This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement **no 619912**

DELIVERABLE D4.437

FINAL SPECIFICATIONS

Project Acronym	**HI-LED**
Project title	**Human-centric Intelligent LED engines for the take up of SSL in Europe**
Website	www.hi-led.eu

Collaborative project

FP7-ICT-2013-11

Start date of project: 01.12.2013

Duration: 36 months

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D4.437 – FINAL SPECIFICATIONS

Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

Document details	
Responsible beneficiary of this Deliverable	PANNON
Work package	WP4
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Document ID	D4 437 – Final specifications - HILED 619912
Release Date	29/02/2016

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List of abbreviations

CIE: International Commission on Illumination - also known as the CIE from its French title, the Commission Internationale de l´Eclairage

CCT: Correlated Color Temperature

R_a: CIE General Color rendering index

CRI: Color Rendering Index

LED: Light-Emitting Diode

SPD: Spectral power distribution

PWM: Pulse Width Modulation

SECTION 1 – Context and scope

One of the objectives of the HI-LED project is to develop a LED-based light-engine capable of complying with museum lighting requirements. With this aim during the first two years of the project different technological approaches were investigated giving rise, in the process, to two different prototyping iterations, both of them, of course, with a wide variety of small variations.

Once a prototype was optimized, the procedure was subjecting it to deep electrical and photometrical characterization. To do so, the finished prototype was sent to UPAN laboratory, where, after the analysis, corrective measures and improvements were suggested. The first prototype was evaluated by M21 and the results of such analysis were summarized in the corresponding deliverable, D4.434 [1] – "Test results of first prototype". The laboratory measurements included the study of electrical and photometric parameters of the LED module. Determination of spectral, photometric and spatial characteristics of the luminaire were measured in a laboratory environment for different input parameters. Actual spectral power distributions, generated by the light engines, were investigated and compared with theoretical (optimized) SPDs by using a spectroradiometer. From spectral measurements, the thermal stability of the spectra was also validated, which is crucial in case of a compound light (composed by phosphor white converters and different narrow-band coloured LEDs). Thermal stability data will serve as an input to the thermal management of the module. A luminaire rotation goniophotometer was used for total luminous flux determination. All these work provided valuable information about first HI-LED modules performance and based on this, a set of improved specifications were proposed and summarized in D4.435 [2]. After the incorporation of most of these corrective measures, the second prototype was ready for analysis. Once again, the characterization of HI-LED prototypes took place at UPAN laboratory, following the procedure described above. The results of this second study were described in D4.436 [3] – "Test results of second prototype".

In this document, we summarize our final conclusions about the performance of HI-LED modules. Since some of the achieved features, in our opinion, are to be improved, we have decided we have decided to include, as an addendum, a description of our third iteration, called to solve most of the issues described in D4.436.

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SECTION 2 – Description of second prototype

Physical parameters:

The housing has a different form factor compared to the first prototype. The main difference is that the luminaire is cooled by active fan with constant rpm. This feature resulted a decrease of 10°C in housing surface temperature.

The second prototype has been designed having in mind a mass production scheme. In this respect, the form-factor and materials involved have been chosen in a way that production in a typical lighting manufacturer facility is guarranteed.

The second prototype is not a luminaire but a module itself. This module has a 52-pin connector by which power and control signals for the different LED channels and integrated spectroradiometer are provided. The drivers and intelligence of the module constitute another separate box, provided with either WiFi or Ethernet communications, that is plugged directly to the LED module through the 52-pin cable.

Construction of the luminaire:

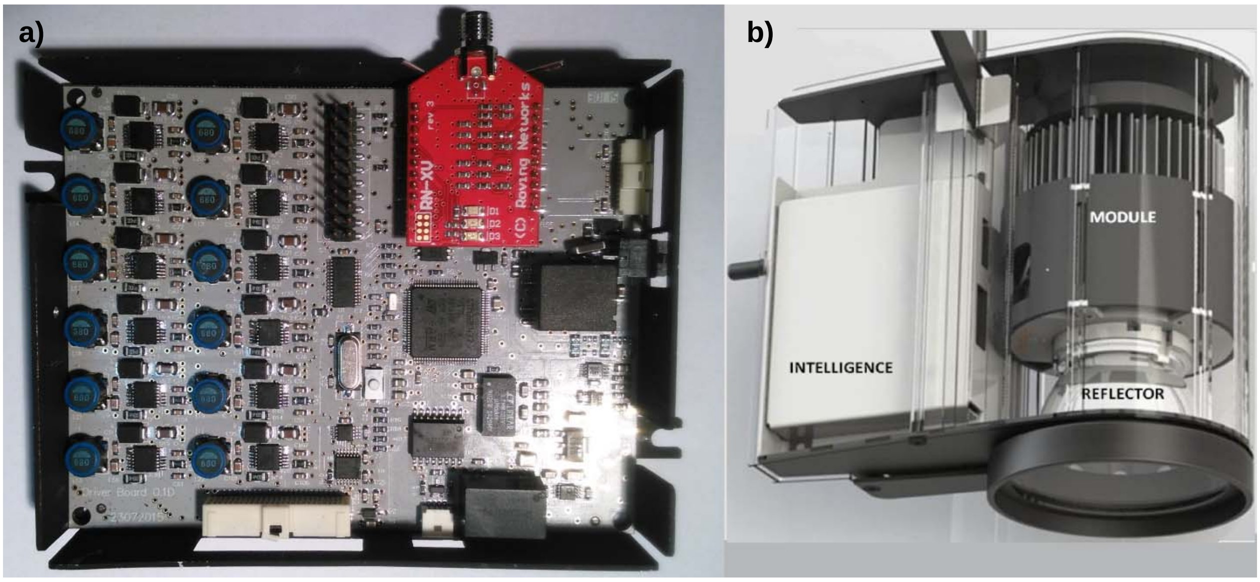

Figure 1. Second prototype designed for art-work and human centric lighting based on conventional LEDs. (a) Controller (intelligence). (b) Construction.

LED channels:

There are 10 different (almost-) monochromatic (coloured) LED channels in this 12 channel LED module. Colour channels #7 (dominant wavelength: ~570nm) and #8 (dominant wavelength: ~590nm) are repeated twice. The reason of the duplication is that the PC (phosphor-converted) colour chips have lower radiant flux compared to colour LED chips. Each channel can only have a limited number of LEDs in series configuration. Each of the current sources that drive a channel has a maximum output voltage of 24V. This limits the number of LEDs in each series string to 24V divided by the sum of the forward voltages of the LEDs in that series string.

Table 1. Details of LEDs used in the second prototype luminaire.

Designator	Number of LEDs	Description	Comment	Channel
Luxeon_Z 425_1-2	2	Lumileds LHUV-0425-0600	BIN KV	Ch1
Luxeon_Z 450_1-2	2	Lumileds LXZ1-PR01 (bin 4)	BIN G45	Ch2
Luxeon_Z 460_1-2	2	Lumileds LXZ1-PB01 (bin 2)	BIN A26	Ch3
Luxeon_Z 475_1-2	2	Lumileds LXZ1-PB01 (bin 4)	BIN B46	Ch4
Luxeon_Z 500_1-4	4	Lumileds LXZ1-PE01 (bin 1)	BIN F16	Ch5
Luxeon_Z 535_1-4	4	Lumileds LXZ1-PM01 (bin 3)	BIN H34	Ch6
Luxeon_Z 560_1-10	10	Lumileds LXZ1-PX01 (bin 1)	BIN U15	Ch7_1 Ch7_2
Luxeon_Z 587_1-10	10	Lumileds LXZ1-PL02 (bin A1)	BIN K-A1-5	Ch8_1 Ch8_2
Luxeon_Z 635_1-2	2	Lumileds LXZ1-PD01 (bin 4)	BIN D42	Ch9
Luxeon_Z 670_1-2	2	Lumileds LXZ1-PA01 (bin 6)	BIN B62	Ch10

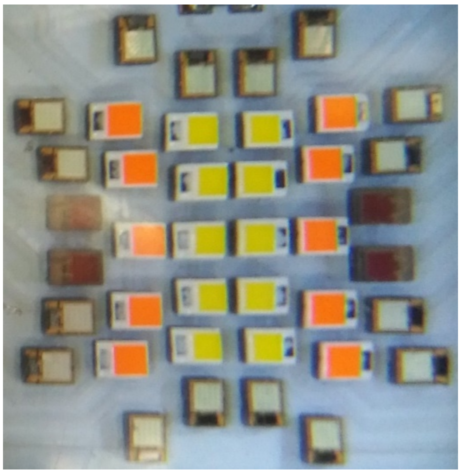

Figure 2. Arrangement of LED chips in the prototype.

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SECTION 3 – Analysis of test results

Results of electrical and goniophotometric measurements:

Luminous efficacies in Table 2 are not directly comparable because the electrical parameters of the first and second prototype were measured [1] [3] in a different configuration. While the first prototype was measured using its own external switched-mode AC/DC power supply (SMPS) the second prototype was operated from a laboratory DC power supply. We are comparing the measurement result at maximum load conditions (all channels set to maximum intensity settings). At this load we are assuming the SMPS's efficiency is ~0.95. Taking into account the power supply's efficiency and the difference between the power consumptions there is an overall 5% percent increase in luminous efficacy by using the latest Philips LED bins and the improved thermal design. On a system level the efficacy is a function of the SPD (which determines the resistive load), the LED junction temperature and the used external reflector optics. Active fan cooling at the specified load resulted in 10°C temperature drop ($T_{Housing\_average}$ temperature dropped from 70°C to 60°C) which is in agreement with the simulation results in Deliverable D2.2.1 [4]. The second prototype's measured total luminous flux output also agrees with the simulation results [4].

Table 2. Results of the measurements taken with identical optics and on same settings (full load).

type of luminaire	effective power	total luminous flux	CCT	R_a	luminous efficacy
HI-LED project first prototype	62.23 W	1344.7 lm	6602 K	97	21.61 lm/W
HI-LED project second prototype	64.68 W	1613.3 lm	5951 K	95	24.94 lm/W

Spatial characteristics of the output light

A new feature in the second prototype is the exchangeable optics. The spatial distributions in Figure 3 are symmetrical in all C planes, but it is possible to create any desired distribution with an appropriate optic.

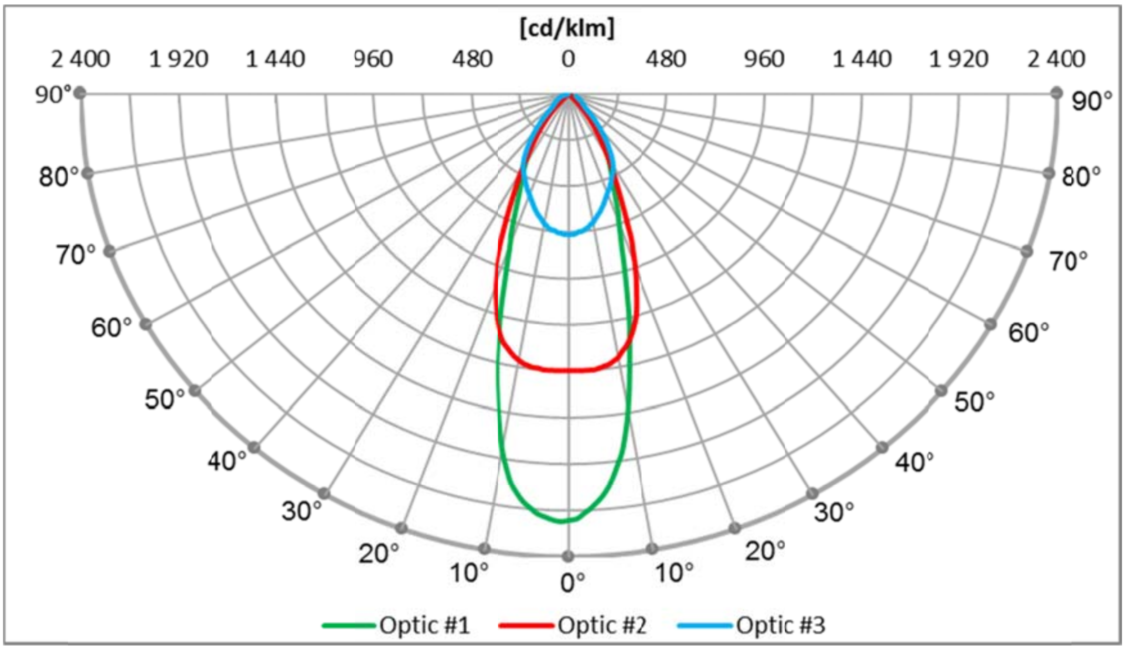

Figure 3. Luminous intensity distribution curves of HI-LED second prototype luminaire mounted with different optics (normalized to 1000 lm output)

Table 1. Light output ratio of the different reflectors.

No optic	#1	#2	#3
100%	87.2%	88.6%	94.1%

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SECTION 4 – Market survey on LEDs to be applied in the final LED module

Optimization of spectral power distribution according to colour quality parameters has been done according to the pigment reflection database categorized for different art periods (see Deliverable D4.4.3.2 [5]–Specification-of-optimized-LED-SPDs-for-dominant-pigments). Based on these results, critical wavelength domains were identified, LED peak wavelength regions can be described as the followings:

- Blue region: 425 nm, 450 nm, 465 nm, 480 nm
- Green region: 500nm, 530 nm, 560 nm
- Red region: 600 nm, 630 nm, 670 nm

The LEDs have limited space within the luminaire. The current LEDs size is 1.3 x 1.7 mm and this size cannot be increased significantly.

Table 4. Technical parameters of Philips LumiLED LEDs currently used in the HI-LED prototypes [prices are valid for at least 2000 pieces of bulk orders as of 2016 February]

Product code	Dominant/Peak* Wavelength [nm]	Max forward current [mA]	Forward voltage [V]	Unit price [USD]
LHUV-0425-0600	425-430*	500	3	8.20626
LXZ1-PR01 (bin 4)	445-450	1000	2.9	1.0605
LXZ1-PB01 (bin 2)	465-470	1000	3.15	1.12363
LXZ1-PB01 (bin 4)	475-480	1000	3.15	1.12363
LXZ1-PE01 (bin 1)	490-498	1000	2.95	1.12363
LXZ1-PM01 (bin 3)	530-535	1000	3.05	1.12363
LXZ1-PX01 (bin 1)	566-569	700	2.85	1.9695
LXZ1-PL02 (bin A1)	588-592	700	2.9	1.80538
LXZ1-PD01 (bin 4)	620-630	700	2.2	1.12363
LXZ1-PA01 (bin 6)	650-660*	700	2.25	1.12363

By using the latest bins of LumiLEDs in the second prototype there was a 5% increase in luminous efficacy. There was no significant change in the price of the LEDs since 2015 January; the cost is still around 80 euros. A market survey was conducted to find alternative LEDs using the two biggest electronic component distributors Digi-key and Mouser. There is no real alternative to replace the LumiLEDs because only LumiLEDs have the required wavelengths. For a low-cost and modest version of the HI-LED luminaire with fewer wavelengths it could be considered to use Cree XLamp® XQ-E LEDs (wavelenghts:465 nm, 485 nm, 535 nm, 590 nm, 620 nm, 630 nm; size:1,6 x 1,6 mm).

SECTION 5 – Final specifications

From the sections above we can derive some notes on to which direction the WP1 should continue development of the final prototype.

The design used in the second prototype is much closer to the demand from the industry. The applied materials and design approach are much closer to the requirements of a market product.

One drawback is the low luminous efficacy of the optical part, but with the current construction the luminous efficacy cannot be significantly improved.

Even though luminous efficacy is not the first priority for museum lighting, it is true we believe there is some room for improvement. For further improvements it would be advisable to implement the chameleon optics engine [4] or the shell integrator in the final prototype for better efficacy while preserving the colour mixing performance.

The problem of flicker, high pitch noise at certain load conditions and the security risk of unencrypted wireless security is still exists. For detailed information please refer to deliverable D4.435 improved specifications [2].

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SECTION 6 – Summary and Conclusions

The current prototype is working according to design #1 laid down in deliverable D2.2.1 **[4]** meeting all specifications, for further improvements it is recommended to switch to design #2 **[4]**.

There are no any other alternatives to Philips LumiLEDs on the market yet that can replace them in case of the current 12 channel design.

The withdrawal of ARCH essentially has had a substantial impact in the project, since it was ARCH the fabrication partner in the project.

Over the last months, IREC has taken over ARCH in its responsibilities, by dedicating efforts in prototyping and fabrication of the LED modules. IREC has been able to tackle this challenge partly because of the close partnership maintained with one of its spin-off companies, LEDMOTIVE, that has already solved the production and industrialization of LED modules. However, the procedure of withdrawal of ARCH and substituting ARCH in HI-LED project resulted in a few month delay in the R&D process.

In order to mitigate the impact of ARCH's withdrawal, another version not initially planned will be presented at the end of the project, incorporating a whole new optical concept that will make it possible a substantial increase in luminous efficacy (see next section for more detailed information on the envisaged module).

Since the final prototype at a new conception will reach UPAN only at the end of summer 2016, UPAN assumes a shift of D4.3.8 – "Test results of final prototype module" (originally due in M30) to M35. **)**

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ADDENDUM – Design of a new concept module

The "Spherical Shell-Mixer", is a hemispherical thin shell comprising arrays of Köhler microlenses on its inner and outer surfaces, each performing Köhler integration over a circular region ("integration zone") located in the vicinity of the shell center. The Köhler illumination concept can be used to obtain uniform illumination of a target with light emitted by a not-necessarily-uniform source. It can be realized in general by means of two lenses placed in sequence (a "Köhler channel"), the first one focusing the source on the second lens and this last focusing the first lens onto the receiver. In our case of interest, this combination can be replaced by a single lens, with its first surface imaging the source onto the second surface and the latter imaging the first surface onto the receiver.

When placed on top of an inhomogeneous multichip Lambertian LED, the Shell-Mixer creates a homogeneous (both spatially and angularly) virtual source, also Lambertian, where the images of the chips merge. The virtual source is located at the same position with essentially the same size of the original source. The diameter of this optics was 3 times that of the chip-array footprint.

This new Shell-Mixer is freeform and equals the original model in terms of brightness, color uniformity and efficiency. These advances make it a good option for Hi-Led application, for 40 LEDs light engine. In the case of track-mounted luminaire, the original light guide and a diffuser could be replaced by the new shell mixer, greatly improving the efficiency.

The efficiency of the Shell-Mixers on top of the light engine is calculated as the total power emitted into a hemisphere, divided by the power emitted by the bare source into the same 2π solid angle. For the Spherical Shell-Mixer, simulations give an efficiency of 90% (taking into account geometric, Fresnel and absorption losses). When the source is a high-reflectivity LED package, part of the light can be recycled, and the efficiency increases to 95%.

The high efficiency comes from the fact that a single part replaces the original mixing rod and diffuser (whose efficiency losses are large) and the shell optics fully cover the angular emission span of the source (i.e. the hemisphere on top of the source). Light which is bounced back by Fresnel reflection returns to the source plane and, if reflective chips and intra-chip surfaces are used, it can be reflected again and sent towards the Shell-Mixer inner microlenses for another chance to be extracted. In the case of the Spherical Shell-Mixer, a prototype has been tested and the results agree with the simulated efficiency.

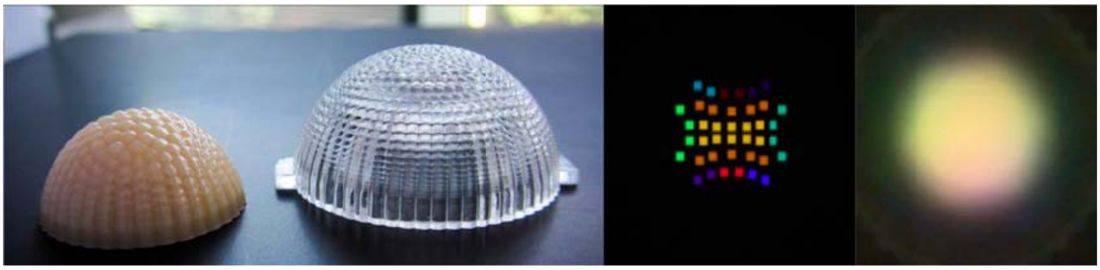

Figure 3. (left) A 3D-printed mock- up of the Freeform Shell-Mixer. (right) Analysis with a perfect wide angle imaging lens as luminaire (image on sensor plane of 40 LEDs with shell mixer)

The next module will be designed with 2 main objectives:

- **Increase the optical efficiency by an amount comparable to that is predicted by the simulations**
- **Making it compatible with current manufacturing processes and under a cost-effective approach. The second prototype, even though it was closer to industrialization, still had some limitations for mass production, being the most important the requirement of man power to assemble the modules. The next version will be thought for being compatible with typical automatization procedures typically found in industrial facilities.**

References

[1] Dr. Ferenc Szabó, Róbert Nagy, Péter Csuti, "D4.434 TEST RESULTS OF FIRST PROTOTYPE - HI-LED - 619912," 2015.

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[4] A.Cvetkovic, J.Chaves, R.Mohedano, M., "D2.2.1 - Base light engine design finished and analysis of cost - HI-LED - 619912," 2014.

[5] Dr. Ferenc Szabó, Dr. János Schanda, Péter Csuti, Renáta Kéri, Péter Gábor Simon, Deliverable D4.4.3.2–Specification-of-optimized-LED-SPDs-for-dominant-pigments.