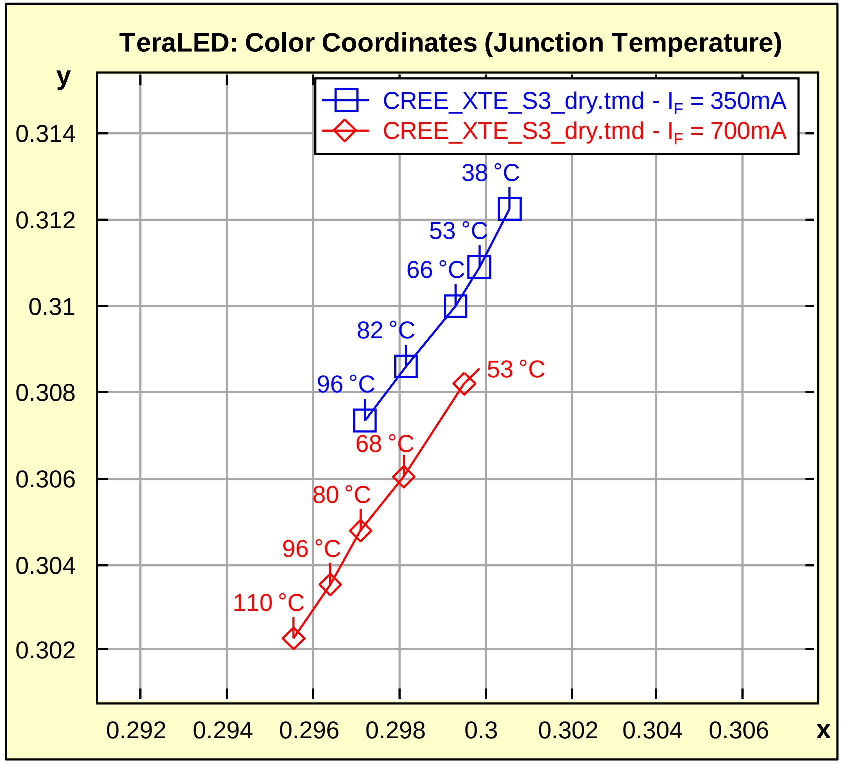
Peak wavelength & intensity vs. T_J for a colour LED

Peak wavelength shifts, intensity diminishes



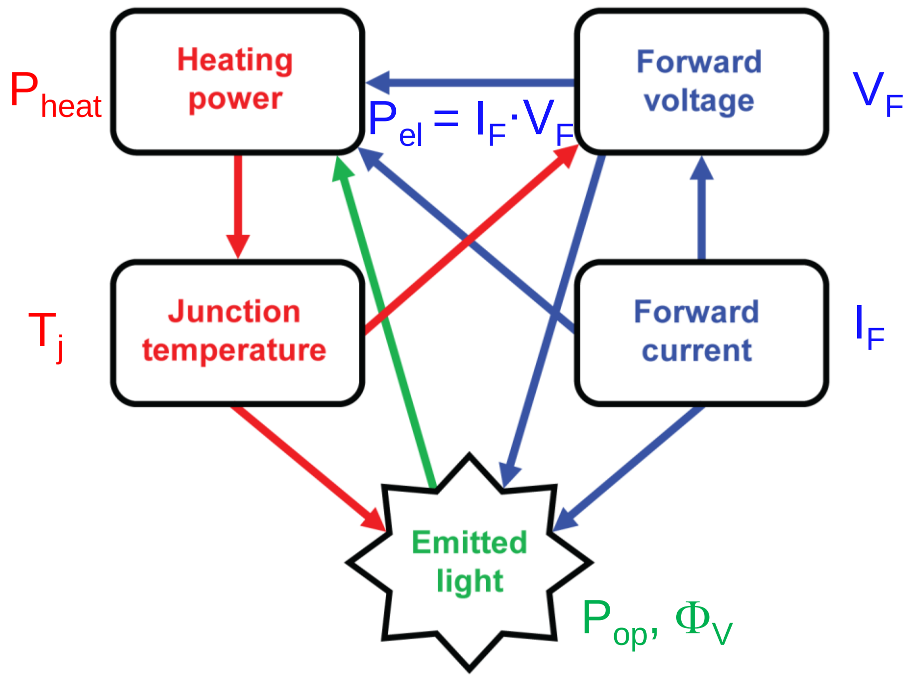
Colour point shifts of a white LED

(CIE 1931 2° observer)



Why to deal with digital twins of LEDs?

LEDs need to be properly modelled for the usual EDA software tools



LED model == digital twin for design

Light output parameters of LEDs depend on *everything*

Their interdependence should be **modelled** for **lighting designers**

"Hot lumens" calculations

- electrical
- thermal &
- optical

properties calculated simultaneously ➔ **multi-domain approach**

Chip level: multi-domain LED model (electrical, optical, thermal)

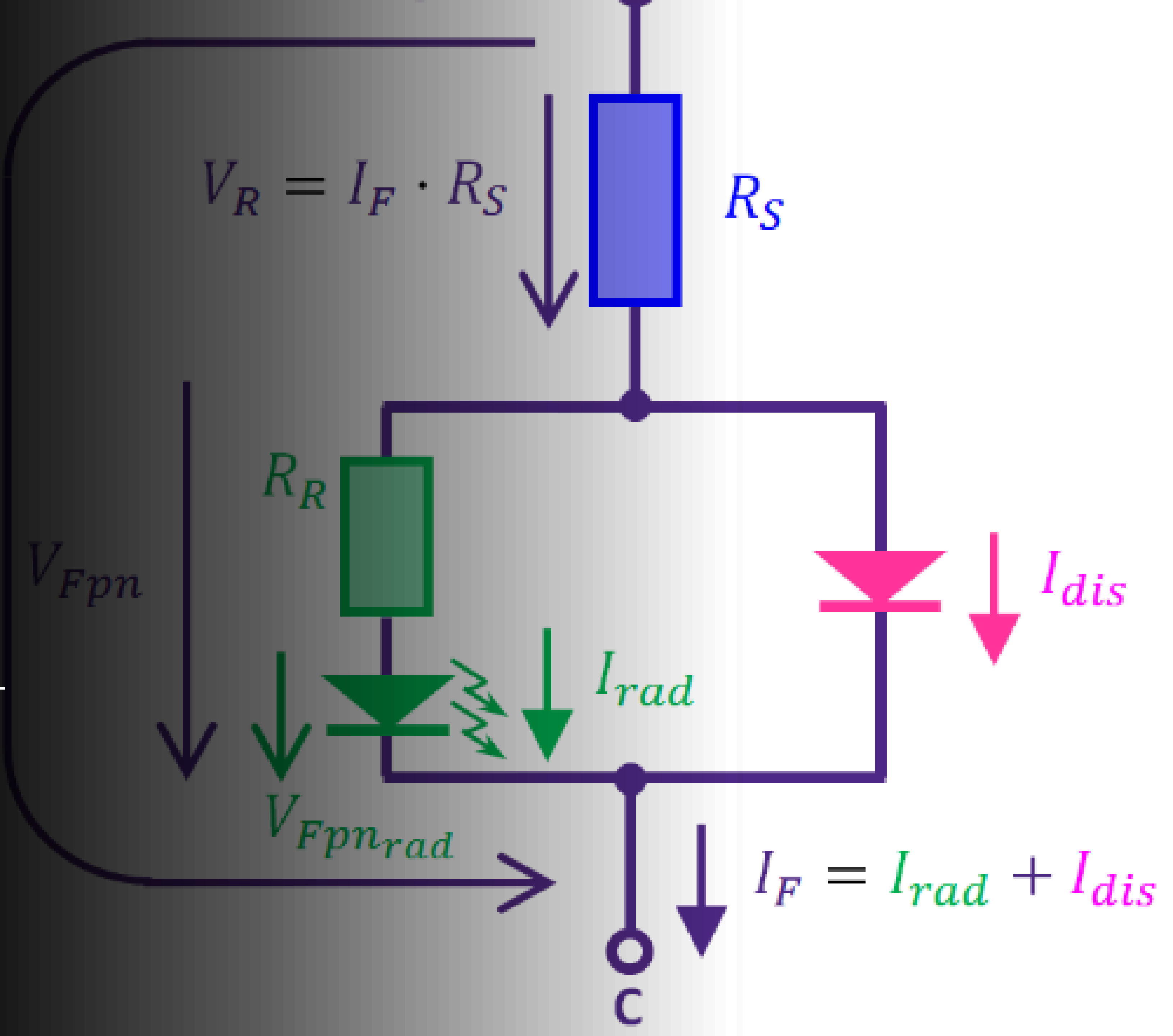
- Calculation of the diode characteristics
- Calculation of the emitted flux (optical power, luminous flux)
  - Effect of lens and phosphor lumped into the model
- Calculation of the temperature dependence of the above

Package level: compact thermal model of the heat-flow path

- Dynamic model, with a complexity corresponding to the mechanical structure of the package

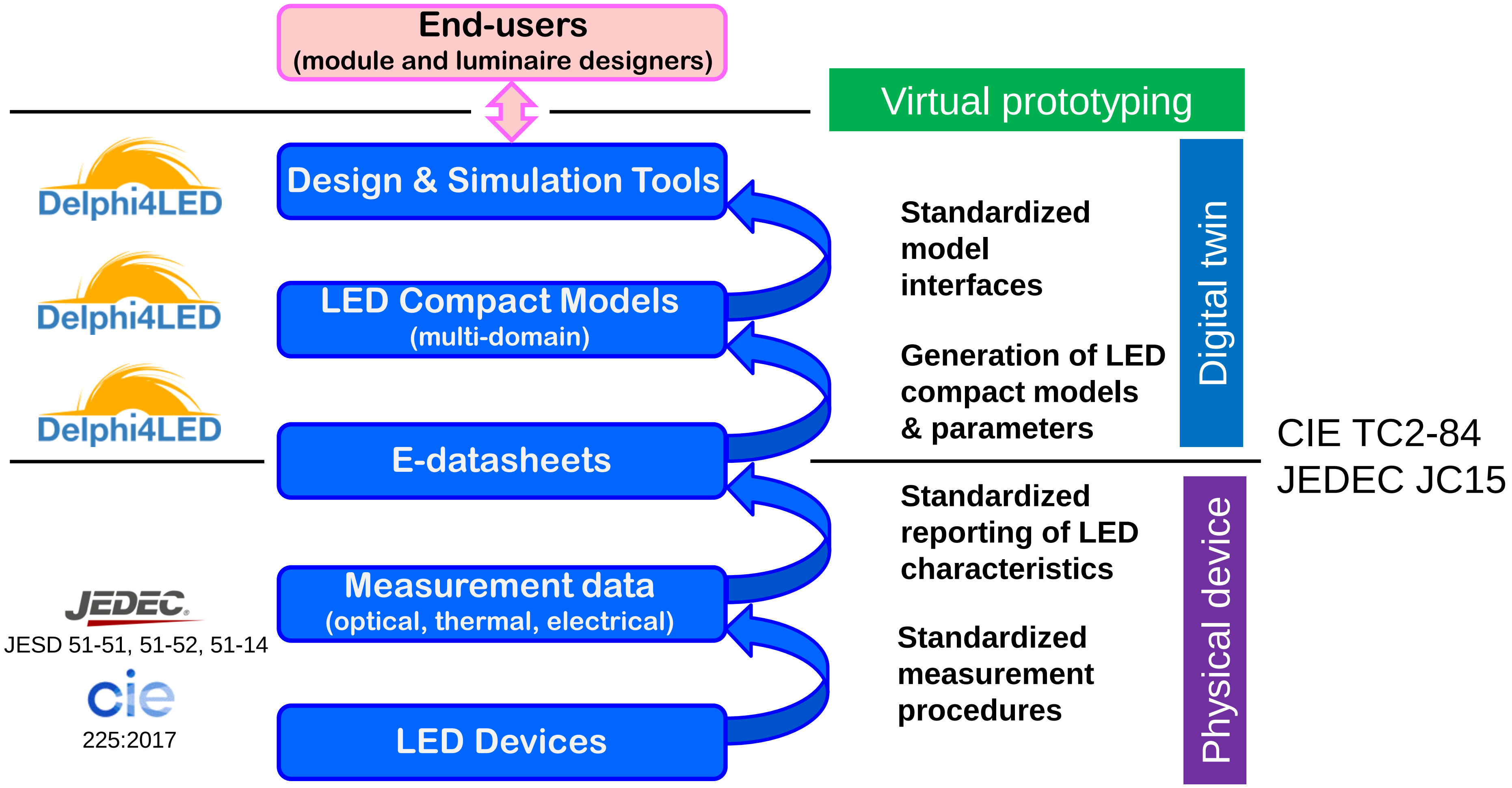
Using LED digital twins: the first approach in Delphi4LED

The concepts and the major research and development results

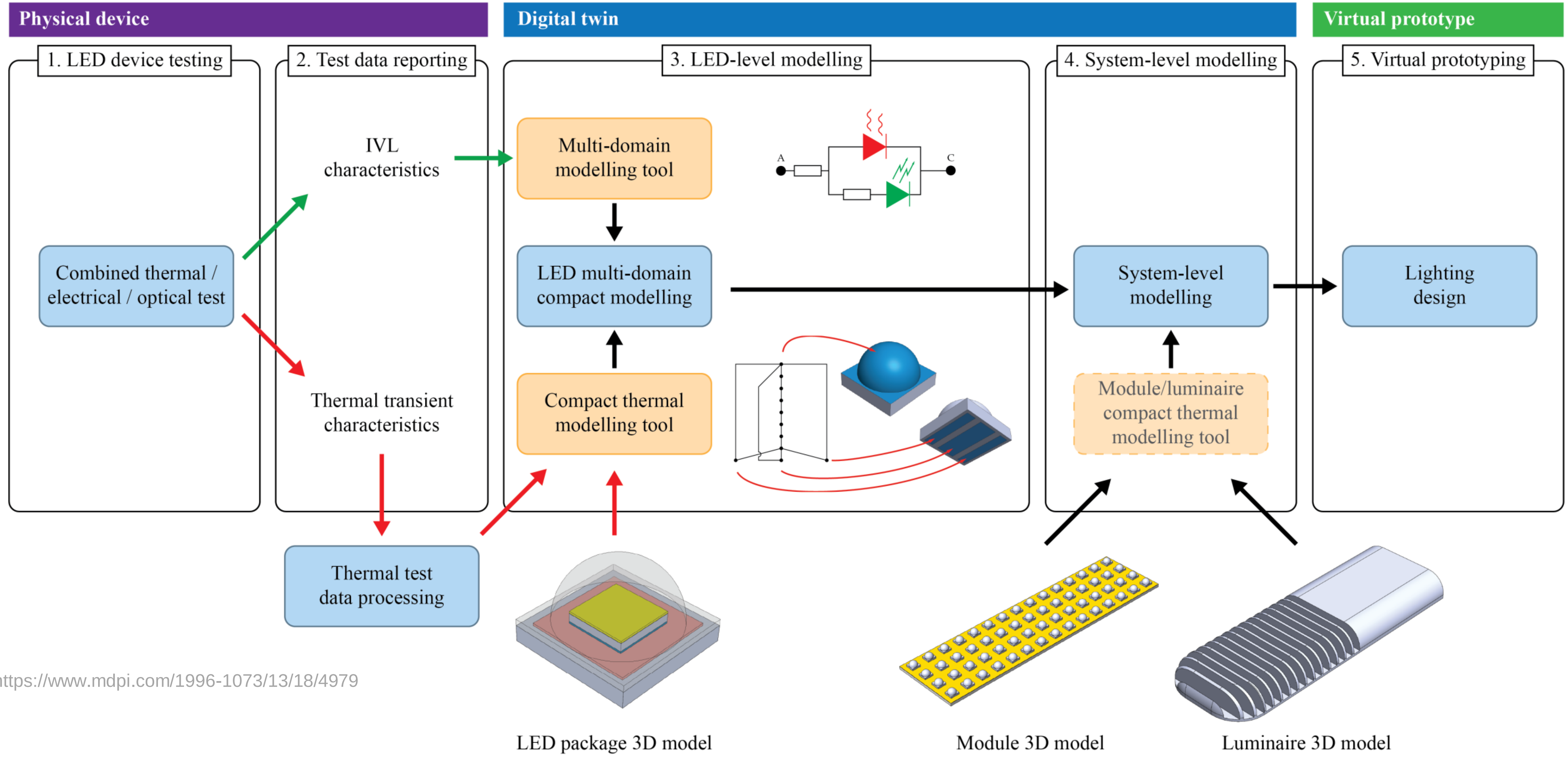


The Delphi4LED approach (EU H2020 ECSEL project, 2016-2019, www.delphi4LED.org)

An Industry 4.0 approach



The Delphi4LED approach



https://www.mdpi.com/1996-1073/13/18/4979

The Delphi4LED approach

Delphi4LED

The major project objectives were

1. Develop **standard methods to create multi-domain LED compact models** from test data
   - Physical samples of LEDs, modules, luminaires replaced by their models

     ➔ **creating digital twins**
2. Improve **simulation of LED thermal, electrical & optical characteristics**
   - **Multi-domain models** at all integration levels using the digital twins

     ➔ buttom-up building of models up to system level (luminaire, lighting system)
3. Reduce design / product cost and time to market
   - Prototype building and physical testing replaced by computer simulation

     ➔ **virtual prototyping**

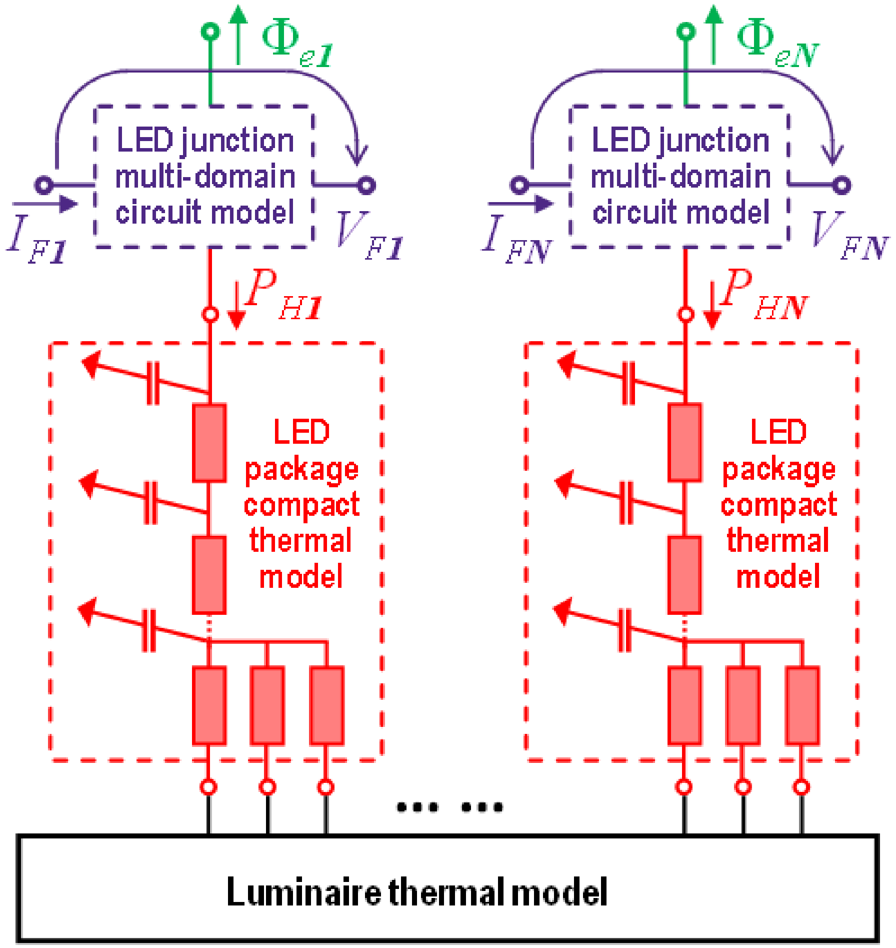
Achieved results include new

- Testing methods
- Modeling and simulation methods
- **Design workflows**

The Delphi4LED modular modelling approach

So called boundary condition independent (BCI) models are used on chip and package level.

The compact thermal model of the luminaire as a substrate carrying the LED packages usual reflects the wider thermal environment.

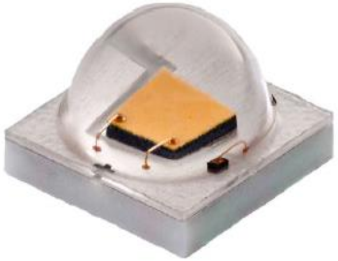


The Delphi4LED approach

Different digital twins on package, module, lamp/luminaire levels

Physical devices

LED package mechanical structure



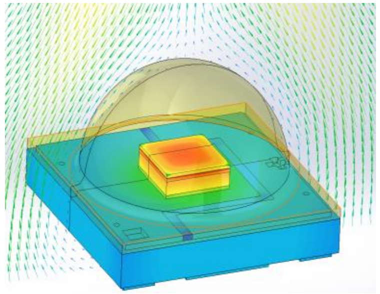
LED luminaire mechanical structure

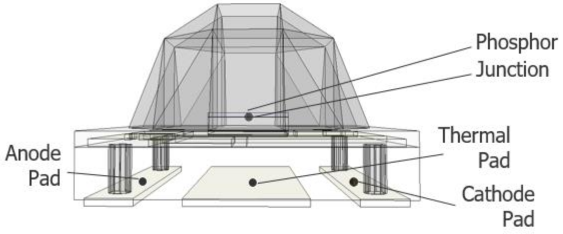
LED luminaire system

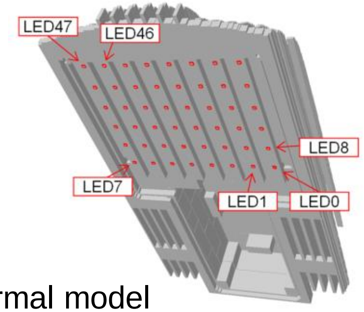
Digital twins

Detailed thermal calibrated to thermal transient measurement results

detailed



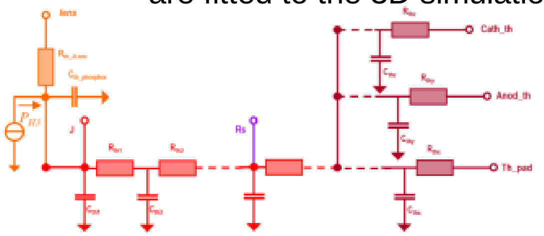


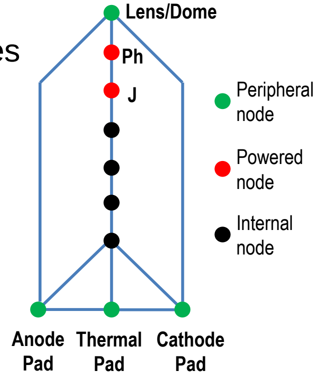


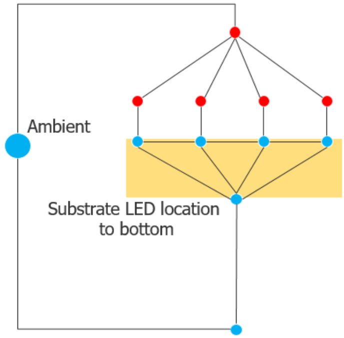
MCAD model ➔ 3D thermal model ➔ compact thermal model

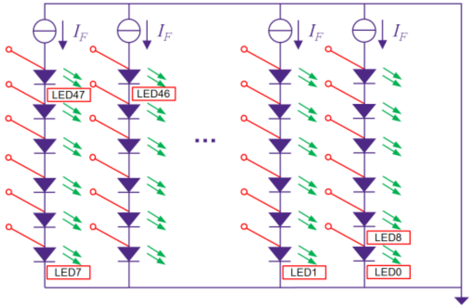
compact

Compact thermal model element values are fitted to the 3D simulation results









 A. Poppe: Creating new multi-domain digital twins of LEDs with an attempt to describe their ageing for predictive maintenace schemes

The Delphi4LED approach: modular modelling

Delphi4LED

Modular approach / Spice circuit macros corresponding to the integration levels along the SSL supply chain:
chip – package – substrate/luminaire

LED chip multi-domain model

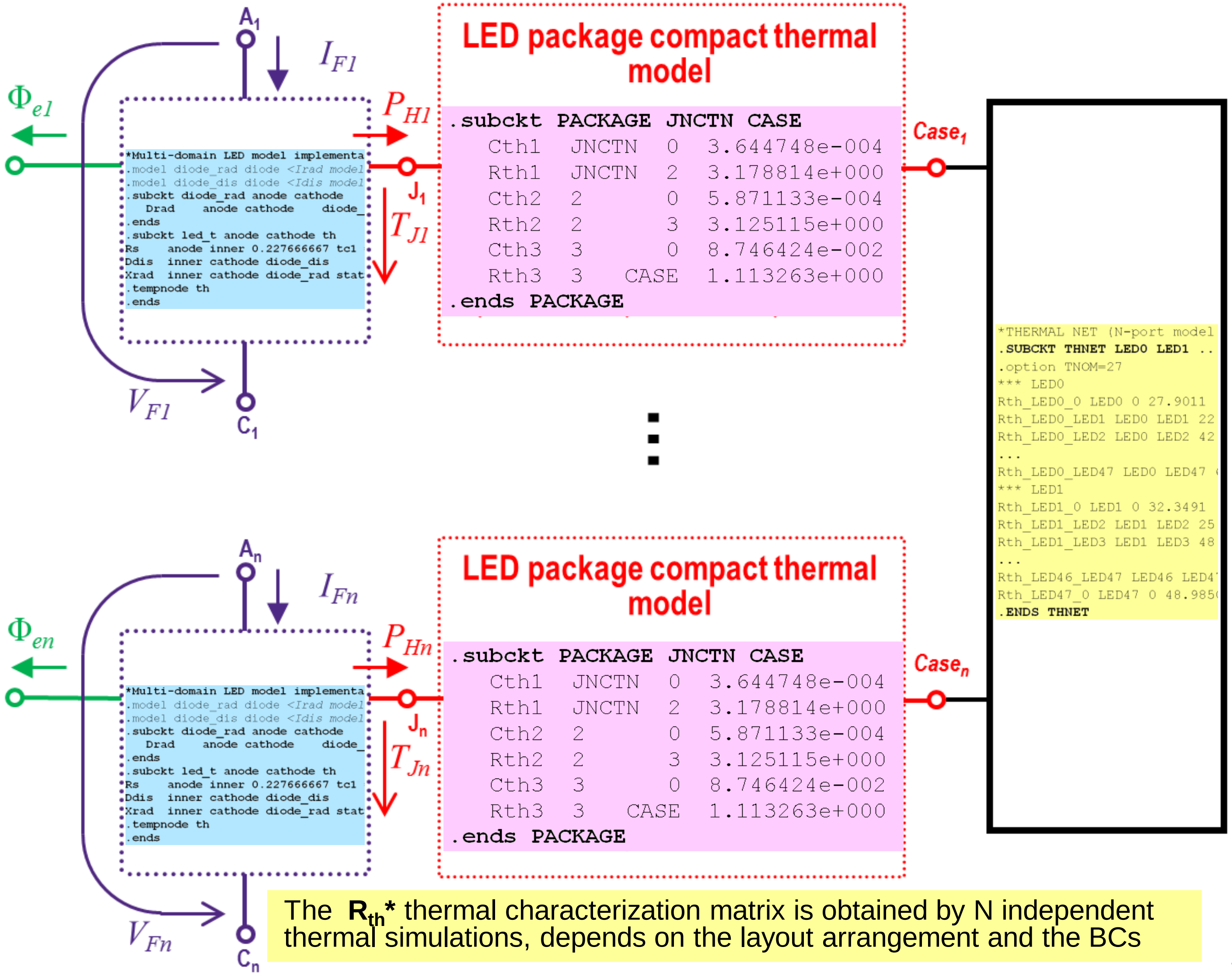
From measured isothermal I-V-L characteristics

LED package DCTM

Extracted with a "DELPHI" like (JEDEC JESD 15-4) methodology with LED specific model topology and boundary conditions

Substrate / luminaire compact thermal model

Obtained from the R_{th}* thermal characterization matrix of a multi heat-source system



The R_{th}* thermal characterization matrix is obtained by N independent thermal simulations, depends on the layout arrangement and the BCs

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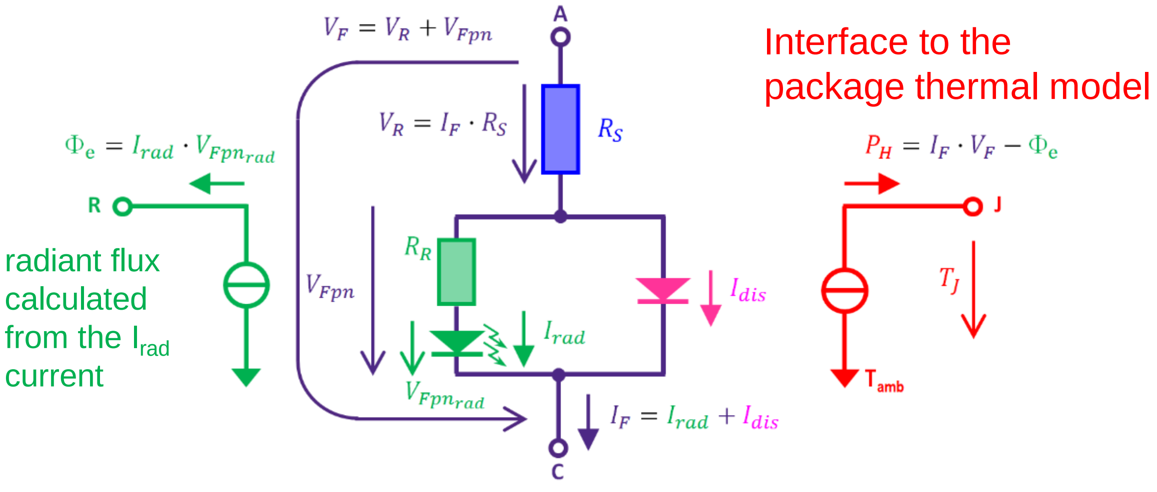
The Delphi4LED chip level multi-domain model

A requirement was to have a model suitable for a generic Spice implementation.

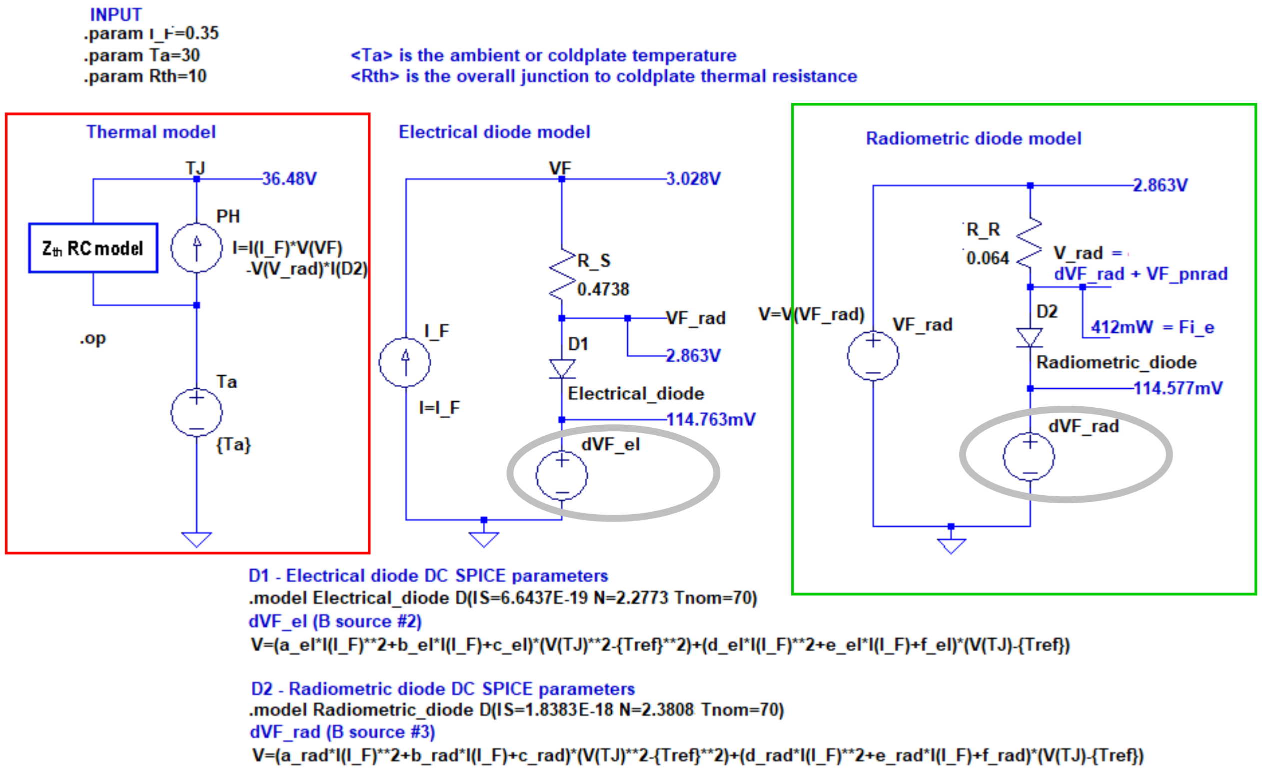
The principle of the model:



radiative diode dissipative diode

both modelled by the ideal diode equation

The generic Spice circuit macro implementation:

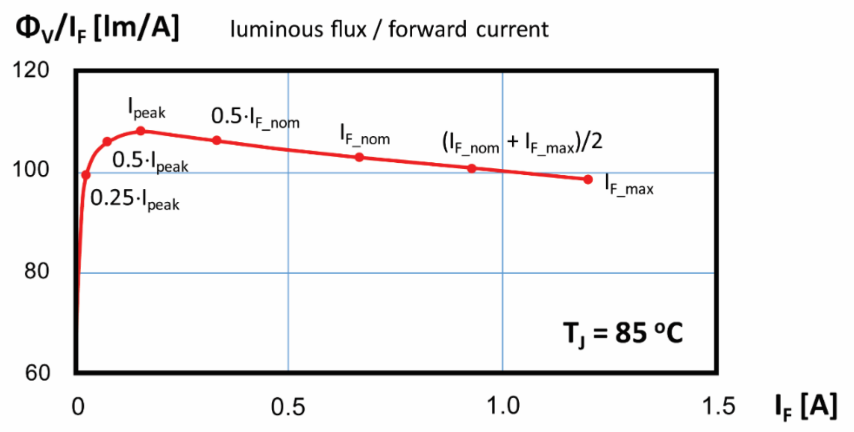


Implemented as an I_F forward current driven model, both on level of equations and as a Spice subcircuit macro.

The voltage of the **TJ** node represents the junction temperature. These voltage controlled voltage source represent the T_J induced change of the diode voltages under constant forward current driving.

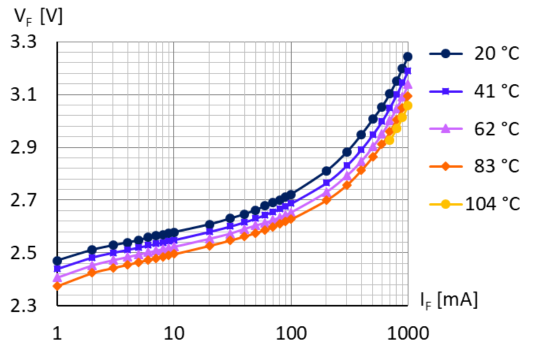
The Delphi4LED chip level multi-domain model

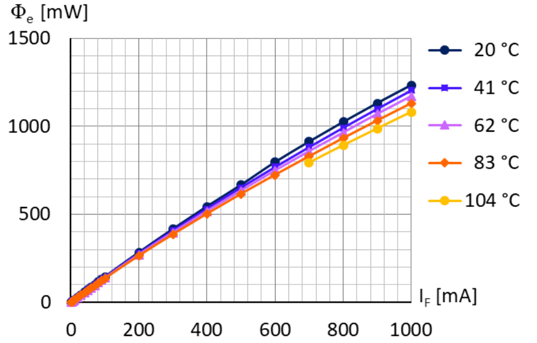
The recommended set of the (I_F, T_J) operating points to which the model has to be fitted during parameter extraction.



34 pairs of (I_F, T_J)

T_J [°C]	30	50	70	85	110
I_F [mA]	20	20	20	20	-
	30	30	30	30	-
	60	60	60	60	-
	100	100	100	100	-
	350	*350*	*350*	***350***	*350*
	500	500	500	500	500
	-	700	700	700	700
	-	-	1000	1000	1000





Forward currents to be chosen from both sides of the efficiency/efficacy peak to represent both the low current and high current operating regimes.

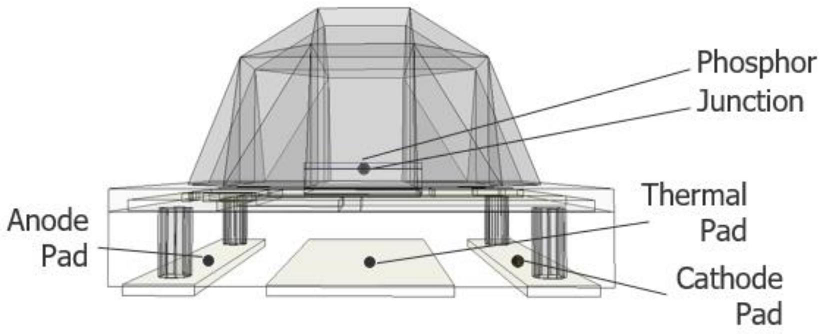
The model is expected to provide voltage and flux values with less than 2% relative error in 3 decades of forward current (from the 1 mA range up to the 1000 mA range).

The Delphi4LED package compact thermal model

A requirement was to have a model suitable for a generic Spice implementation and suitable also as a compact model for CFD simulation tools.

A 3D model of an LED package with sufficient level of details to properly identify the element values of the dynamic compact thermal model of the package:

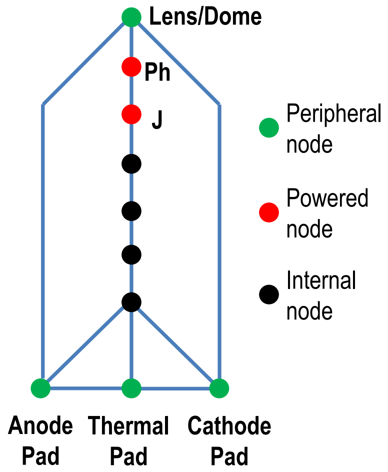
Delphi4LED-style compact thermal model of LED packages.



$$f_{\text{cost}} = \sum_h \sum_i \sum_j \frac{\left(Z_{\text{th},ih}^{\text{detailed}}(t_j) - Z_{\text{th},ih}^{\text{CTM}}(t_j)\right)^2}{Z_{\text{th},ih}^{\text{detailed}}(t_j)}$$

JEDEC DELPHI-style optimization

See JEDEC JESD 15-4



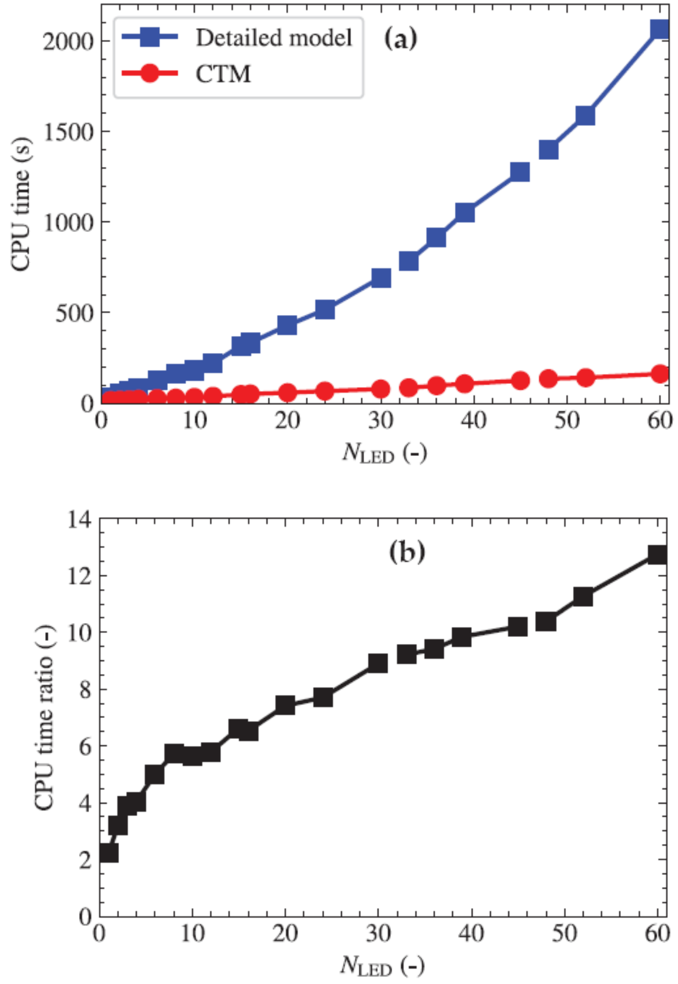
The **model is calibarted** against the **thermal transient test results** of the physical package samples using ***structure functions***.

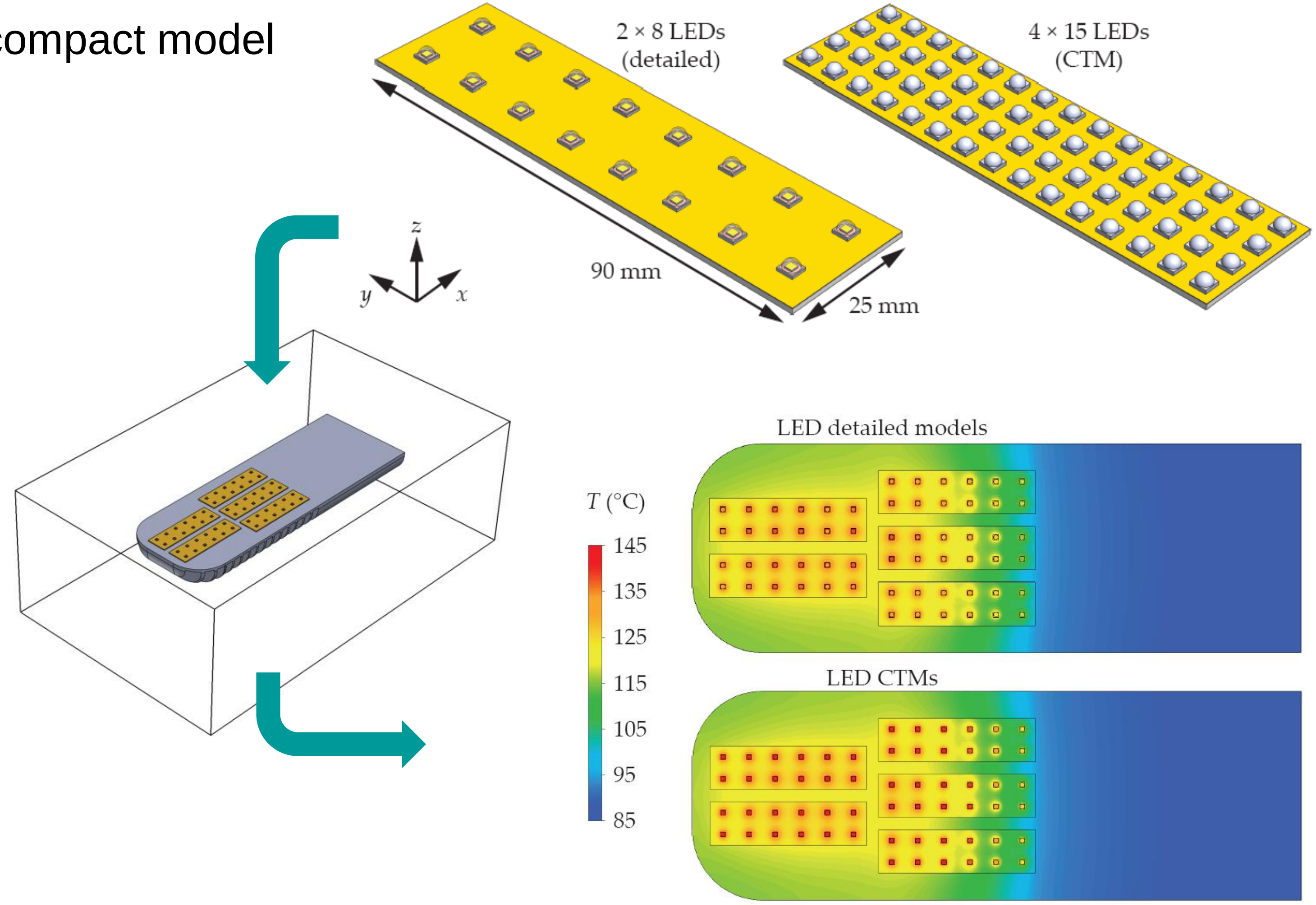
The phosphor can be considered as an additional heat source and the thermal mass of the dome can also be represented in the model.

Benefits of using compact models (a case-study from Signify, OA, DOI: 10.3390/en13184979)

There are multiple benefits of using compact models instead of detailed ones:

- Reduced computational times
- No proprietary information is found in a compact model



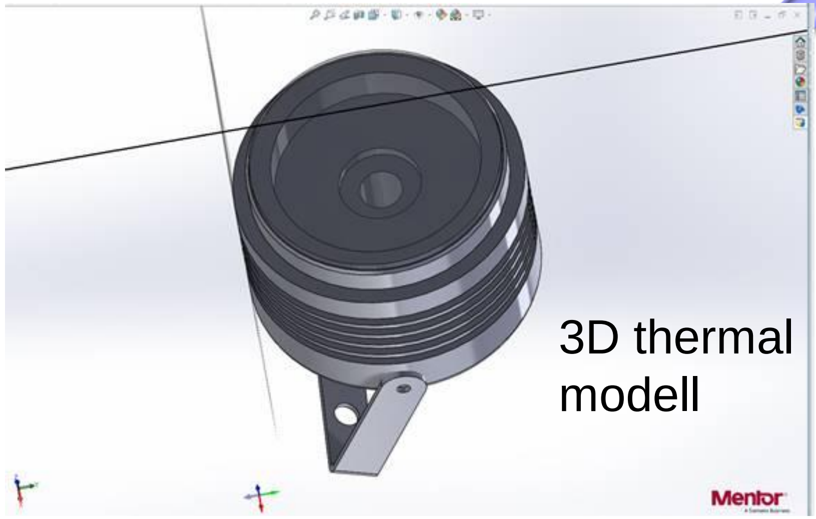


The Delphi4LED luminaire compact thermal model

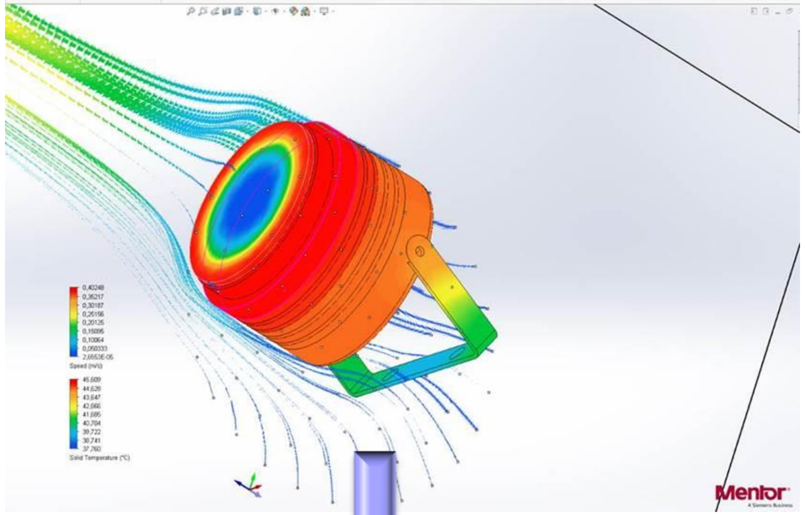
A requirement was to have a model suitable for a generic Spice implementation. Such a model can be generated with the $\mathbf{R}^{*}_{th}$ thermal characterization matrix method or by means of ROM techniques such as published by L. Codecasa as the "FANTASTIC“ method.

MCAD model

Import of CAD geometry into the CFD tool



Thermal characterization of the luminaire / substrate with a series of CFD simulations



Create the $\mathbf{R}^{*}_{th}$ thermal characterization matrix of luminaire / substrate and conversion to compact model
(For *N* heat-sources an *N*x*N* matrix by *N* CFD simulations)

luminaire / substrate
thermal compact model in Spice netlist format

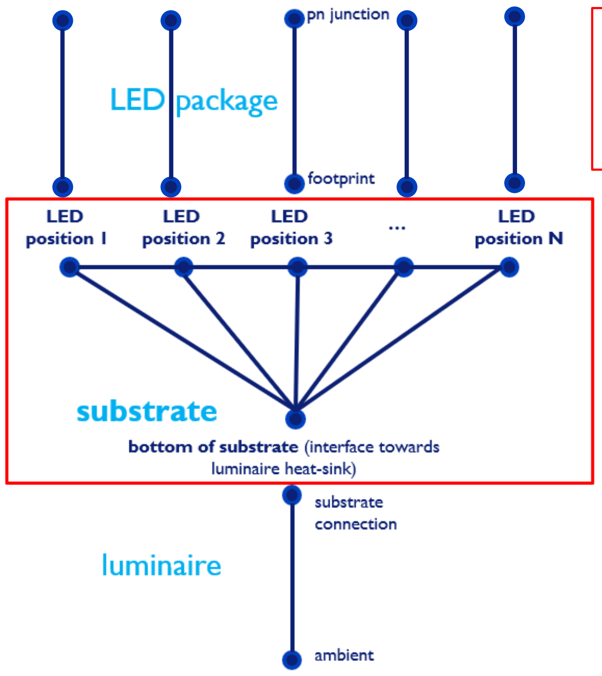
LED package footprint areas are connected to the footprint nodes of the package compact thermal models

The Delphi4LED luminaire compact thermal model

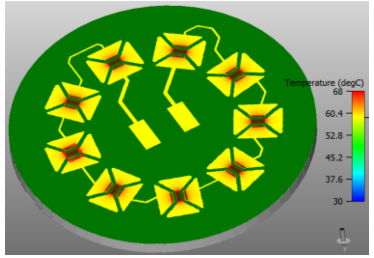
Simplified approach in a so called LED luminaire calculator tools (demo tool as an Excel spreadsheet app)

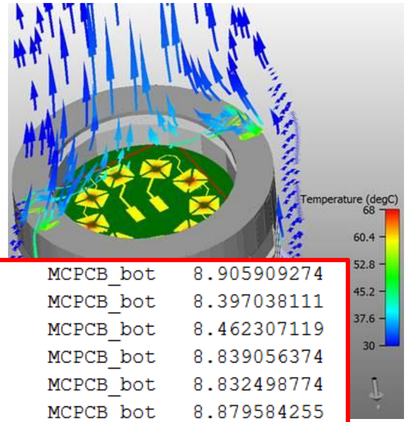
A demonstrator

- The modelled substrate



Populate the substrate with multi-domain LED package models and study the design alternative on high level with Spice simulations





Rth Matrix Symmetricised								
	8.674556331	0.085851129	0.020079796	0.003120538	0.0001	0.0001	0.005169335	0.0213
	0.085851129	**8.158273354**	0.082818568	0.033955277	0.00688263	0.000846208	0.00063092	0.0013
	0.020079796	0.082818568	**8.254507996**	0.080956448	0.021946782	0.001555395	0.0001	
	0.003120538	0.033955277	0.080956448	**8.58891147**	0.088246138	0.030947062	0.007448014	
	0.0001	0.00688263	0.021946782	0.088246138	**8.591994956**	0.089068462	0.032253405	0.0009
	0.0001	0.000846208	0.001555395	0.030947062	0.089068462	**8.632464978**	0.091306825	0.024
	0.005169335	0.00063092	0.0001	0.007448014	0.032253405	0.091306825	**8.609615549**	0.0842
	0.021366075	0.001397169	0.0001	0.0001	0.000969649	0.02402132	0.084291787	**8.2980**
	0.086297521	0.03532229	0.00519363	0.0001	0.000354614	0.007242548	0.035421427	0.0832

Rth Matrix Inversion								
	0.115304596	-0.0012054	-0.00026732	-3.4552E-05	9.58433E-07	1.36726E-06	-6.1535E-05	-0.000
	-0.0012054	0.12260425	-0.00122199	-0.00047178	-9.01E-05	-8.6547E-06	-5.2344E-06	-1.242
	-0.00026732	-0.00122199	0.121170791	-0.00113409	-0.00029673	-1.4541E-05	1.36173E-06	1.7874
	-3.4552E-05	-0.00047178	-0.00113409	0.116455501	-0.00118828	-0.00040401	-9.1959E-05	9.9692
	9.58433E-07	-9.01E-05	-0.00029673	-0.00118828	0.116414387	-0.00119234	-0.00042237	-5.815
	1.36726E-06	-8.6547E-06	-1.4541E-05	-0.00040401	-0.00119234	0.115869403	-0.00122048	-0.000
	-6.1535E-05	-5.2344E-06	1.36173E-06	-9.1959E-05	-0.00042237	-0.00122048	0.116177266	-0.001
	-0.00028433	-1.2421E-05	1.78745E-07	9.96921E-07	-5.8159E-06	-0.00032197	-0.00117163	0.1205
	-0.00116879	-0.00049906	-6.6576E-05	2.41457E-06	-1.4717E-06	-9.0896E-05	-0.00047353	-0.001

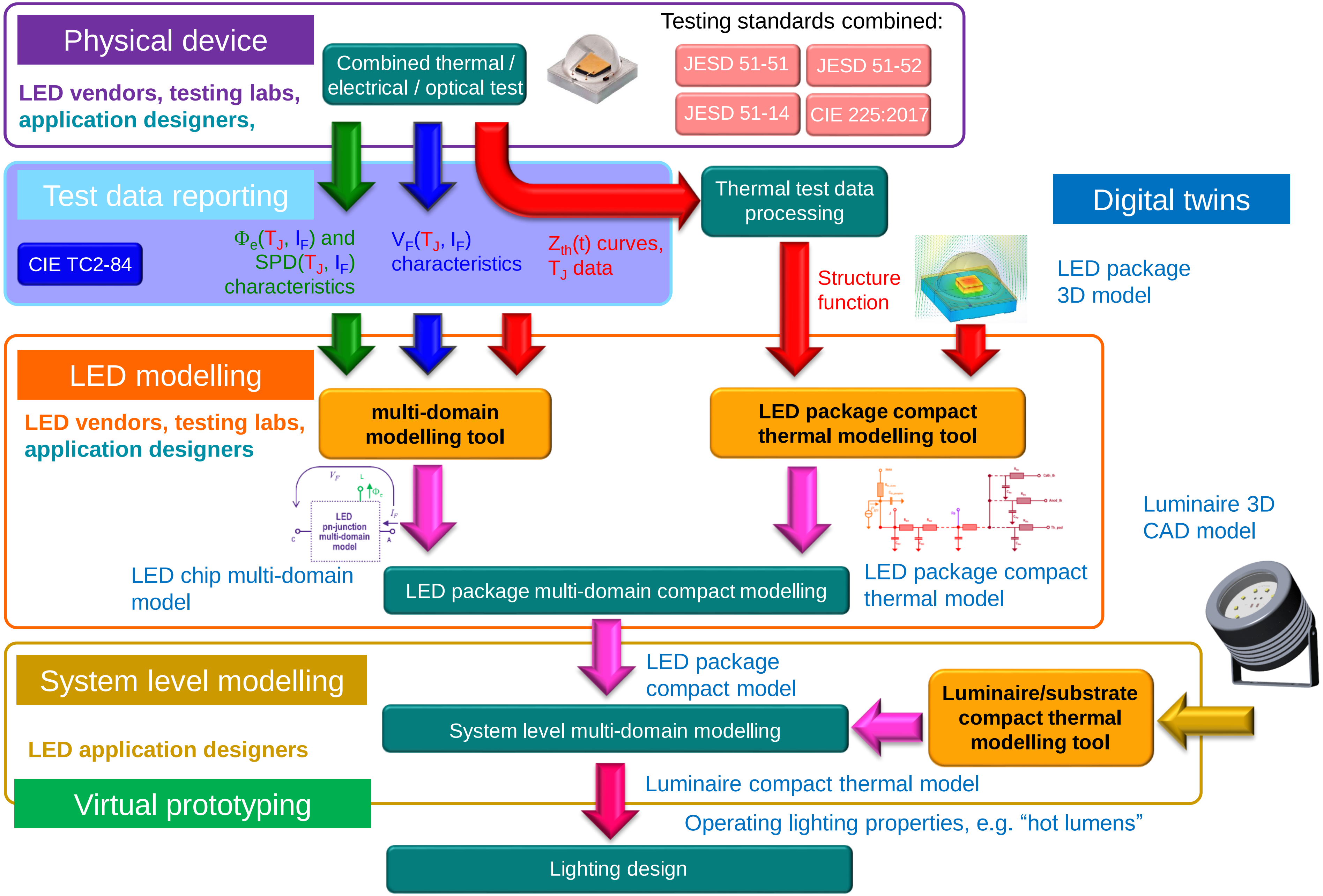
Rth Network Formulation									
	8.905909274	829.5982526	3740.853548	28941.82279	-1043369.51	-731392.172	16250.91857	3517.0	
		8.397038111	818.3373091	2119.639289	11098.77527	115543.9267	191045.41	80511.	
			8.462307119	881.7643185	3370.046818	68769.28145	-734359.432	-5594	
				8.839056374	841.5554918	2475.190628	10874.46967	-1003	
					8.832498774	838.6877354	2367.609253	17194	
						8.879584255	819.3514046	3105.	
							8.870603828	853.50	
								8.5062	
									8.707730701

```
RPos1MCPCB_bot Pos1    MCPCB_bot    8.905909274
RPos2MCPCB_bot Pos2    MCPCB_bot    8.397038111
RPos3MCPCB_bot Pos3    MCPCB_bot    8.462307119
RPos4MCPCB_bot Pos4    MCPCB_bot    8.839056374
RPos5MCPCB_bot Pos5    MCPCB_bot    8.832498774
RPos6MCPCB_bot Pos6    MCPCB_bot    8.879584255
RPos7MCPCB_bot Pos7    MCPCB_bot    8.870603828
RPos8MCPCB_bot Pos8    MCPCB_bot    8.506230548
RPos9MCPCB_bot Pos9    MCPCB_bot    8.707730701
RPos1Pos2   Pos1    Pos2    829.5982526
RPos2Pos3   Pos2    Pos3    818.3373091
RPos3Pos4   Pos3    Pos4    881.7643185
RPos4Pos5   Pos4    Pos5    841.5554918
RPos5Pos6   Pos5    Pos6    838.6877354
RPos6Pos7   Pos6    Pos7    819.3514046
RPos7Pos8   Pos7    Pos8    853.5095604
RPos8Pos9   Pos8    Pos9    847.774583
RPos9Pos1   Pos9    Pos1    855.5876525
RPos1Pos3   Pos1    Pos3    3740.853548
RPos2Pos4   Pos2    Pos4    2119.
RPos3Pos5   Pos3    Pos5    3370.
RPos4Pos6   Pos4    Pos6    2475.
RPos5Pos7   Pos5    Pos7    2367.
RPos6Pos8   Pos6    Pos8    3105.
RPos7Pos9   Pos7    Pos9    2111.
RPos8Pos1   Pos8    Pos1    3517.
RPos9Pos2   Pos9    Pos2    2003.
```

LED package footprint areas are connected to the footprint nodes of the package compact thermal models

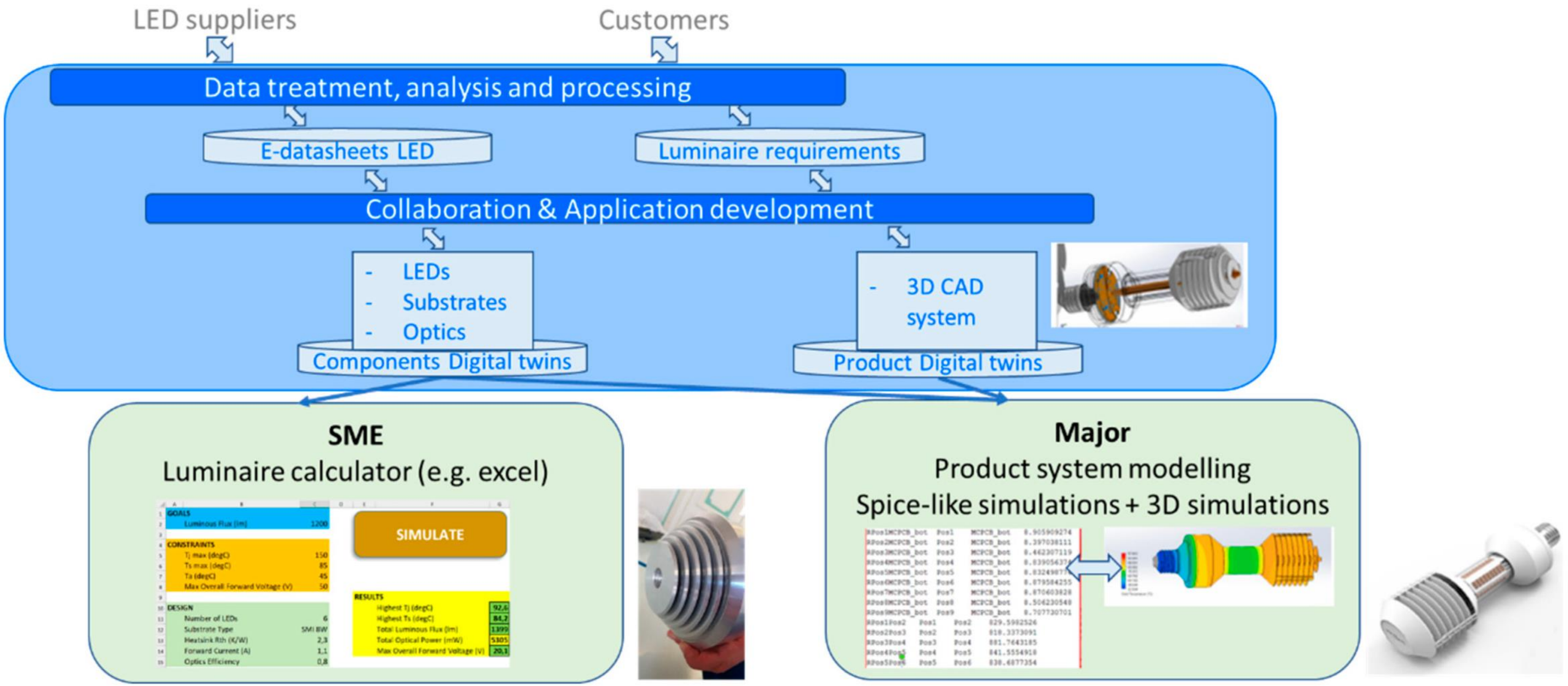
By courtesy of Robin Bornoff (Siemens Digital Industry Software Simulation and Test Solutions Strategy and Innovation, Technology Innovation group)

Digital twins on multiple integration levels – in a digitalized development workflow



First implementations – two foreseen options for different company environments

With the vision of component libraries available from vendors (LEDs, drivers, etc.)

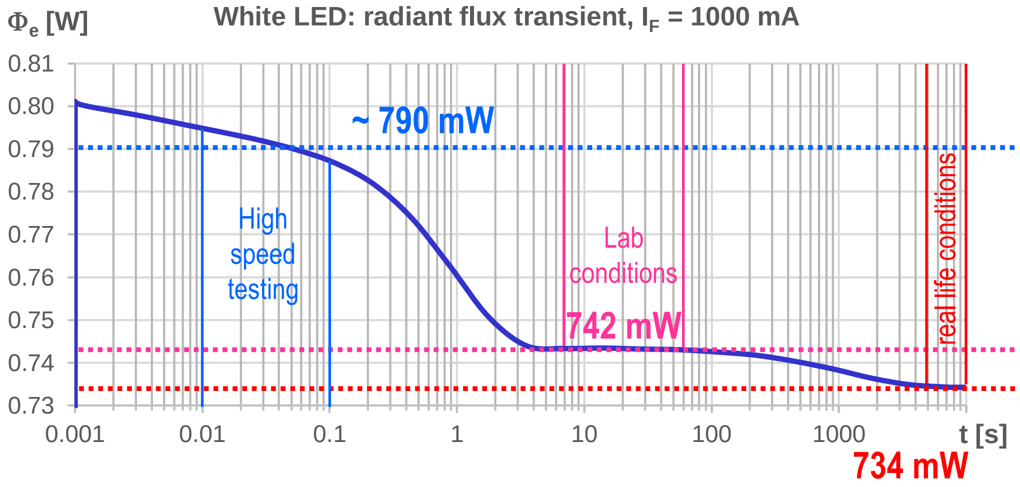


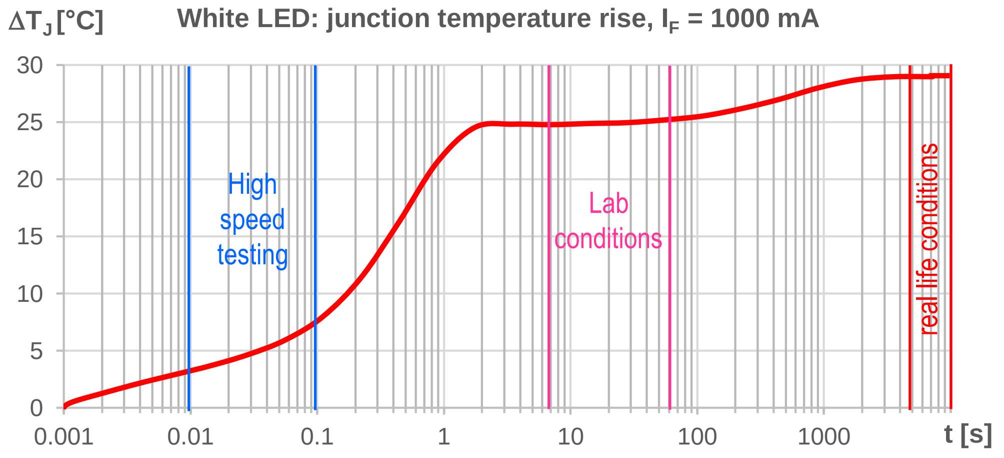
https://www.mdpi.com/1996-1073/12/12/2389/htm

First implementations – trials with two options for different company environments

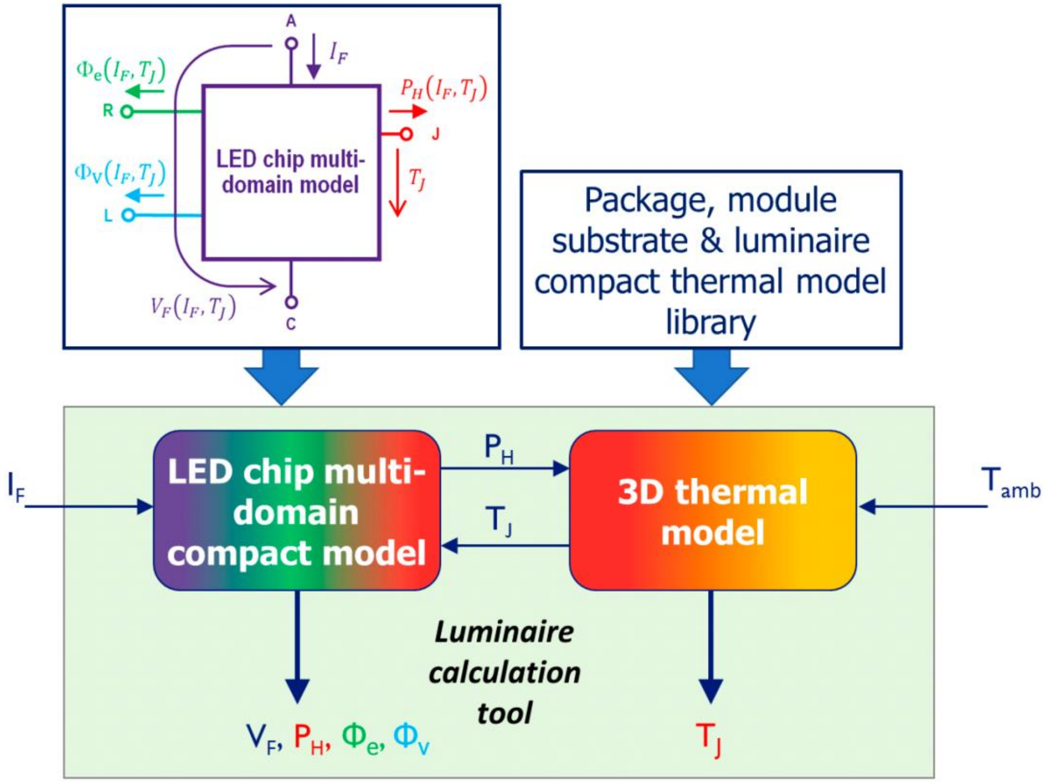
Delphi4LED

All models merged in a Spice netlist and simulated with Spice only (direct method)➔ *any signal for any driving mode…*





Electrical and thermal solvers iterate (relaxation method). Demo tool in an Excel spreadsheet application ➔ *quick evaluation of basic design choices*



https://www.mdpi.com/1996-1073/12/12/2389/htm

First implementations – luminaire design calculator

1. Set design goals/objectives (total flux)
2. Define (temperature) constraints
3. Enter design choices
4. Simulate and evaluate

GOALS	
Luminous Flux (lm)	1200
CONSTRAINTS	
Tj max (degC)	150
Ts max (degC)	85
Ta (degC)	45
Max Overall Forward Voltage (V)	50
DESIGN	
Number of LEDs	5
Substrate Type	SMI 5W
Heatsink Rth (K/W)	2,3
Forward Current (A)	1,1
Optics Efficiency	0,8

SIMULATE

RESULTS	
Highest Tj (degC)	89,9
Highest Ts (degC)	81,5
Total Luminous Flux (lm)	1170
Total Optical Power (mW)	4433
Max Overall Forward Voltage (V)	16,8

Total luminous flux target not met

GOALS	
Luminous Flux (lm)	1200
CONSTRAINTS	
Tj max (degC)	150
Ts max (degC)	85
Ta (degC)	45
Max Overall Forward Voltage (V)	50
DESIGN	
Number of LEDs	6
Substrate Type	SMI 5W
Heatsink Rth (K/W)	2,3
Forward Current (A)	1,1
Optics Efficiency	0,8

SIMULATE

RESULTS	
Highest Tj (degC)	95,3
Highest Ts (degC)	86,9
Total Luminous Flux (lm)	1395
Total Optical Power (mW)	5291
Max Overall Forward Voltage (V)	20,1

Solder point temperature constraint violated

GOALS	
Luminous Flux (lm)	1200
CONSTRAINTS	
Tj max (degC)	150
Ts max (degC)	85
Ta (degC)	45
Max Overall Forward Voltage (V)	50
DESIGN	
Number of LEDs	6
Substrate Type	SMI 8W
Heatsink Rth (K/W)	2,3
Forward Current (A)	1,1
Optics Efficiency	0,8

SIMULATE

RESULTS	
Highest Tj (degC)	92,6
Highest Ts (degC)	84,2
Total Luminous Flux (lm)	1399
Total Optical Power (mW)	5305
Max Overall Forward Voltage (V)	20,1

Design target met without violation of constraints

GOALS	
Luminous Flux (lm)	1200
CONSTRAINTS	
Tj max (degC)	150
Ts max (degC)	85
Ta (degC)	45
Total Power Consumption (W)	15
DESIGN	
Number of LEDs	6
Substrate Type	SMI 3W
Heatsink Rth (K/W)	2.5
Forward Current (A)	1.5
Optics Efficiency	0.8
Driver Efficiency	0.9

SIMULATE

RESULTS	
Highest Tj (degC)	85.38
Highest Ts (degC)	79.27
Total System Power Consumption (W)	29.96
Total System Luminous Flux (lm)	2465
Total Luminous Flux from LEDs (lm)	3082
Total System Optical Power (mW)	7582
Total Optical Power from LEDs (mW)	9478
Total System Lumens/Watt (lm/W)	82.28
Total Lumens/Watt from LEDs (lm/W)	113.1

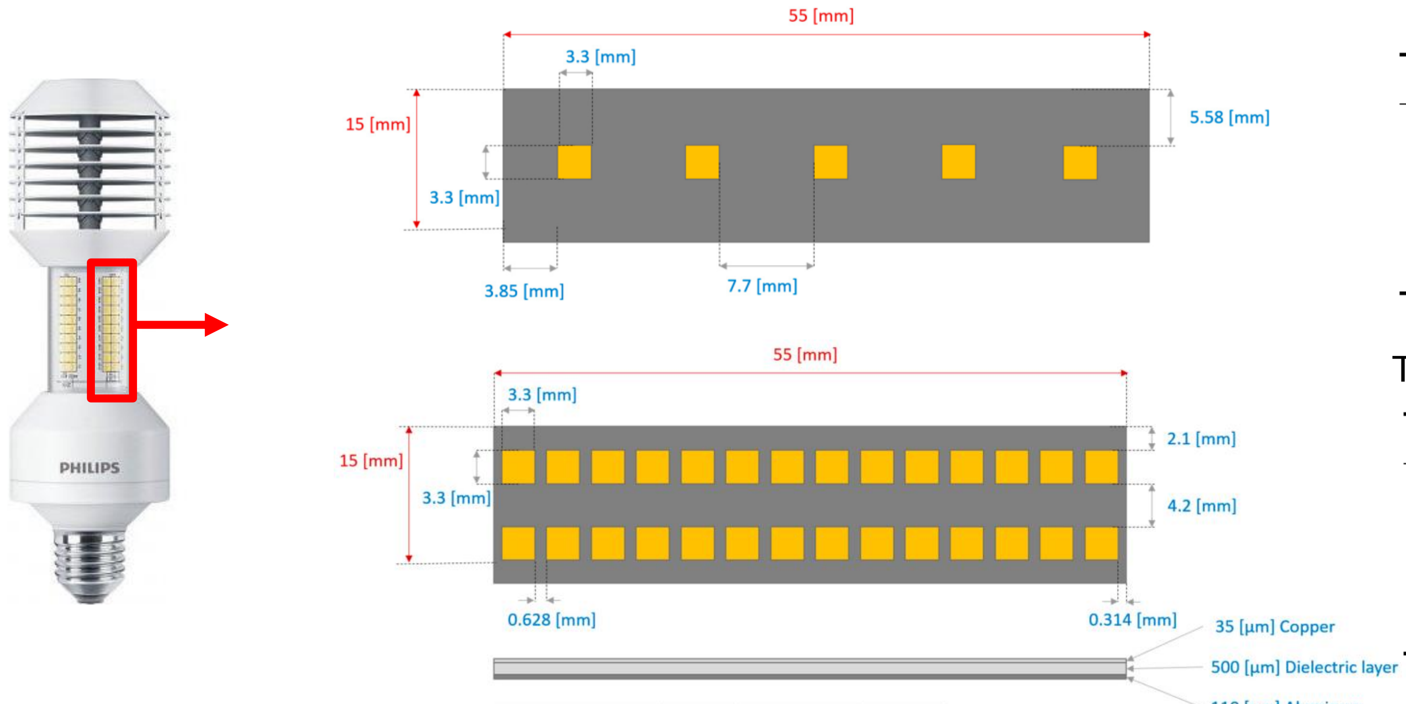
PER LED RESULTS	Vf (V)	Luminous Flux (lm)	Tj (DegC)	Ts (DegC)	P (W)	Pdis (W)
1	3.03	513.47	85.38	79.27	4.5	2.96
2	3.03	513.69	85.17	78.84	4.5	2.96
3	3.03	513.61	85.25	79.00	4.5	2.96
4	3.03	513.63	85.23	78.96	4.5	2.96
5	3.03	513.62	85.24	78.98	4.5	2.96
6	3.03	513.65	85.21	78.92	4.5	2.96

Application in product optimization

Demo example, following the architecture of the 70 W HPS replacement lamp

Design choices were:

1. Type A or Type B LED?
2. Smaller number of LEDs driven by higher current (less mfg. cost, smaller LED efficiency) or higher number of LEDs driven by a smaller current (more mfg. cost, higher LED efficiency)



Material	Copper	Dielectric layer	Aluminum
Conductivity [W/mK]	400	1	237

Type A

Calculated Property	5 LEDs; I_F = 500 mA	22 LEDs; I_F = 100 mA
Solder point temperature [°C]	51.6	46.9
Junction temperature [°C]	54.3	47.3
Light output per PCB [lm]	1056	1049
Total Light output [lm]	6336	6294
Efficacy [lm/W]	150	180

Type B

Calculated Property	5 LEDs; I_F = 200 mA	22 LEDs; I_F = 60 mA
Solder point temperature [°C]	51.8	47.6
Junction temperature [°C]	61.1	49.7
Light output per PCB [lm]	664	1008
Total Light output [lm]	3984	6050
Efficacy [lm/W]	105	136

https://www.mdpi.com/1996-1073/12/12/2389/htm

Evaluating the benefits

Benefits of the digitalized development flow: reduced development time and cost.

Overall gainis 28% (SME environment) .. 42% (major company environment)

Demo experiments in Delphi4LED:

Main design costs	"SME" old process	"SME" new proces	Gain
Personal costs	0.896	0.633	29%
Material costs	0.049	0.028	43%
Testing	0.056	0.056	0%
Total	1.000	0.717	**28%**
Main design costs	**"Major" old process**	**"Major" new proces**	**Gain**
Personal costs	0.819	0.502	39%
Material costs	0.055	0.028	48%
Testing	0.126	0.045	65%
Total	1.000	0.575	**42%**

SIMULATE

RESULTS	
Highest Tj (degC)	47.55
Highest Ts (degC)	43.33
Total System Power Consumption (W)	11.71
Total System Luminous Flux (lm)	1302
Total Luminous Flux from LEDs (lm)	1628
Total System Optical Power (mW)	3971
Total Optical Power from LEDs (mW)	4964
Total System Lumens/Watt (lm/W)	111.2
Total Lumens/Watt from LEDs (lm/W)	139

10,7 W measured

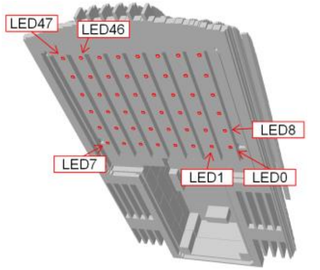
1339 lm measured

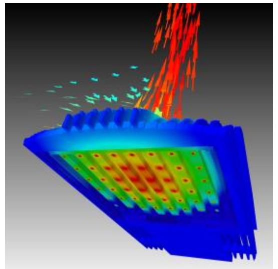
Simulated major performance indicators were confirmed by measurements

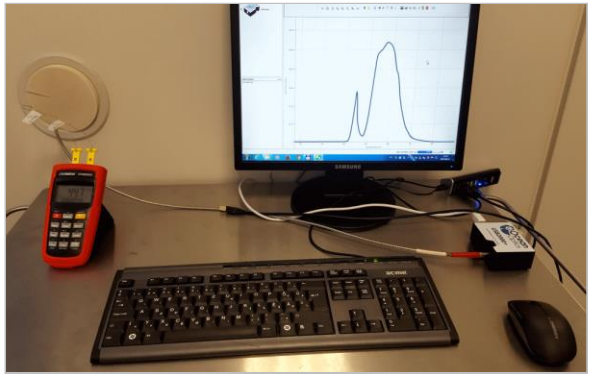
Yet another application example: a smart luminaire with temperature compensated CLO

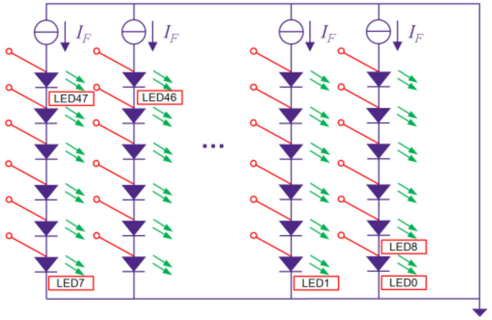
Background: street-lighting luminaires have to provide required level of illumination of roads, even under the *worst case conditions* ➔ hottest summer night / least efficient LED operation ➔ over-lighting most of the year

Finding the $\mathbf{I_F(T_{amb})|_{\Phi=const}}$ function:

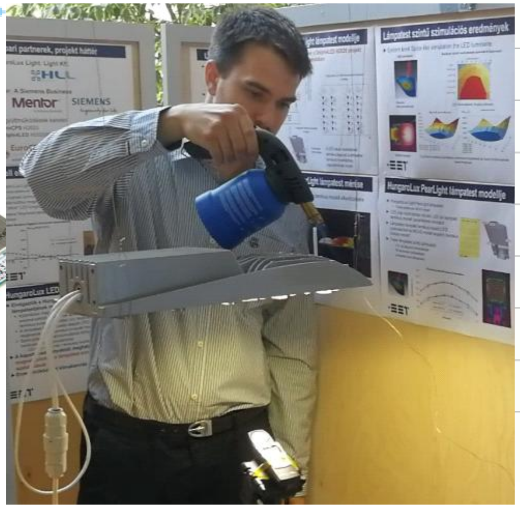


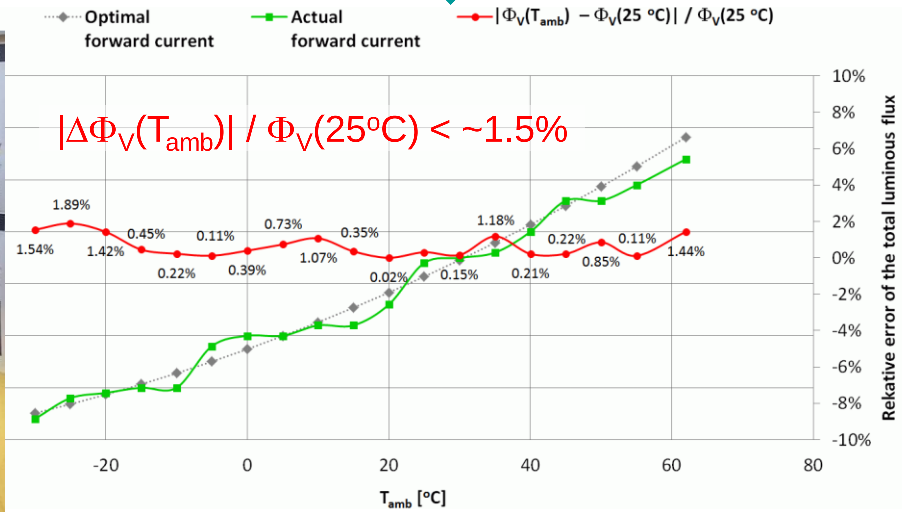






Delphi4LED type modelling and simulation was performed ➔ **results converted into an embedded model**



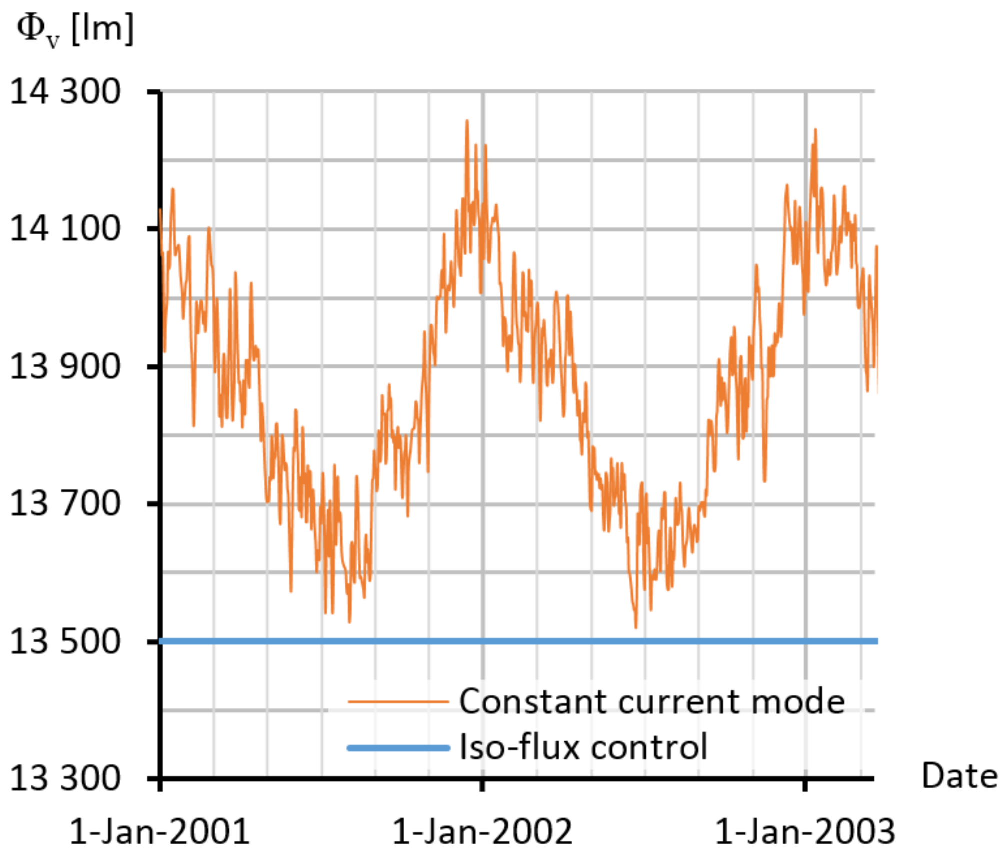


 A. Poppe: Creating new multi-domain digital twins of LEDs with an attempt to describe their ageing for predictive maintenace schemes

Annual Φ_V variation with/without CLO control

EuroCPS Cyber-Physical Systems

- Simulated light output variation during a year: 6-8%
  - T_A taken from archived met data of Szombathely, Hungary



The bottlenecks of Delphi4LED

Delphi4LED

Though in the public domain, **Delphi4LED models did not become widespread**

- The **measurement of a set of isothermal IVL characteristics for 34 operating points** for pre-defined (I_F, T_J) pairs is not yet a common practice
  - The measurements comply with the most recent JEDEC standards and CIE recommendations and an automated procedure is available in commercial measurment tools.
  - With these, the full characterization of an LED package **is impedingly long**, it takes ~8 hours
- Measurement results are not reported in a standard electronic data format

  ➔ **CIE TC2-84, JEDEC JC15 committee work in progress…**
- There is no efficient parameter extraction tool available

  ➔ **needs for an improved test method, for a standard data format, for a parameter extraction tool…**
- The Delphi4LED type **multi-domain digital twin of LEDs is valid for the 0 of operation**

  ➔ **add at least the elapsed product lifetime as a further model parameter…**

  ➔ **add lifetime / reliability aspects on luminaire level too…**

Modelling the LED drivers was missing

➔ **add LED driver models with electro-thermal features and connect them to reliability prediction…**

Only total fluxes were calculated

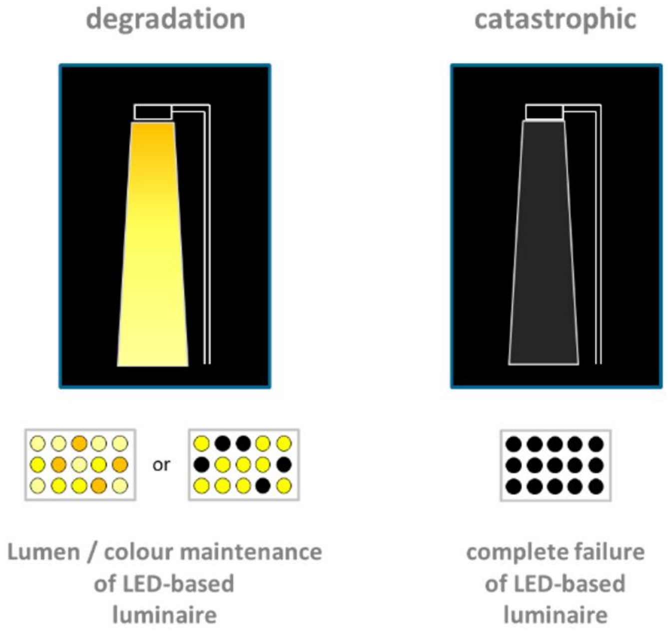
➔ **add at current, temperature and lifetime dependent spectrum model…**

Too simplistic luminaire level model, only the effect of the static thermal environment was considered

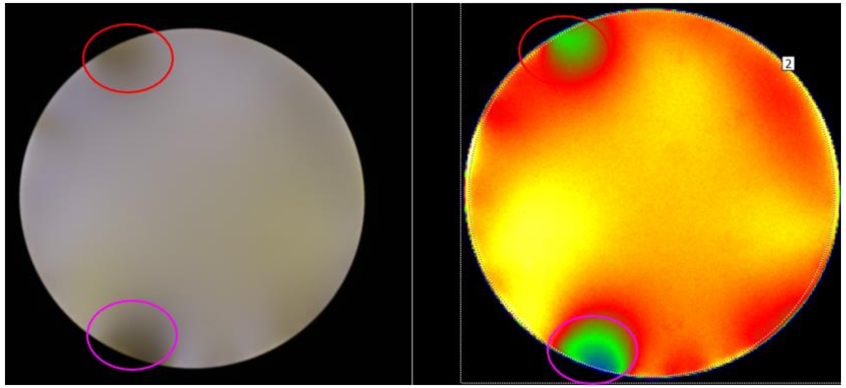
➔ **find ways of considering the mission profile of luminaires to predict RUL…**

Extend the Delphi4LED concepts with lifetime/reliability aspects towards lifetime prediction during operation

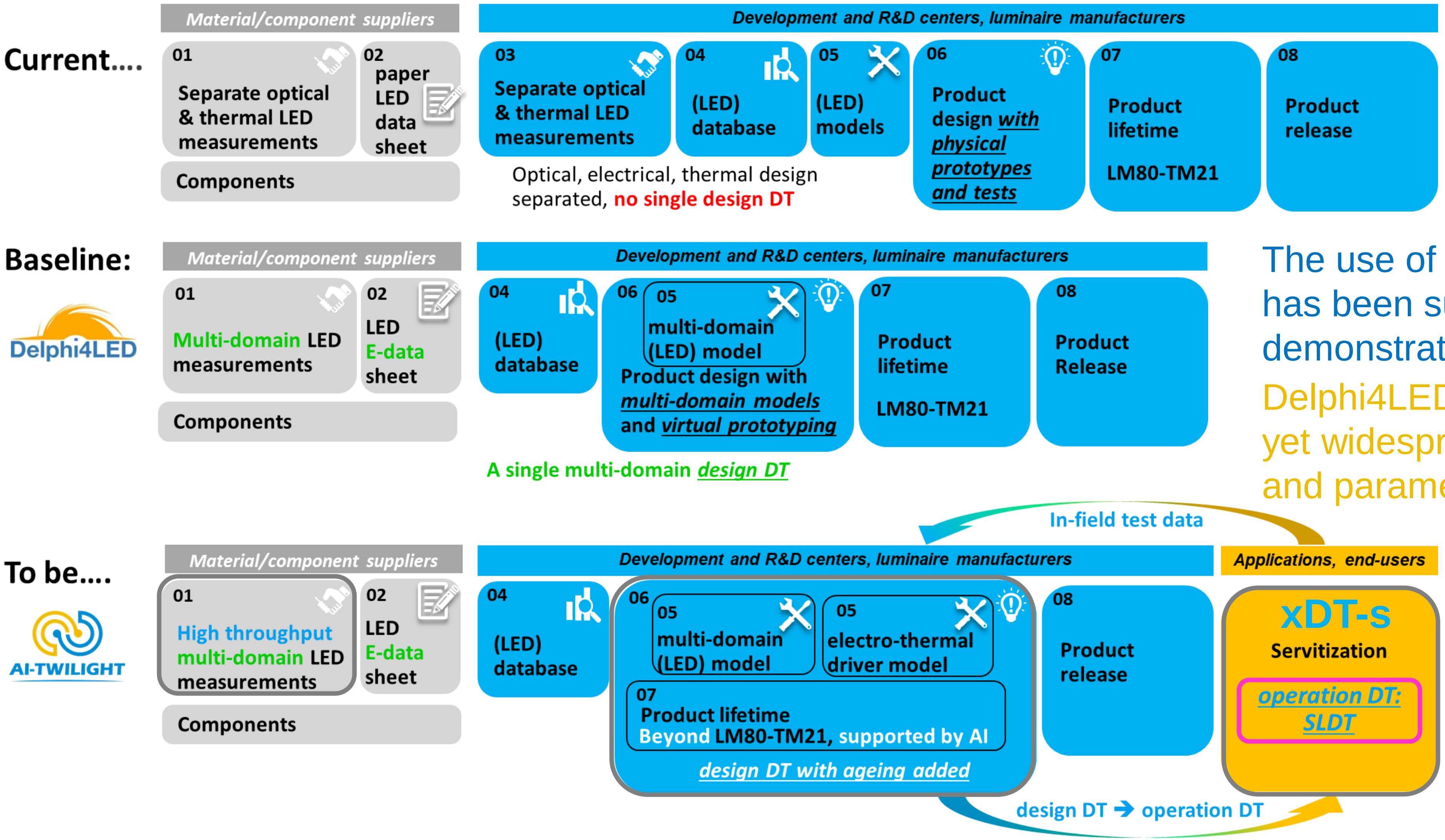
The approach of **AI-TWILIGHT**, a new European project



AI-TWILIGHT



The baseline and vision of AI-TWILIGHT:



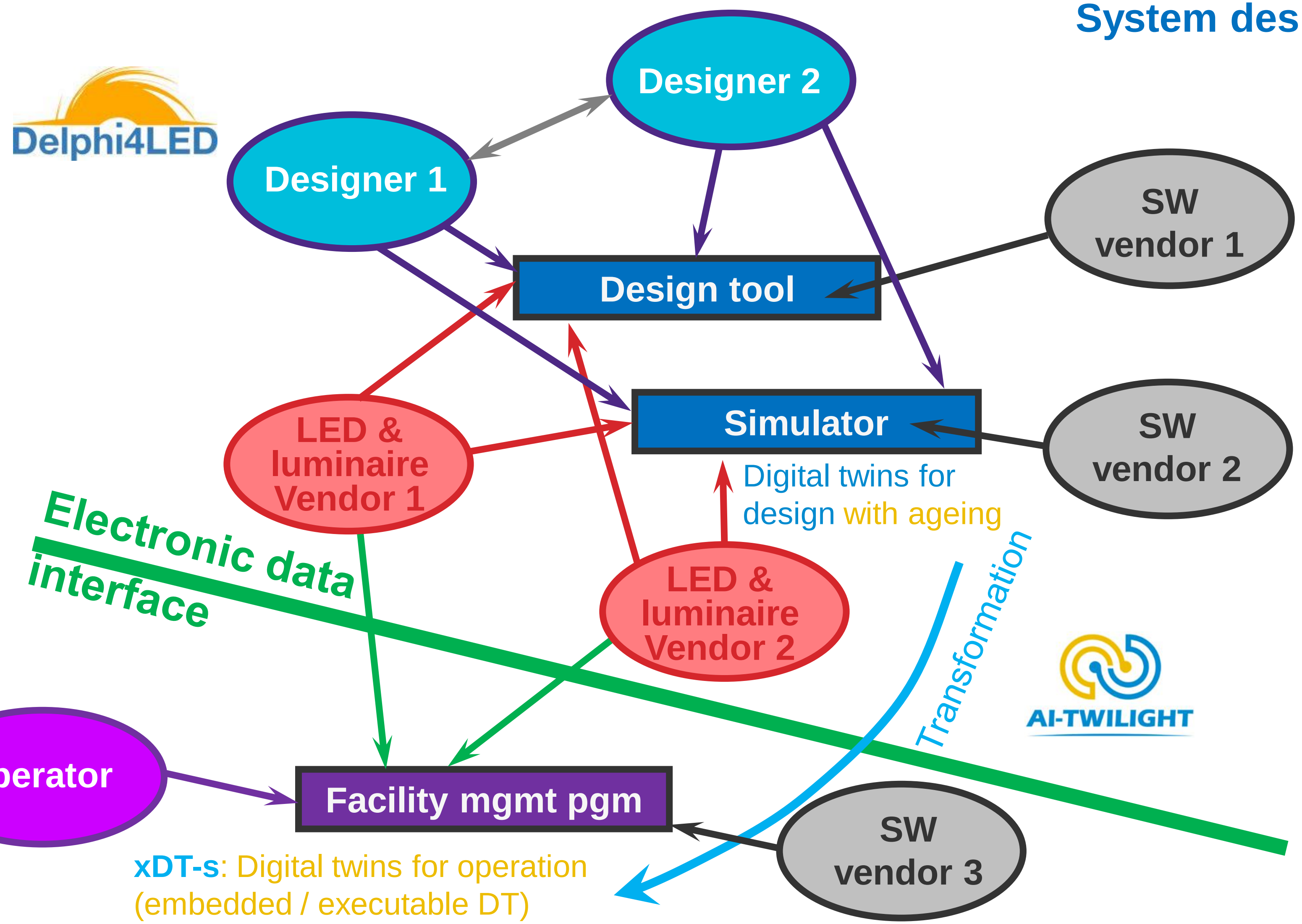
The use of the Delphi4LED workflow has been successfully demonstrated.

Delphi4LED methodologies are not yet widespread... (testing throughput and parameter extraction issues)

Apply **AI methods** in creating models for *predictive / prescriptive maintenance* and LED product *lifetime prediction*.

The wider vision: Lighting 4.0 with AI support

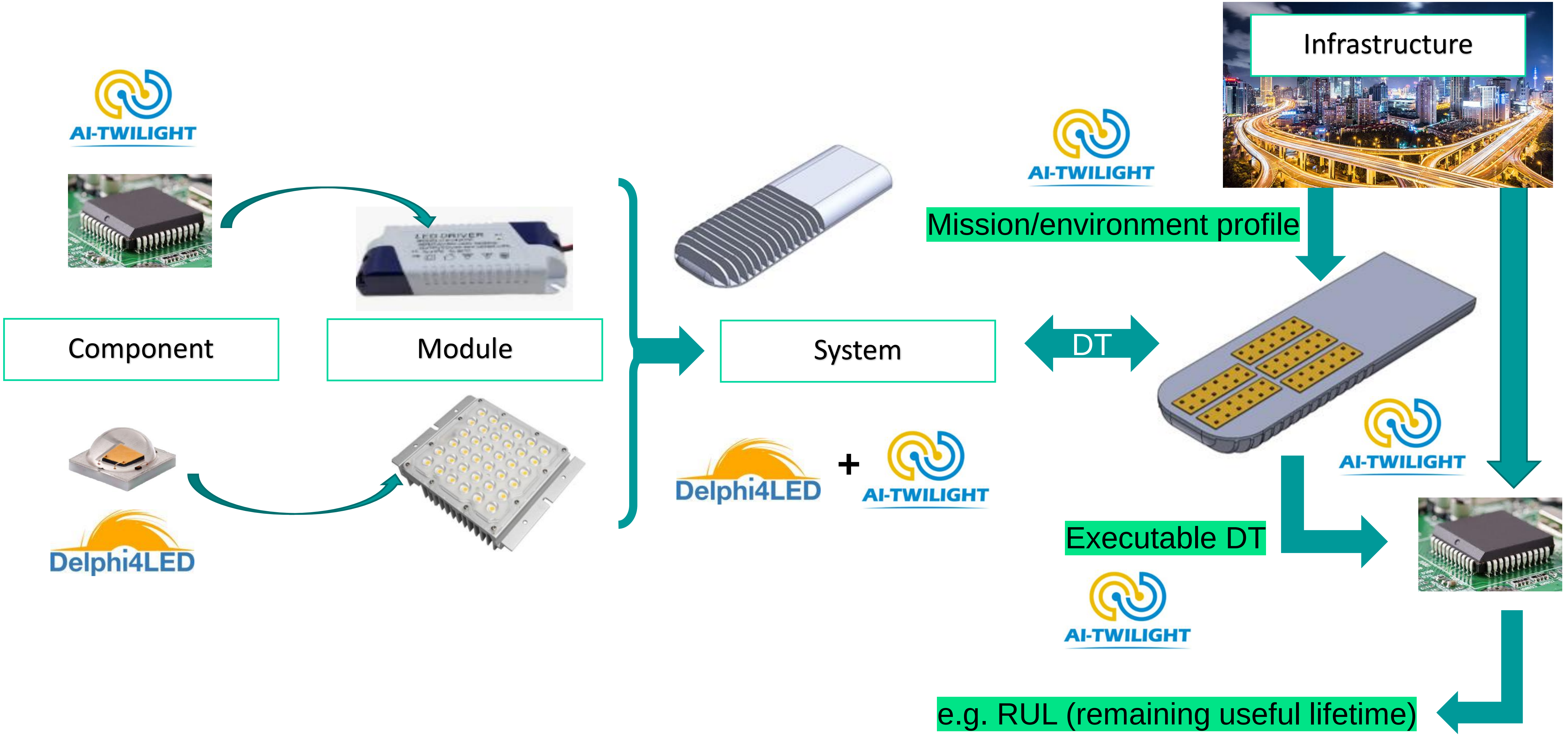
System design



Lighting system operation

Life-time modelling and prediction of remaining useful life time supported by AI methods

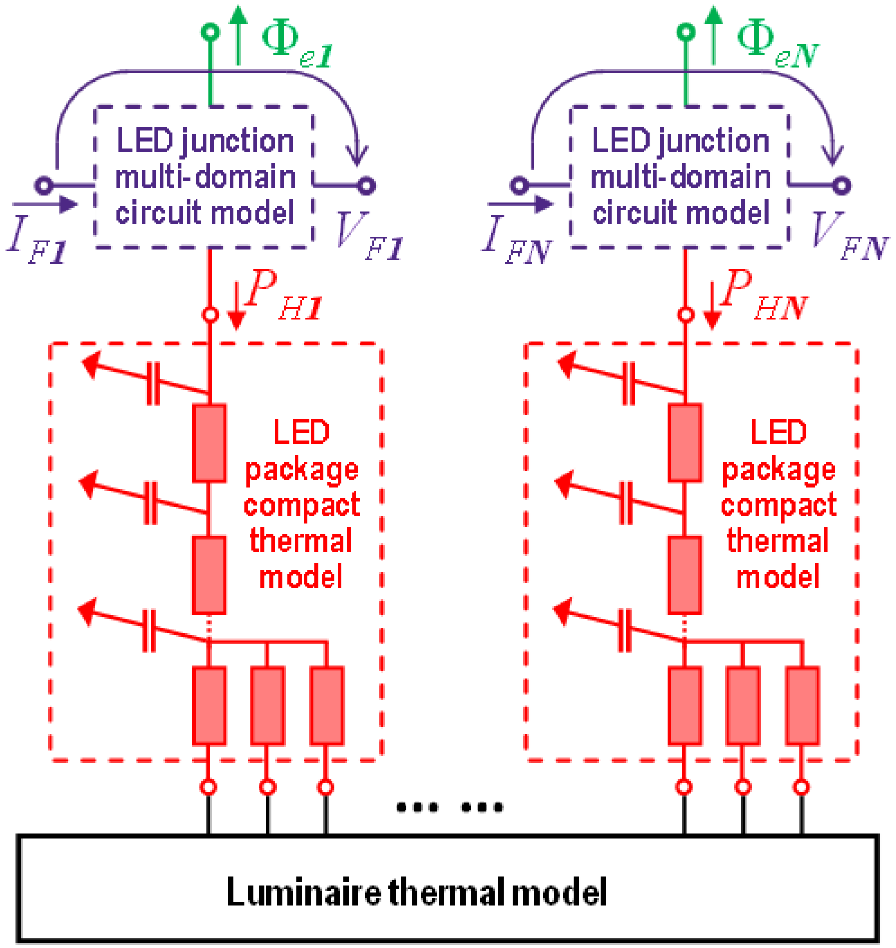
The extended approach: digital twin (DT) for design and for operation



Adding new items to the former Delphi4LED modules (digital twins for design)

transformation into an xDT

add SPD model extended with ageing (possible inputs: I_F, T_J, Φ_e, elapsed lifetime)



add driver model to the overall luminaire model

consider ageing in the diode characteristics (e.g. elapsed lifetime as parameter)

model the degradation of the heat-flow path (e.g. elapsed lifetime as parameter)

create different transfer functions for the executable version of the DT, etc.

add ageing to the models

Some details of the work done so far…

Focusing on data analysis and modelling issues

Discussing the foreseen improvement of tests requires another talk of about 40 min.

Some steps taken forward: parameter extraction for the chip level multi-domain model

Global optimization in a 18 dimensional space with a procedure based on the Nelder-Mead method

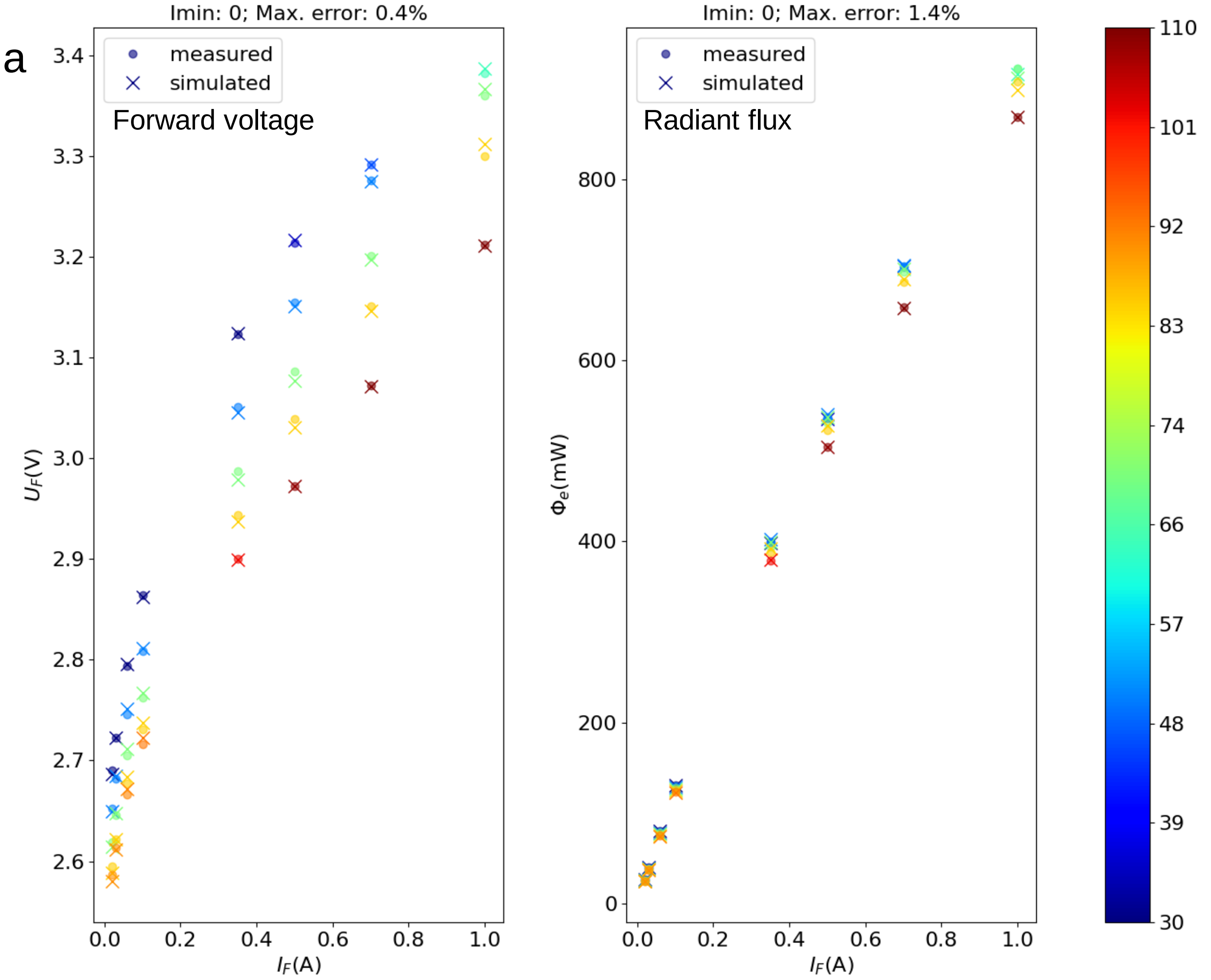
- The extraction was tested on all Delphi4LED measurements, which are available; including both white and colour LEDs
- The relative error of the modelled radiant flux for the whole was below 5%.
  - This is the same order of magnitude as the measurement uncertainity of the radiant flux)
- The relative error for the forward voltage was below 1%.
- The execution time for parameter extraction from **40 operating points was less than 1 minute**

$$V_{F,T_J=T_{ref}} = I_F \cdot R_S + m \cdot U_T \cdot \ln\left[\left(\frac{I_F}{I_0}\right) + 1\right]$$

$$\Delta V_{F_{el}} = (a_{el} \cdot I_F^2 + b_{el} \cdot I_F + c_{el}) \cdot (T_J^2 - T_{ref}^2) + (d_{el} \cdot I_F^2 + e_{el} \cdot I_F + f_{el}) \cdot (T_J - T_{ref})$$

$$I_{rad}(V_{Frad}) = I_{0_{rad}} \cdot \left[\exp\left(\frac{V_{Frad} - \Delta V_{F_{rad}} - I_{rad} \cdot R_R}{m_{rad} \cdot U_T}\right) - 1\right]$$

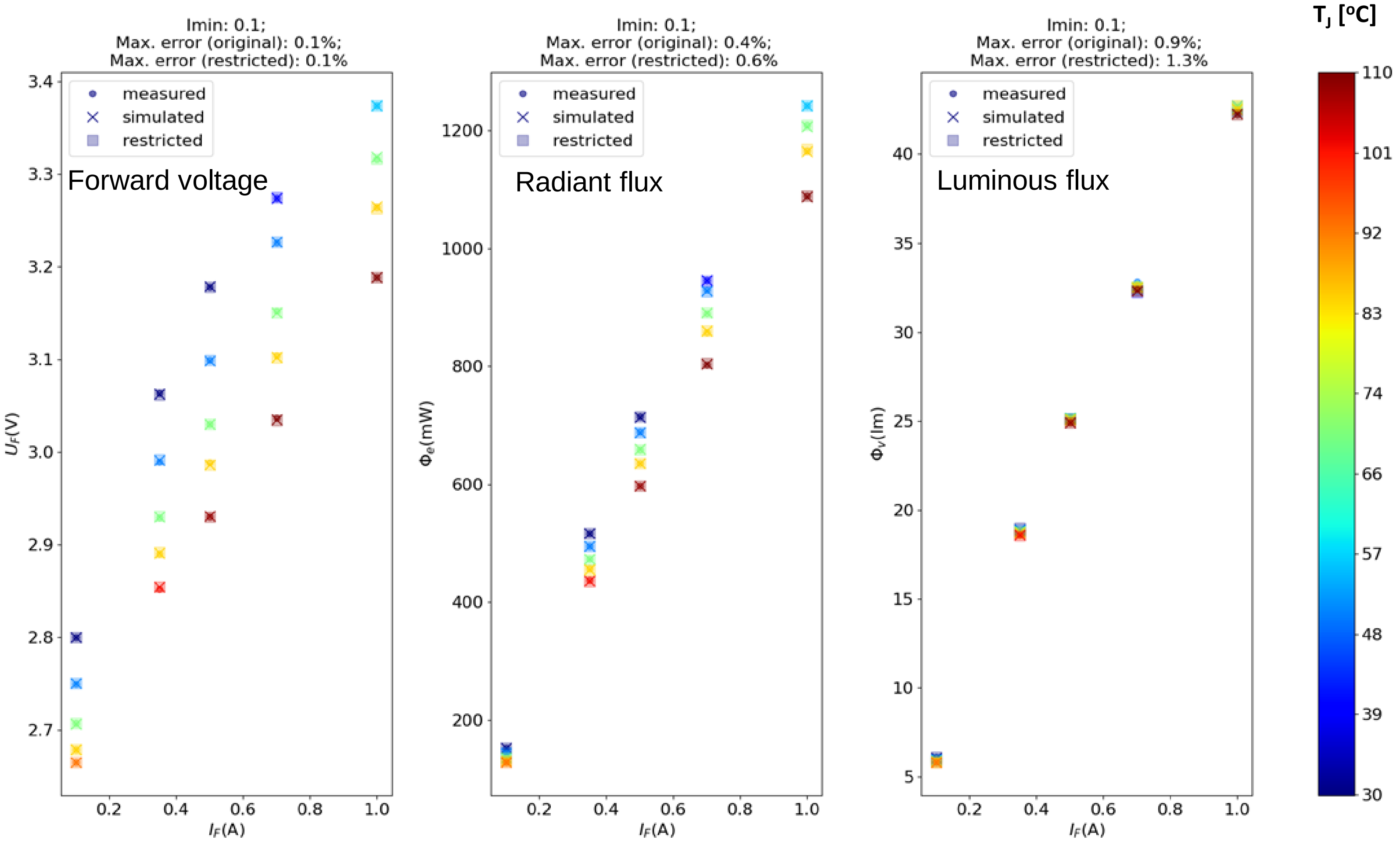
$$\Delta V_{F_{rad}} = (a_{rad} \cdot I_F^2 + b_{rad} \cdot I_F + c_{rad}) \cdot (T_J^2 - T_{ref}^2) + (d_{rad} \cdot I_F^2 + e_{rad} \cdot I_F + f_{rad}) \cdot (T_J - T_{ref})$$



Some steps taken forward: parameter extraction for the chip level multi-domain model

Reduce the number of necessary (I_F, T_J) operating points of Delphi4LED measurements:

- It seems that measuring at 3 temperatures and 4 currents (12 operating points instead of 40) results in less than 1% additional error in the model.
- A more detailed analysis is in progress that compares the data from 170 operating points reduced down to 12-15 ones.
- **The measurement time can be halved without significant errors in the results: additional benefit on top of developments aimed at speeding up tests (isothermal IVL characterization)**



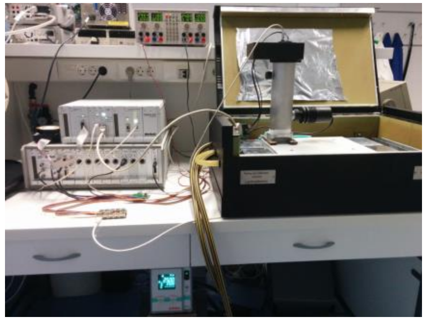
Elapsed lifetime – age dependence of model parameters

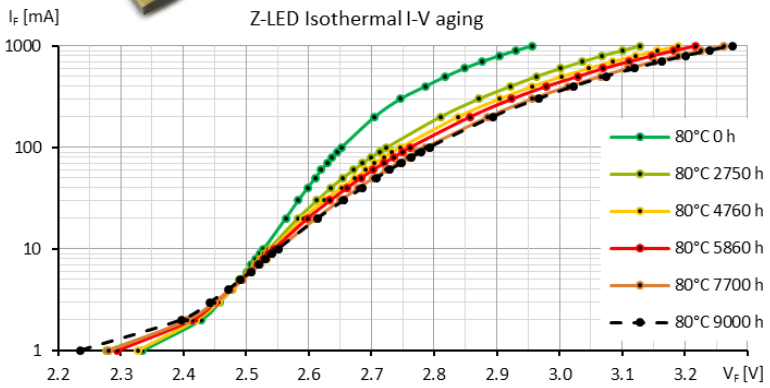
$$V_{F,T_J=T_{ref}} = I_F \cdot R_S + m \cdot U_T \cdot \ln\left[\left(\frac{I_F}{I_0}\right) + 1\right]$$

From past ageing measurements

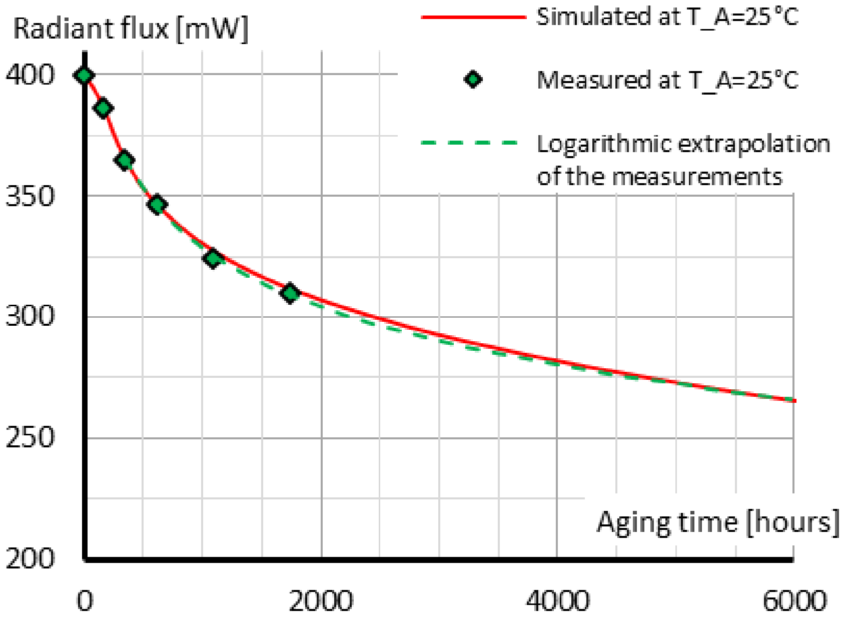
- **Elapsed lifetime in the multi-domain LED model (fixed current and temperature)**
  - 100% … 78% aging range (in terms Φ_V)
- Successful implementation of this very first approach – fitting LM80 test data
  - 0.5% absolute and
  - 1.2% maximum simulation inaccuracy

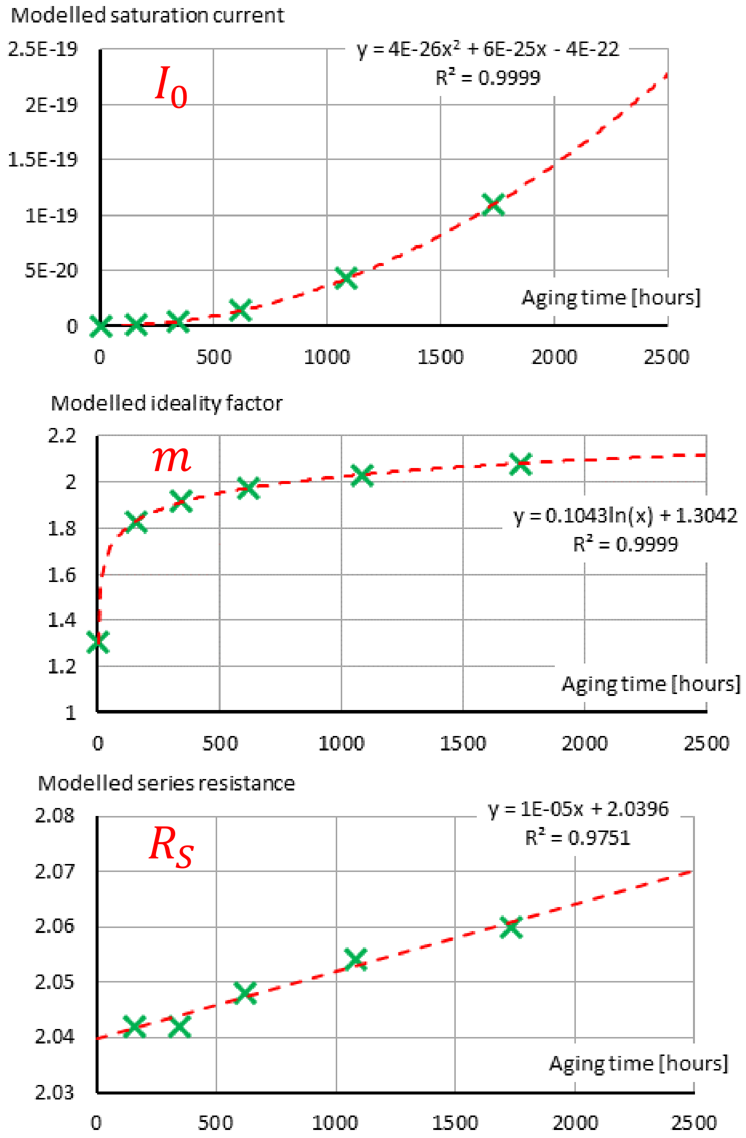
LM80 aging test setup completed with equipment for isothermal IVL characterization at an academic partner





Isothermally measured IV characteristics obtained at different aging times during an LM80 test



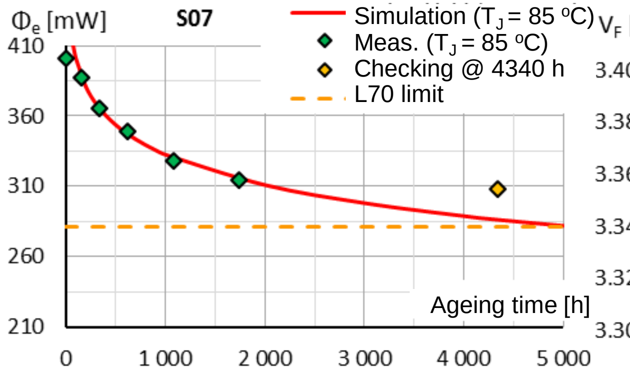


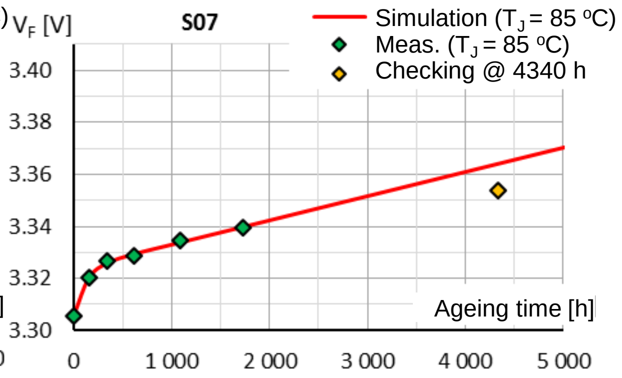
Elapsed lifetime – as an additional parameter of the Spice-like multi-domain model

From previous LM80 aging test of another set of samples

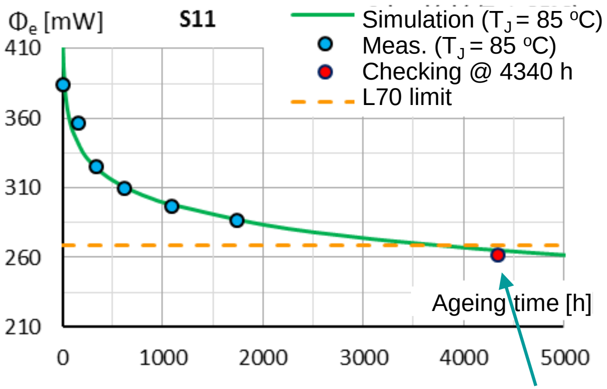
- models were generated from data measured up to 1735 hours,
- after further ageing up to 4340 hours, the samples were measured again.

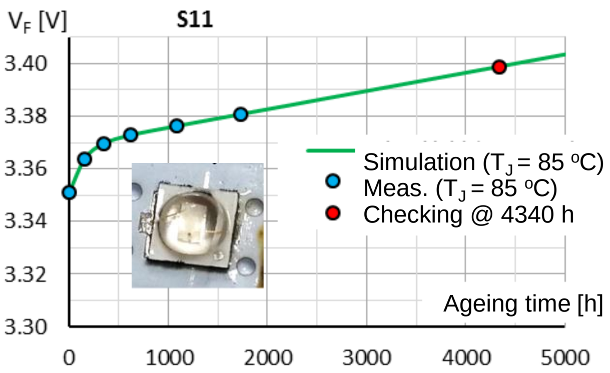
The model predicted flux depreciation and the measured one matched well.





	V_F error of modelling [mV]	V_F error related to the zero hour value [%]	Φ_e error of modelling [mW]	Φ_e error related to the zero hour value [%]
S07	10.2 mV	0.3%	-21.7 mW	5.4%
S11	0.1 mV	0.003%	3.2 mW	0.8%





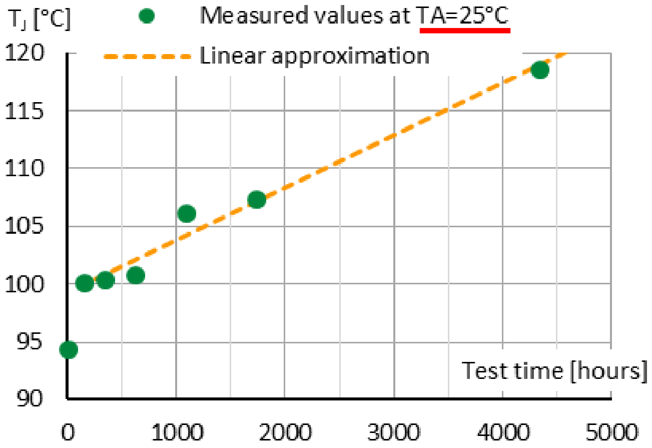
Poor product, L70 end-of-life reached in ~4300 hours.

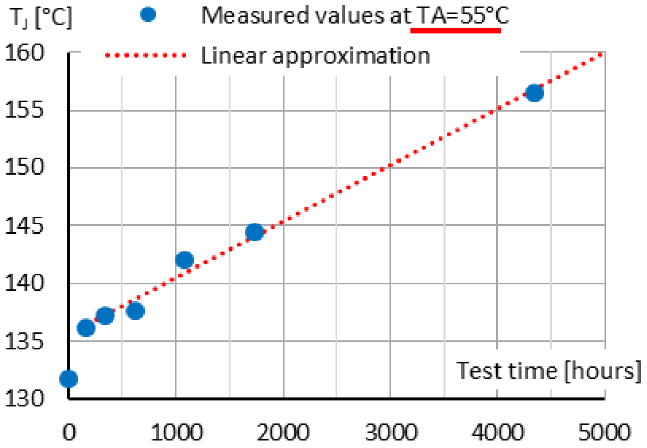
Problems:

- Too few samples were studied
- LM80 aging test + isothermal IVL characterization in 40 operating points takes impedingly lot of effort
- Only one aging current and aging temperature was used

Some measurement issues need also be clarified...

During LM80 tests continous increase of the junction temperature was observed (BME's experiments)





In the TM21 based life-time esimation the constant ambient temperature is used…

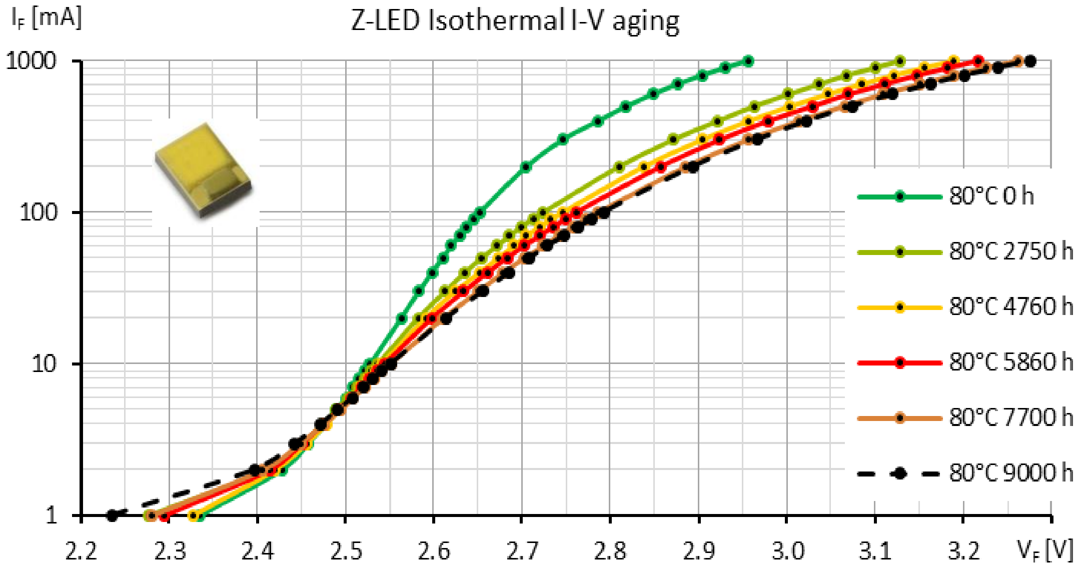
At least for chip level ageing, the junction temperature counts, though.

What if, we are interested in the predicted life-time at

- another constant forward current,
- at another temperature,
- or both?

➔ **mission profile**

LM80 tests:
Conditions: LEDs driven by a constant DC current in a constant temperature (e.g. 55 ºC, 85 ºC) environment.
Aging indicator: maintenance of the emitted total luminous flux

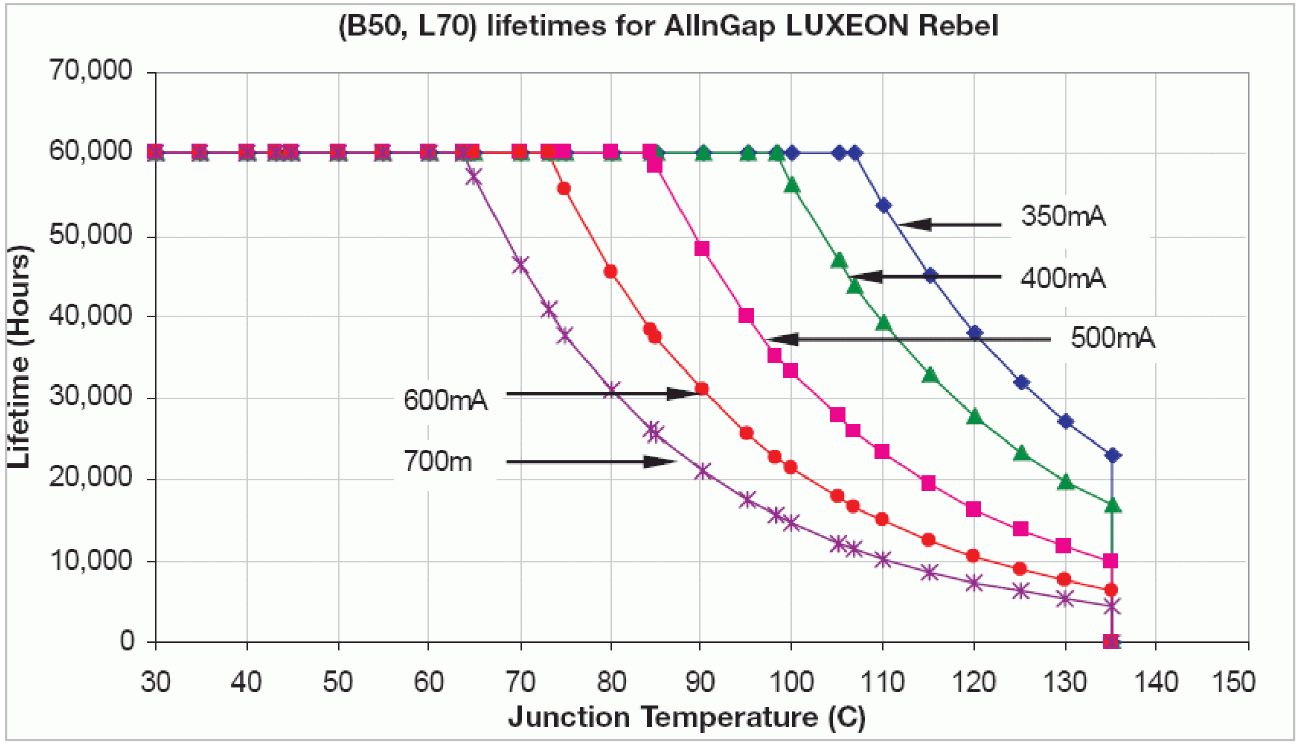


TM21 life-time prediction:
Fitting an Arrhenius-type relationship to the LM80 **luminous flux maintenance** data

SCEE 2022: The 14th Conference on Scientific Computing in Electrical Engineering, July 11-14, Amsterdam, The Netherlands

Why is the mission profile interesting?

Both higher forward current and higher remperature speed up LED ageing



Changing I_F and T_J are due to changes

- as part of **normal operation**,
- and due to **changin environment** (weather)

often superimposed, resulting e.g. in

- short term active cycles (dimming, on/off cycles)
- daily and seasonal passive cycles.

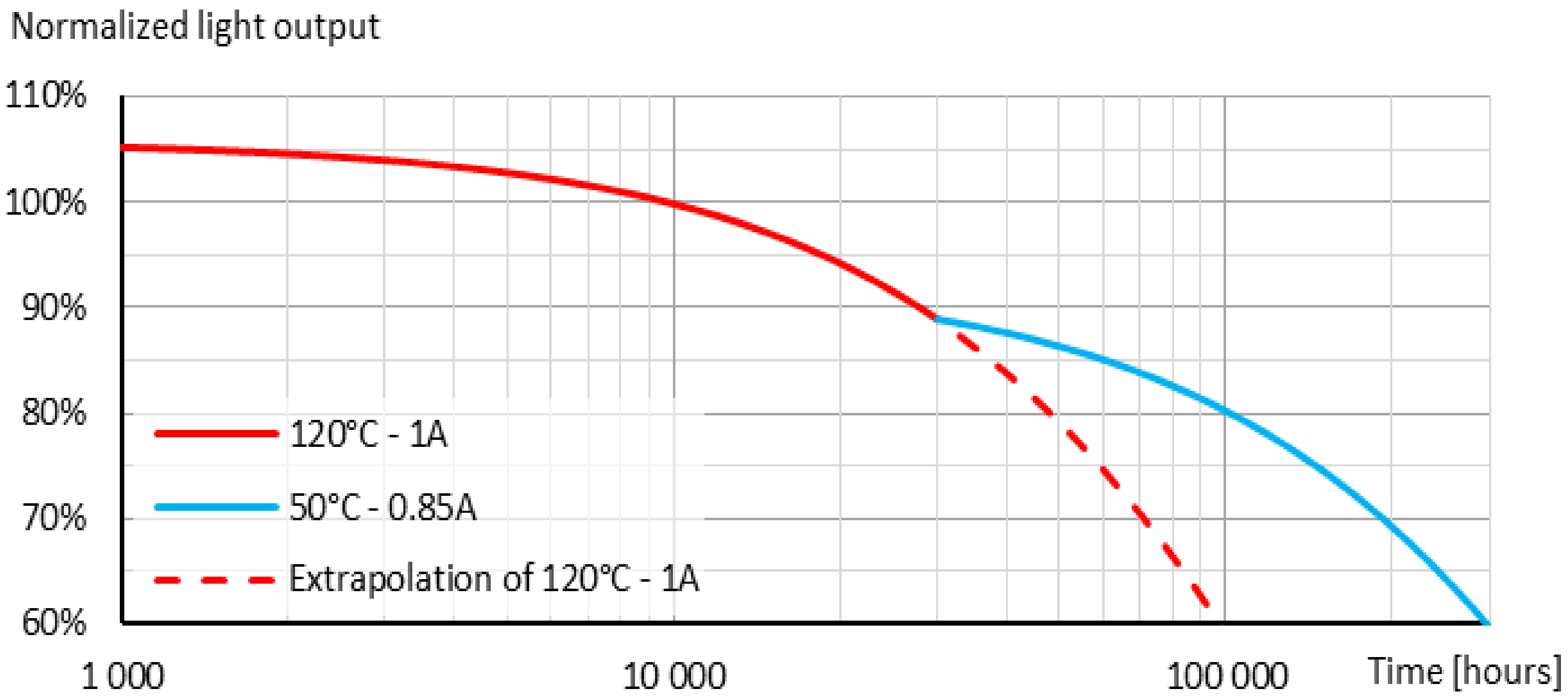
mission profile

Besides e.g. chip level ageing, **thermo-mechanical stresses** develop, resulting in degradation of the heat-flow path ➔ **increased R_{th}** ➔ **increased T_J**

Hypothesis:
- There is a "**life-time budget**" identified through an LM80 aging process (given I_F and T_J) and TM21 prediction.
- **This budget is consumed faster or slower with changing I_F and T_J**
- Acceleration can be **calculated also with an Arrhenius-type relationship** (analogy with the description of kinetics of chemical reactions)

The effect of "mission profile" on the LM80/TM21 luminous flux maintenance curve

At L90 temperature and current are reduced – projected L70 life-time got prolonged:



A proposed alternat, physics+data-based model for lifetime prediction

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Degradation dynamics (data-based part)

$$\dot{x}(t) = f\big(x(t), u(t)\big),\ \ x(0) = x_0$$

Effects of degradation dynamics on the LED chips' optical output

$$\Phi_V(t) \ = g(x(t), u(t), \theta)$$

$x(t)$: the state of degradation, $0 < x < 1$

$g(1, u, \theta)$: the multi-domain LED model

θ: parameters of the multi-domain model

u: vector of operating conditions (current, temperature, etc) – the "mission profile"

$\Phi_V(t)$: luminous flux

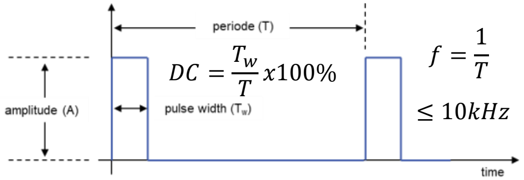
SCEE 2022

Considering the ageing effect of cyclic electro-mechanical stresses

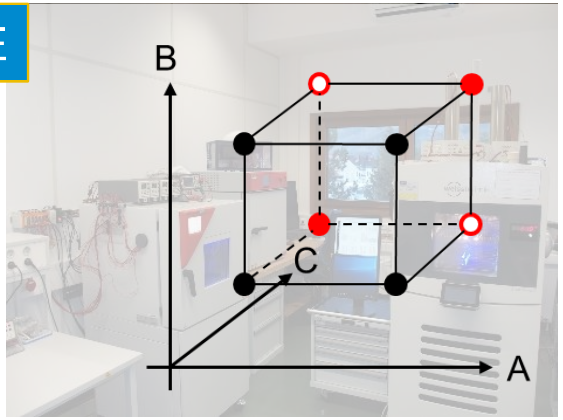
In relation this we can learn again a lot from the practice of the semiconductor industry…

LM80

+ Power Cycling (Duty Cycle)



+ DoE



Collect Knowledge + Data

- System Understanding
- Fault types, States
- Measurements

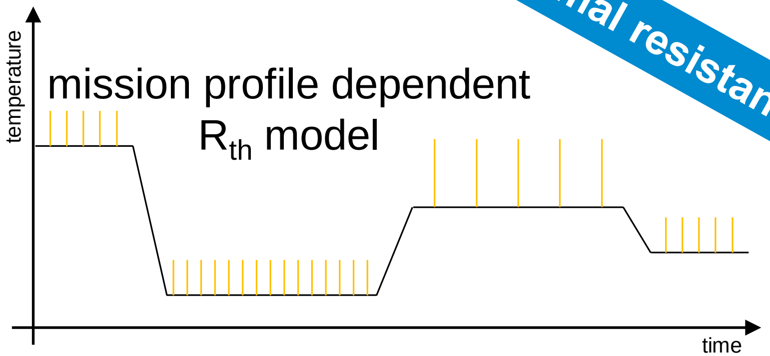
Modelling changes of thermal resistance due to ageing

Construct inverse model family

- Exploratory Data Analysis
- Analytical inverse model
- Data-driven inverse model

Explore inverse model family

- Trade-off studies
- Uncertainty quantification
- Model complexity

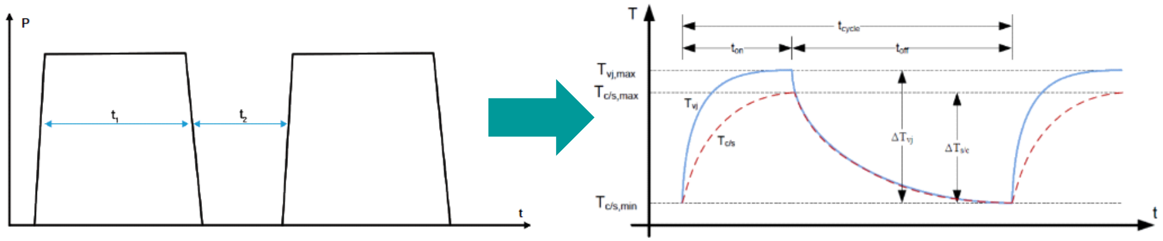


Slide by courtesy of Julien Magnien, MCL, Leoben, Austria

Learning from electronics again: power cycling of power semiconductor devices (IGBTs)

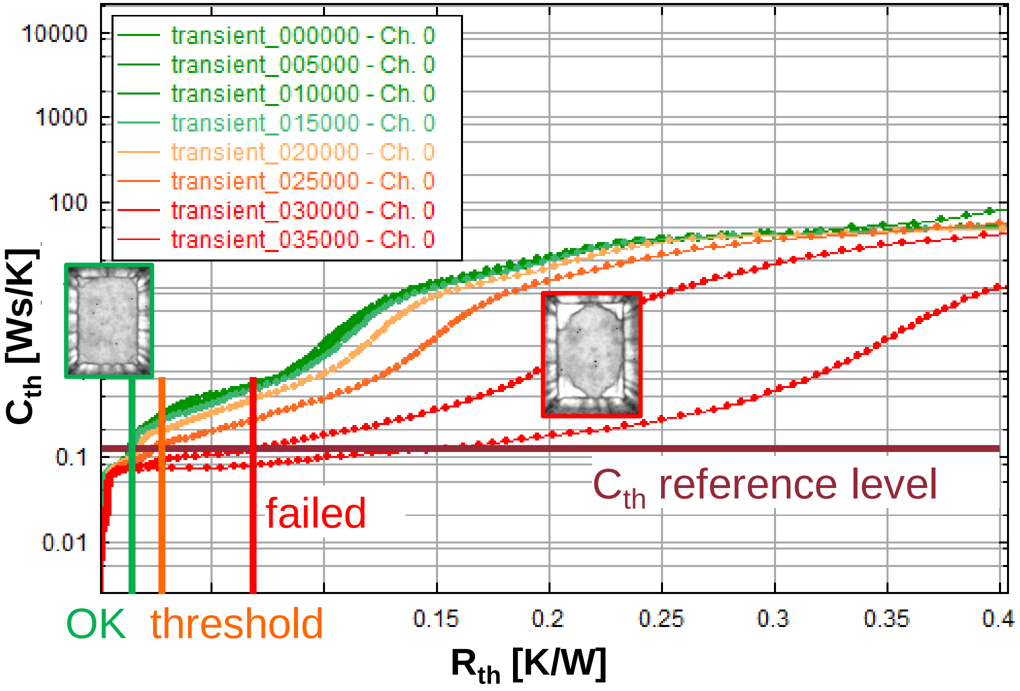
Life-time assessment of a power semiconductor device after cyclic stress

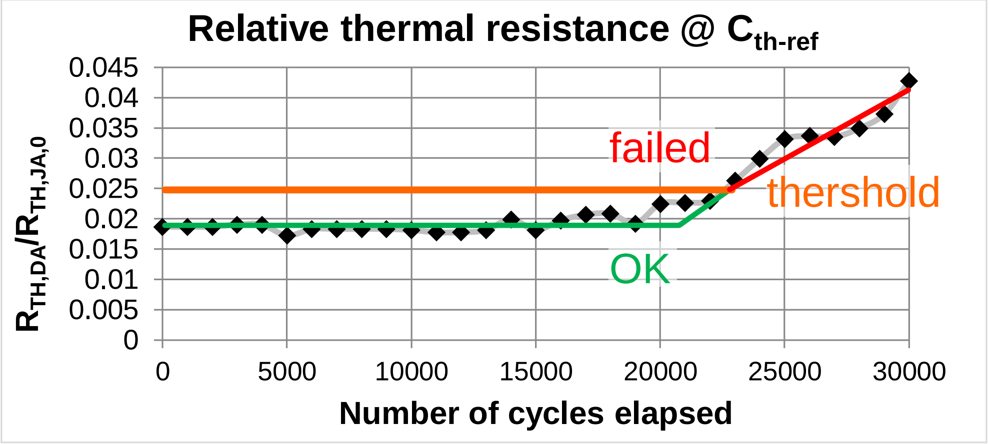
- Find the location and degree of degradation
- Early detection of future failures before fatal failure of the device
- *In-situ*, non-destructive method, applicable during field operation



A failure mode also possible in LED packages: die attach degradation/delamination

Structure functions after different numbers of elapsed cycles



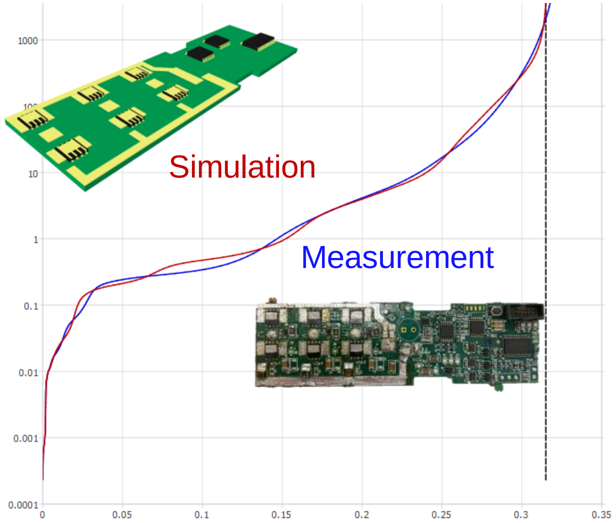


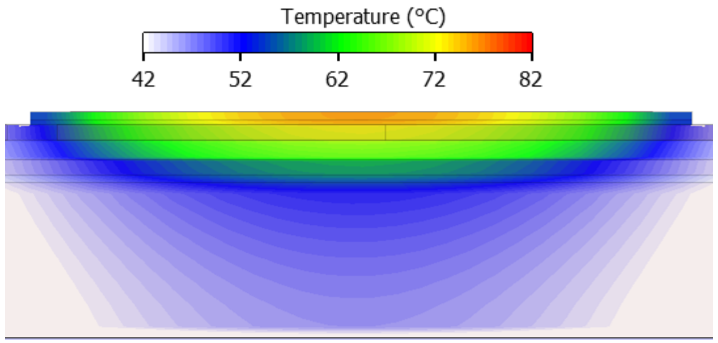
Failure condition: intersection of the structure function and a $C_{th} = C_{th/ref}$ reference level is beyond an R_{th} threshold.

The question is how many cycles are needed to reach it…

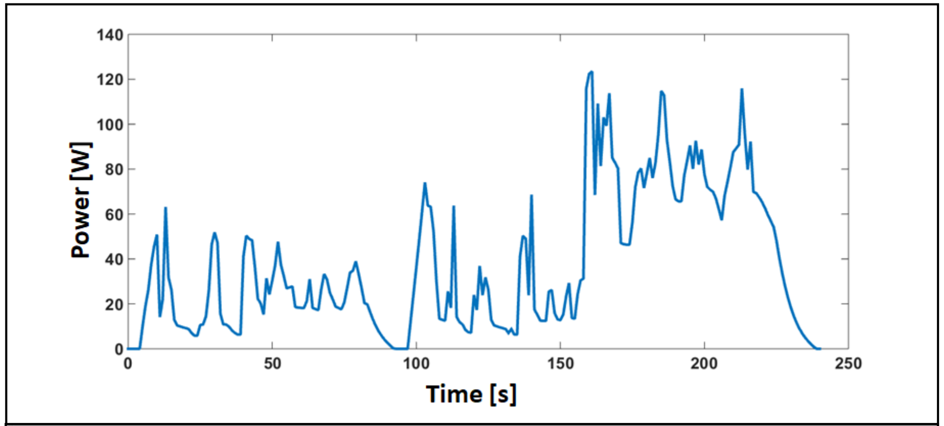
Slide by courtesy of Andras Vass-‘várnai, SIMENS DISW STS, Chicago, USA

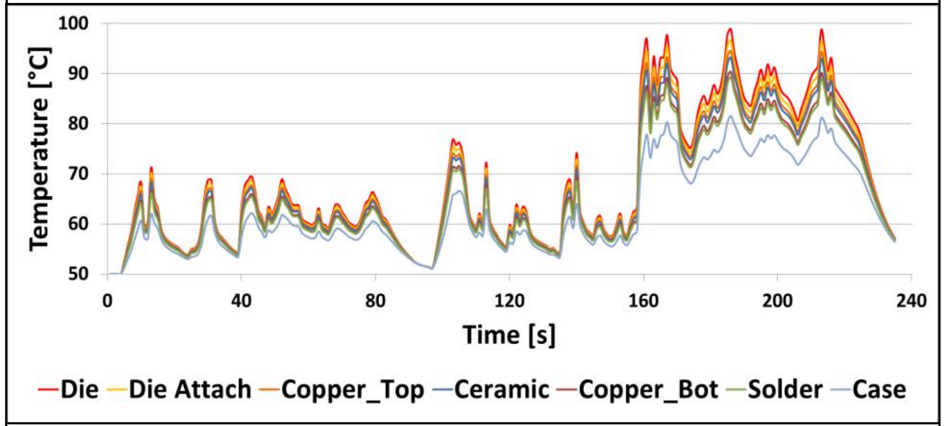
Life-time assessment of a power semiconductor device after cyclic stress





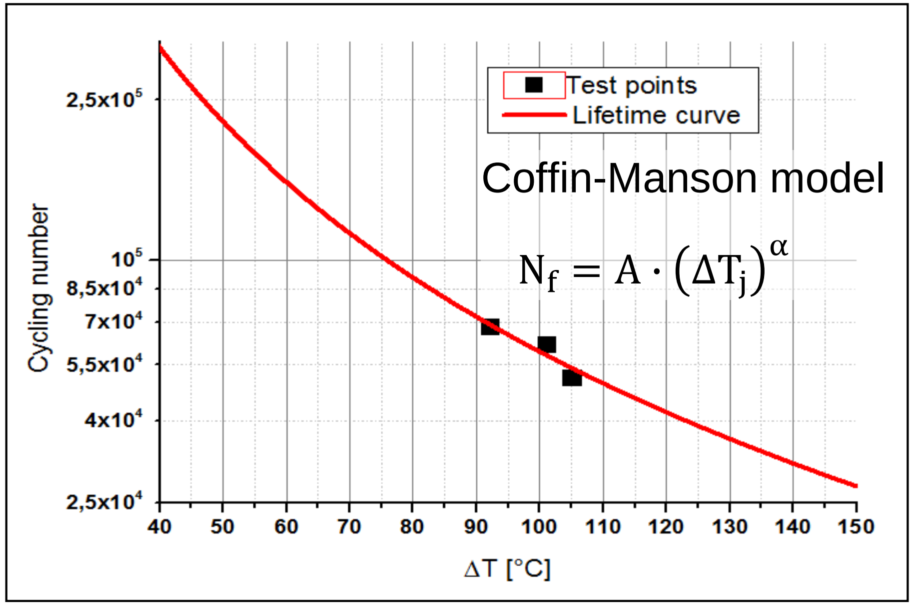
Calibrated detailed 3D model
(ROM based compact model would also work)

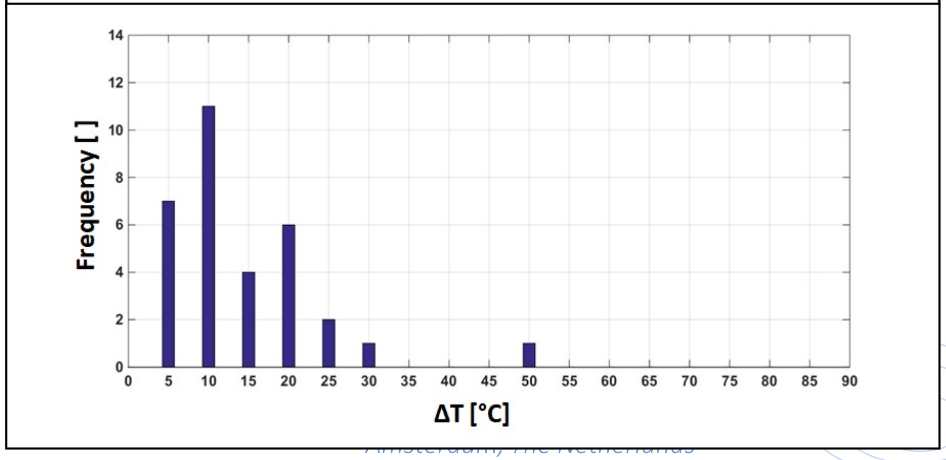




$$N_{f\_sum} = \frac{1}{\sum_{k=1}^{n} \frac{w_i}{N_{f\_i}}}$$

$$t_{operation} = N_{f\_sum} \cdot t_{cycle}$$





Slide by courtesy of Andras Vass-‘várnai, SIMENS DISW STS, Chicago, USA

Example: self-learning digital twin assisted age and temperature compensated CLO

Life-long constant light output control: a street-lighting luminaire use-case example planned

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- A Delphi4LED digital twin application example was a temperature compensated CLO scheme in a street-lighting luminaire.
- It relied on a multi-domain LED model valid at 0 h
- Its benefits were
  - Overlighting was avoided at low temperatures (winter) by reducing the forward current
  - According to model calculations and archived met data for Hungary, this solution may result in the redection of the necessary electric power of about 5-8%

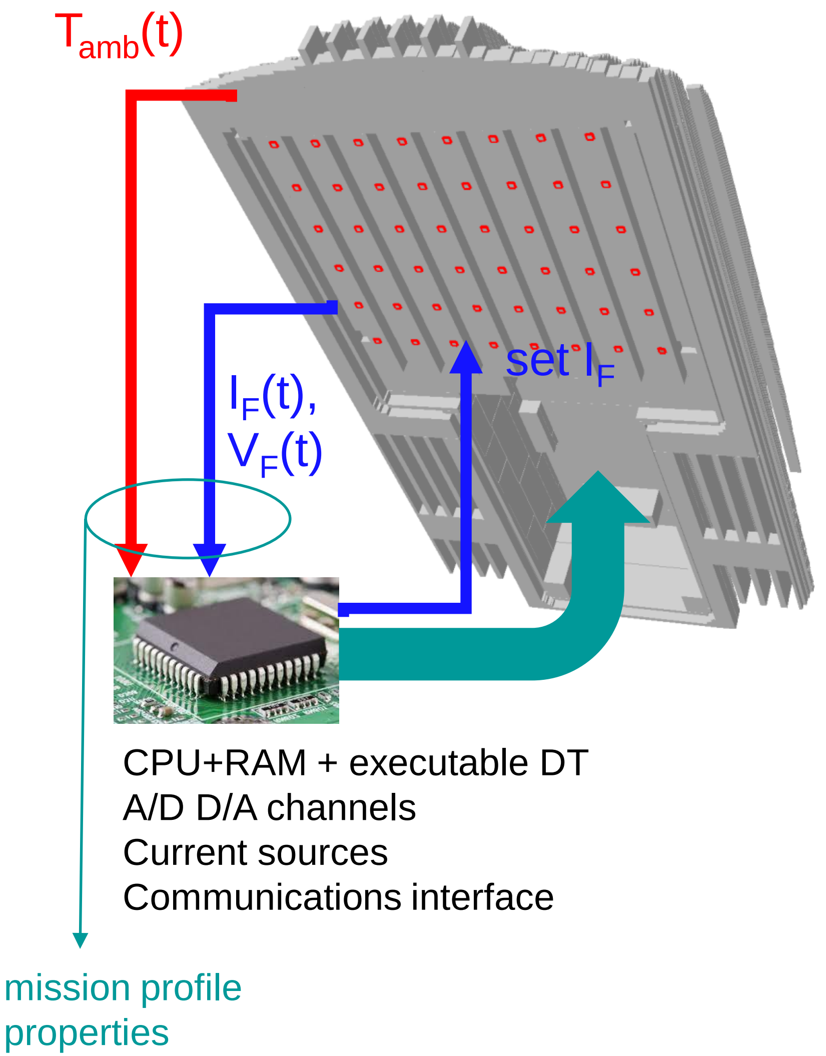
Why to deal with ageing in a CLO scheme?

- The required illumination level has to be provided even when the product is close to the L70 condition (luminous flux shrank to 70% of its initial value)
- This could be achieved by increasing the forward current as the LEDs get aged.
  - For a precise setting of the forward current, instead of the standard LM80/TM21 luminous flux maintenance, the actual elapsed mission profile based luminous flux maintenance function should be considered
  - The self-learning feature in this case means the continuous update of the consumed life-time budget

Life-long constant light output control: a street-lighting luminaire example (cont.)

Self-learning feature, remaining useful life-time (RUL) prediction

- The self-learning == continuous update of the consumed life-time budget according to the mission profile measured
- This requires the following features in the luminaire
  - Some monitoring / diagnostic features such as
    - measurement of the luminaire/ambient temperature
    - measurement of diode voltages
    - measurement of other parameters like RH, color, etc.
  - Fine resolution in the setting of the forward current in the LED driver
  - Data processing capabilities in the LED driver
    - hosting the executable digital twin (age-extended multi-domain LED model)



CPU+RAM + executable DT
A/D D/A channels
Current sources
Communications interface

As an application use-case, the previously presented temperature compensated CLO scheme is panned to be extended with such an SLDT (self-learning digital twin) in AI-TWILIGHT

Some *expected* quantified benefits of ageing compensated CLO using an SLDT

The below table is based on the properties of a white LED aged a few years ago at BME and on temperatures from archived met data (Szombathely, NW Hungary)

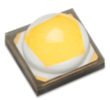
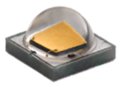
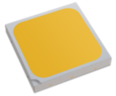
	No CLO (constant current during life-time)	CLO with temperature and ageing compensation	Benefits of using the SLDT assisted CLO
Projected life-time until L90 condition	64.4 khours	83 khours	+29%
	16.7 years	21.4 years	+4,7 years
Power consumption during 64.4 khours	130.8 kWh	112.8 kWh	-13.7%
Power consumption in the first year	7.9 kWh	6.5 kWh	-17.7%

Where AI can help…

Where is AI support expected?

Help model (parameter) extraction from physical test results

- The concept of "carrier devices": an LED vendor agnostic approach
  - Catalog of different LED devices representative in a given application domain established (multiple classes of similar architectures)
  - A few devices will be fully characterized (isothermal IVL characteristics in multiple operating points)
  - These will be a training set for an AI that is aimed at producing model parameter sets of other devices of the same architecture

Example/typical values

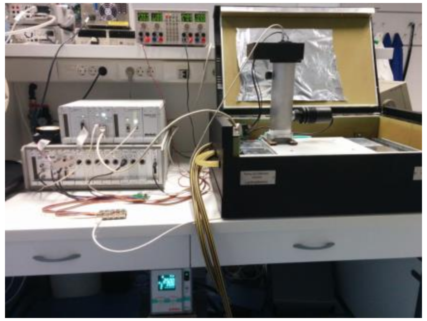
Category	PSS-FC based HP	HP VTF based HP	Multi-die single emitter
Example product models	LUXEON HL2X Cree XP-G3 Nichia 219C Samsung LH351C	Cree XP-G2 Oslon Square	LUXEON 5050 SSC 5050 Duris S8
Package type	Ceramic	Ceramic	Lead frame
Die type	PSS-FC	VTF	Lateral
Die area (mm2)	2	2	
Die wavelength (nm)	440-460	440-460	440-460
CCT (K)	2700 4000	4000	4000
CRI	70	70	70

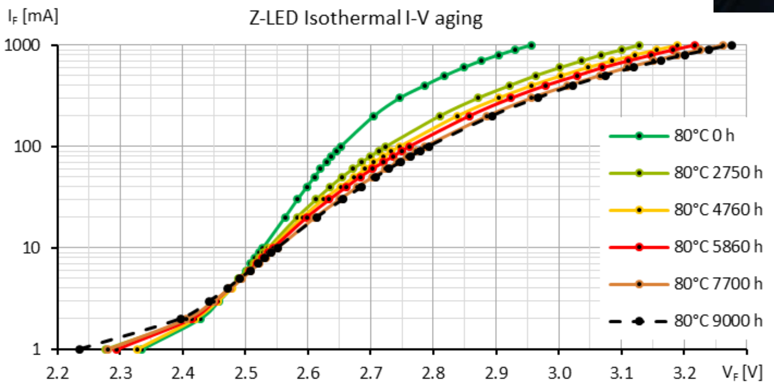
Some carrier devices for outdoor applications

Help using archive sets of data (the AI-TWILIGHT database)

- Large amount of **industrial test data** (qualification test data, LM80 life-time test data), **Deelphi4LED datasets**, detailed isothermal IVL data sets obtained during LM80 ageing for a few LEDs from **academic experiments**
  - The detailed academic test data sets and their corresponding industrial counterparts will be a training set for an AI aimed at generating parameter sets for LEDs for which only the industrial data sets are available

LM80 aging test setup completed with equipment for isothermal IVL characterization at an academic partner



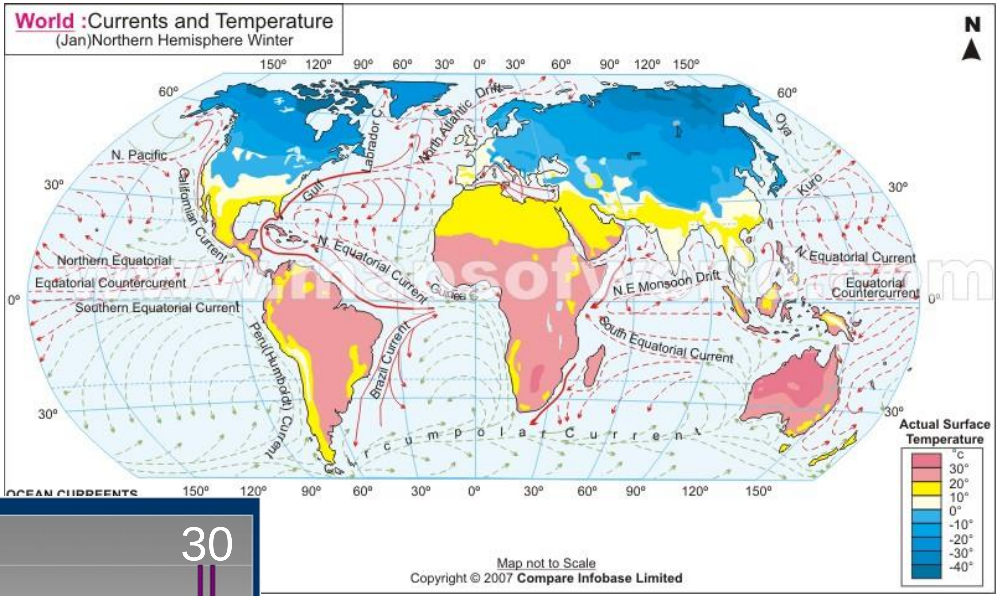


Isothermally measured IV characteristics obtained at different aging times during an LM80 test

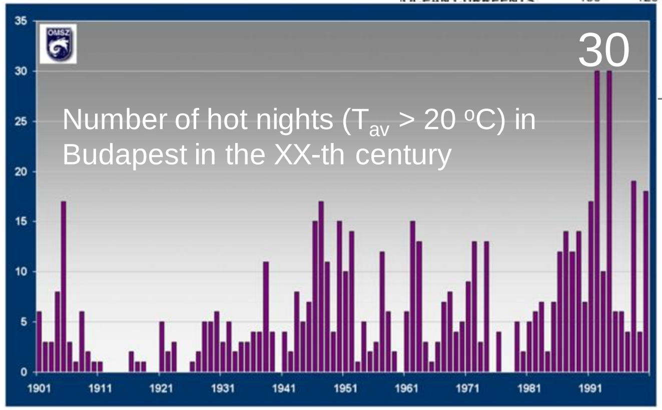
Where is AI support expected?

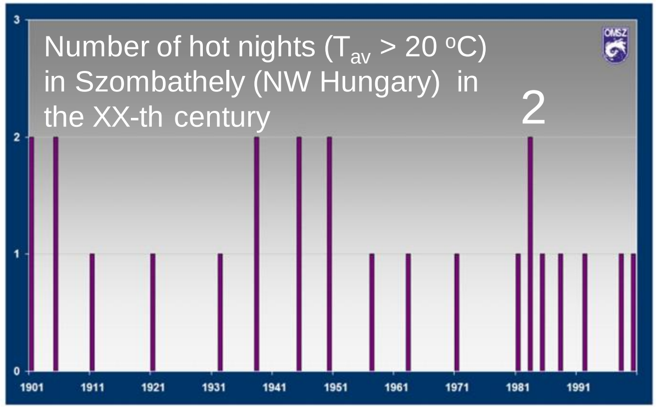
Help connect test data from the field with lab test data

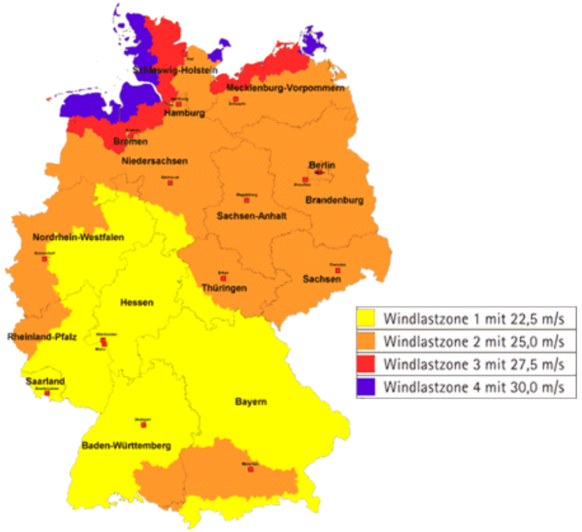
- There are luminaires in the field equipped with different diagnostic capabilities and sensors
- Historical data sets are available from such sources
  - Temperature data (ambient, luminaire, solder point, etc.)
  - Forward voltage data (that can be related to T_J)
- From the above data find actual “mission profiles” of luminaires resulting from
  - the operation (on/off cycles) and
  - the environmental conditions (ambient temperature variations)
- Such luminaires can be brought back to the lab to be tested in details



Global world temperature distribution in January

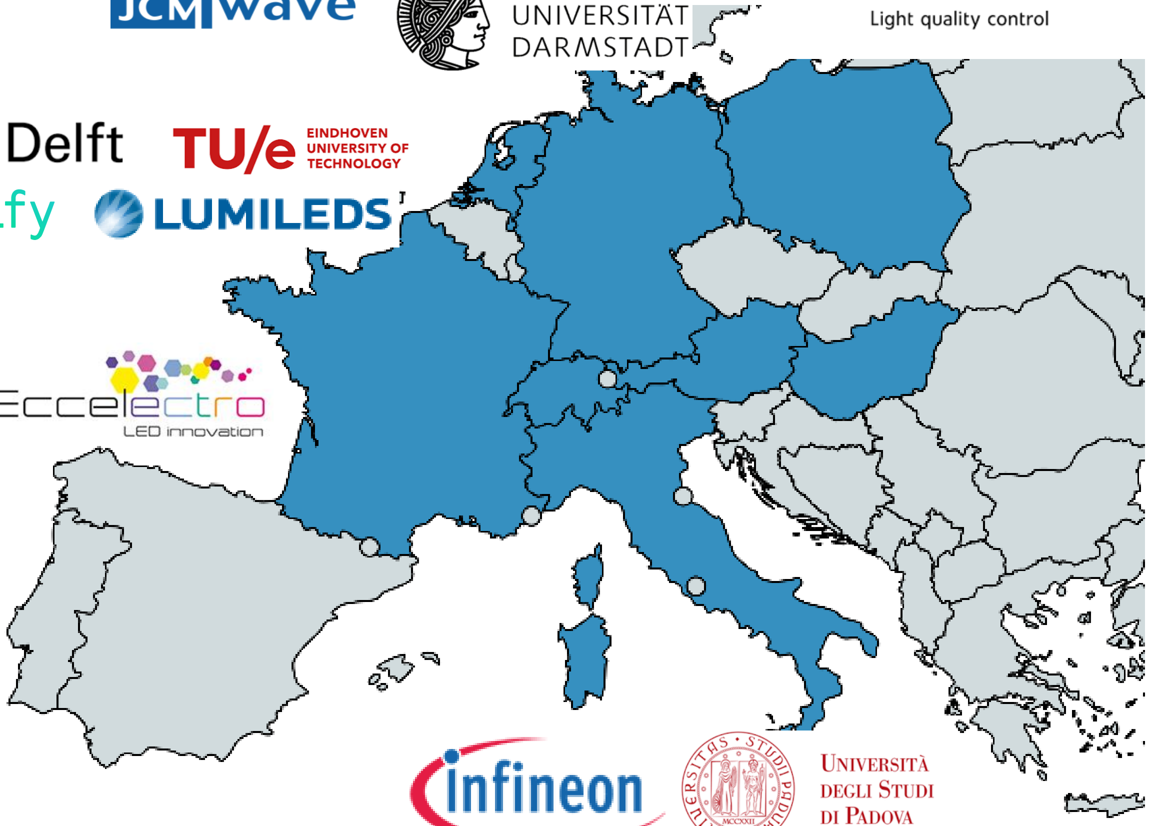






Average wind speed distribution in Germany

The team behind this:



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24 partners from 8 European countries

AI-TWILIGHT: AI powered Digital twin for lighting infrastructure in the context of front-end Industry 4.0

The team behind this:

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AI-TWILIGHT: AI powered Digital twin for lighting infrastructure in the context of front-end Industry 4.0

Open access papers on some of the addressed topics

https://doi.org/10.3390/en12101909
https://doi.org/10.3390/en12122389
https://doi.org/10.3390/en12091628
https://doi.org/10.3390/en13184979
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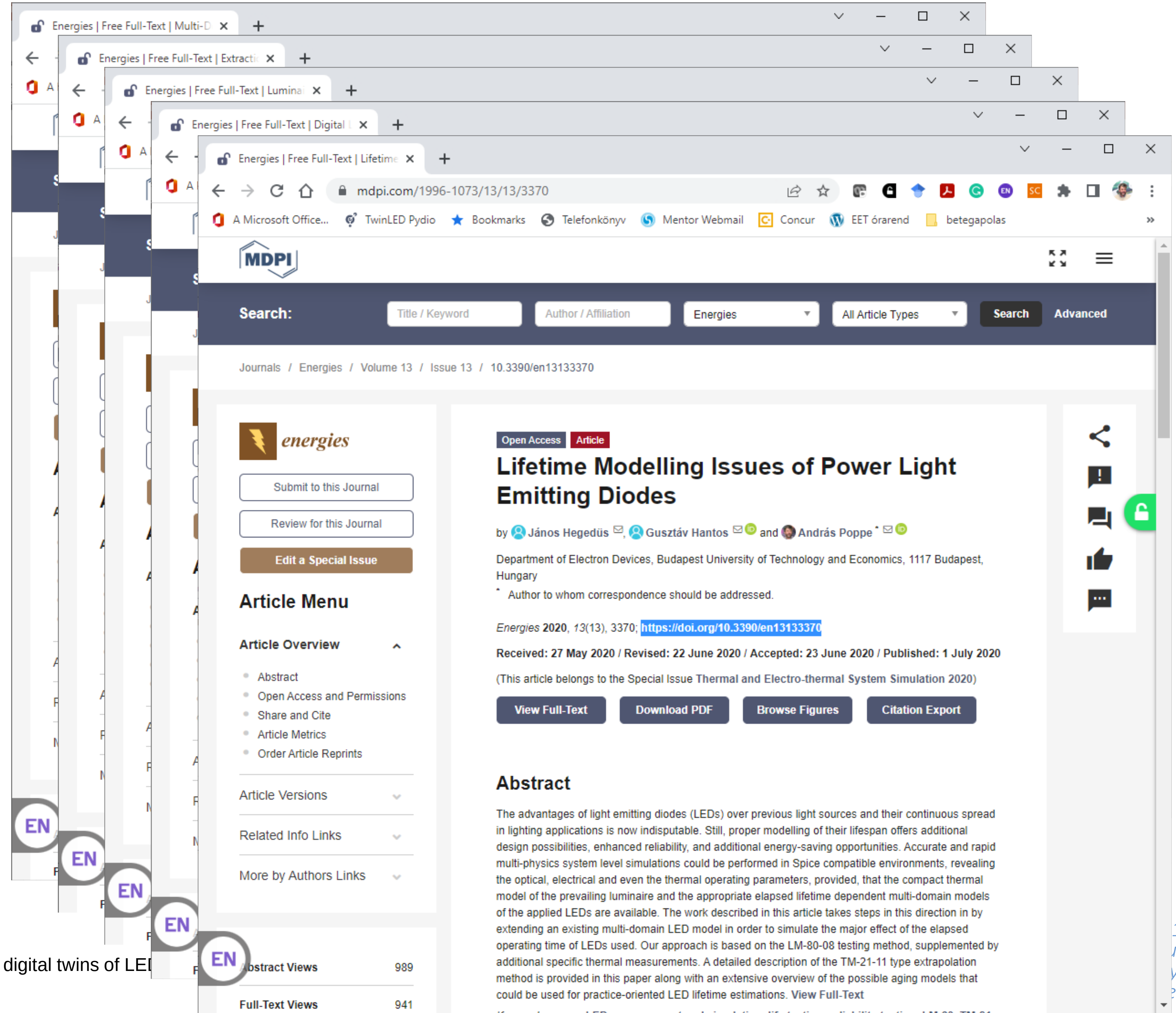

Acknowledgments

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