

The LED Display Manufacturing Reference Model

A nine-layer architecture for defining, specifying, and benchmarking direct-view LED display performance and quality.

Modelled on the discipline of OSI for networking, ISO 9001 for manufacturing, and ITU-R for broadcast video – the LDM-RM separates LED display manufacture, integration and operation into nine independently verifiable layers, each with its own KPIs, failure modes, test methods, and standards.

VERSION

v1.0 • Public
Draft for industry review

SCOPE

Direct-view LED
(excluding LED-backlit LCD)

AUDIENCE

Specifiers • Integrators
AV Consultants • OEMs

LAYERS DEFINED

9 layers • 60+ KPIs
50+ standards mapped

THE 9 LAYERS		↑ TELEMETRY • ↓ DATA
L9	Operations & Lifecycle	
L8	Application & Content	
L7	Signal & Source	
L6	Transport & Routing	
L5	Data Link • Receiving Card	
L4	Cabinet & Mechanical	
L3	Module	
L2	Packaging	
L1	Photonic & Substrate	

A shared vocabulary for direct-view LED.

The direct-view LED display industry has matured into a multi-billion-dollar global market — broadcast XR studios, control rooms, sports venues, transit hubs, retail signage, and architectural facades — yet has never adopted a unified reference architecture. This paper proposes the model the industry has been operating without.

Specifications are written in the vocabulary of the loudest vendor. A bid document might call for a P1.5 COB cabinet with 3,840 Hz refresh and a calibrated white point of 6,500 K, while another in the same tender lists "high refresh rate, fine pitch, calibrated." Both look compliant on paper. Neither tells the buyer whether the LED die came from a top-bin wafer, whether the receiving card supports 16-bit grayscale at full refresh, whether the cabinet meets IP65 across its seams, or whether the calibration coefficients survive a panel swap two years after installation.

This white paper proposes the **LED Display Manufacturing Reference Model (LDM-RM)**: a nine-layer architecture that separates the concerns of LED display manufacture, integration, and operation into discrete, independently verifiable layers. Each layer carries its own performance KPIs, failure modes, test methods, and supply-chain dependencies.

The intent is the same as the OSI model: not to dictate vendor implementation, but to give every stakeholder a shared vocabulary and a layered way to reason about quality. A **specifier** should be able to demand a Layer 2 (Packaging) compliance statement without redefining what Layer 2 means. A **QA engineer** should be able to fail a shipment at Layer 5 (Receiving Card) without that failure being confused with a Layer 1 (Photonic) defect. A **facility owner** should be able to read a telemetry dashboard at Layer 9 (Operations) and trace a degradation pattern back through the stack.

THESIS

The model is descriptive of how LED displays already work, and prescriptive about how they should be specified, tendered, and benchmarked.

The networking precedent — and what its absence costs.

When OSI was published in 1984, internetworking was a tangle of incompatible protocols. The seven-layer model did not solve interoperability by mandating a single stack — TCP/IP eventually won that fight — but by giving the industry a shared mental model. Direct-view LED has reached an analogous inflection point.

Specifications are non-comparable

Failures are misattributed

Procurement is captured by marketing

Lifecycle economics are opaque

Two cabinets of nominally identical pixel pitch, brightness, and refresh rate can differ by an order of magnitude in lifetime, color stability, and serviceability — and the spec sheet will not reveal it.

L1

L2

L4

L9

A perceived "image quality problem" might originate at the LED die (L1), the encapsulant (L2), the driver IC and PCB (L3), the receiving-card calibration coefficients (L5), or the upstream video processor (L6). Without a layered diagnostic vocabulary, blame falls on whichever vendor is closest to the customer.

L1

L2

L3

L5

L6

"4K", "HDR", "3,840 Hz", and "COB" are sold as headline numbers without disclosure of the manufacturing decisions that determine whether those numbers translate into real-world performance.

L7

L8

Total cost of ownership depends on serviceability, parts compatibility, calibration data portability, and degradation curves — concerns that live at Layers 4, 5, and 9 but are rarely contracted for.

L4

L5

L9

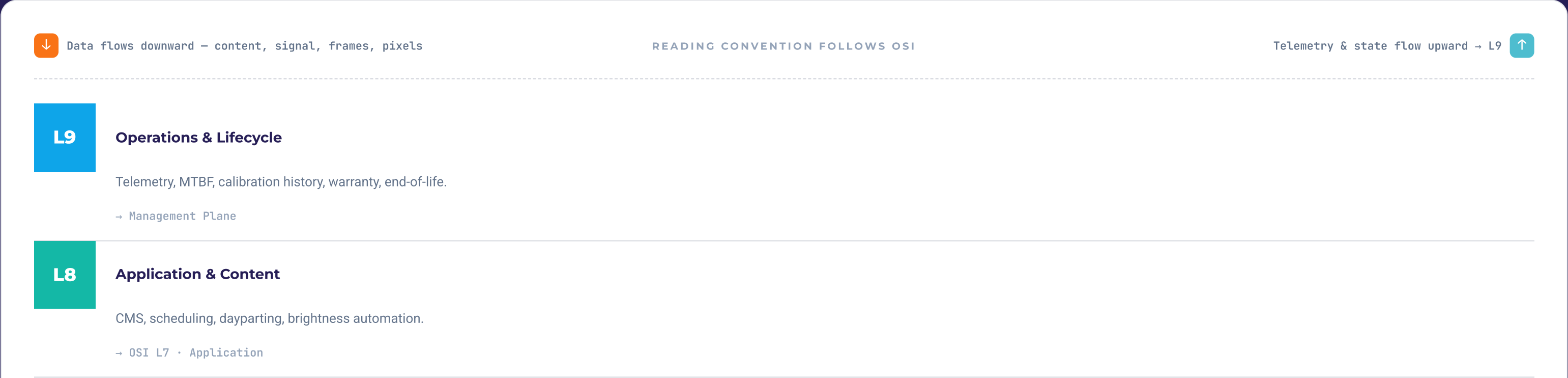
DESIGN GOALS OF THE LDM-RM

Separation of concerns — each layer addresses a distinct manufacturing or operational function. **Testability** — every layer has at least one objective test method that a third party can perform with commercially available instruments. **Vendor-neutrality** — the model names functions, not products. **Backwards compatibility** — describes installations built before its publication as accurately as those built after. **Traceability** — a defect observed at any layer must be traceable to its originating layer and supplier.

// 02 · THE LDM-RM STACK AT A GLANCE

Nine layers, ascending from physics to people.

The LDM-RM defines nine layers, numbered from the photonic substrate upward to operational lifecycle — from the gallium nitride lattice in a single LED die to the SLA dashboard in a facilities manager's office. Lower layers are constrained by the laws of materials science; upper layers by business process. The interfaces between layers are where the industry's contractual and diagnostic boundaries should sit.



L7	Signal & Source HDMI, SDI, DP, NDI, IP video, EDID, color space, EOTF. → OSI L6/L7
L6	Transport & Routing Sending card, video processor, mapping, redundancy, genlock. → OSI L3/L4
L5	Data Link · Receiving Card HUB75, scan, gamma, pixel-level calibration coefficients. → OSI L2 · Data Link
L4	Cabinet & Mechanical Chassis, IP rating, thermal, serviceability, alignment. → OSI L1 · Physical
L3	Module PCB, driver IC, mask, pixel pitch, power distribution. → OSI L1 · Electrical
L2	Packaging DIP, SMD, COB, IMD, MIP, COG, flip-chip — encapsulation. → Below OSI
L1	Photonic & Substrate LED die, wafer, phosphor, binning, quantum efficiency. → Below OSI

Mapping to familiar frameworks

Each LDM-RM layer is positioned against its closest OSI analogue and the existing industry standards that already address some — but not all — of that layer's concerns. The gaps are intentional and motivate the rest of this paper.

LDM-RM LAYER	OSI ANALOGUE	EXISTING STANDARDS (PARTIAL COVERAGE)
L9 Operations & Lifecycle		
L8 Application & Content	L7 (Application)	DSF - OAAA - ISE/AVIXA digital signage practices
L7 Signal & Source		
L6 Transport & Routing	L3/L4 (Network/Transport)	Vendor-specific (NovaStar - Brompton - Megapixel)
L5 Data Link (Receiving Card)		
L4 Cabinet & Mechanical	L1 (Physical, structural)	IEC 60529 (IP) - IEC 60068 (environmental) - UL 48
L3 Module		
L2 Packaging	(below OSI)	JEDEC JESD22 - IEC 60810
L1 Photonic & Substrate		

// 03 • THE LAYERS IN DETAIL

Each layer — definition, components, KPIs, failure modes & standards.

Each section follows a consistent structure: a definition, the OSI analogue, the components and sub-layers contained within, the performance KPIs that should appear in any specification or test report, the failure modes characteristic of that layer, and the existing standards that partially govern it.

OSI analogue: Below OSI Layer 1. The equivalent of the silicon and copper that underlie any digital system.

The photonic layer is the foundation of the entire stack. It comprises the semiconductor materials that emit light — the gallium nitride and indium gallium nitride epitaxial layers grown on sapphire or silicon-carbide wafers — and the phosphor systems that convert blue or UV emission into the broader spectrum required for full-colour display. Every claim about brightness, colour gamut, lifetime and energy efficiency made anywhere higher in the stack is constrained by what happens in the LED die. **Wafer-level binning** is the single most important quality decision in the entire LED display industry, and the one most opaque to buyers.

COMPONENTS & SUB-LAYERS

- LED die (chip):** GaN/InGaN epitaxial structure on sapphire, silicon-carbide, or silicon substrate; lateral, vertical, or flip-chip architecture.
- Phosphor system:** typically YAG:Ce or KSF for red conversion in white-light systems. For RGB displays, the red die uses AlGaInP and the blue/green dies use InGaN.
- Wafer & binning:** each wafer yields tens of thousands of dies; binning sorts by dominant wavelength (typically ± 2.5 nm), forward voltage (Vf), and luminous flux. Top-bin material is the foundation of consistent calibration.
- Die size:** ranges from sub-100 μm (Mini and Micro LED) through 4 mil to 14 mil. Smaller dies enable smaller pixel pitches but concentrate thermal load.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Dominant wavelength binning	Spectroradiometer at 25 °C, IF per data sheet	± 2.5 nm batch · ± 1.0 nm premium
Forward voltage (Vf) binning	Curve tracer or LED tester at rated current	Vf spread within ± 0.1 V across a panel
Luminous flux binning	Integrating sphere per CIE 127	$\pm 7\%$ standard · $\pm 3\%$ premium across a panel
LM-80 lumen maintenance	IES LM-80-20 testing, 6,000 hours minimum at three temperatures	$L90 \geq 50,000$ hours projected via TM-21 extrapolation
Quantum efficiency	External quantum efficiency at rated drive current	$\geq 35\%$ blue · $\geq 60\%$ red AlGaInP at nominal current

COMMON FAILURE MODES

- Wavelength drift** across a wafer or between wafers, producing visible colour banding that no upstream calibration can fully remove.
- Phosphor degradation** under sustained thermal load, shifting white point toward blue over years of operation.
- Electrostatic discharge (ESD)** damage during die handling, producing latent failures that surface months after deployment.
- Substrate defects** (threading dislocations) reducing quantum efficiency and accelerating lumen depreciation.

RELEVANT STANDARDS

CIE 127:2007

IES LM-80-20

IES TM-21-21

JEDEC JESD51 series

OSI analogue: Below OSI; analogous to the package that turns a silicon die into a usable IC.

The packaging layer determines how the bare LED die is transformed into a manufacturable, mountable, durable component. The choice — DIP, SMD, IMD, COB, COG, MIP, or flip-chip — propagates through every layer above it. Pixel-pitch capability, viewing angle, contrast ratio, mechanical robustness, repairability and unit cost are all set here. The industry's transition from DIP through SMD to COB and now MIP is the most visible technology shift in direct-view LED, and it is fundamentally a Layer 2 transition, not a Layer 1 one.

COMPONENTS & SUB-LAYERS

- DIP** (Dual In-line Package): legacy through-hole, large pitches (P10+), high brightness, very wide outdoor use; viewing angles 100–120°.
- SMD** (Surface Mounted Device): the dominant packaging from 2010 onward; subtypes SMD3535, 2727, 2020, 1515, 1010, 0808; viewing angles 120–160°.
- COB** (Chip on Board): multiple bare dies bonded directly to PCB and encapsulated in a single resin layer; enables sub-P1.0 pitches with superior impact resistance and shorter thermal path; reduced repairability.
- IMD** (Integrated Matrix Device): multiple sub-pixels integrated into a single SMD-style package, combining SMD repairability with COB-class consistency; common in P0.9–P1.5 fine-pitch and rental.
- MIP** (Micro LED in Package): bare Micro LED chips pre-bound into SMD-format packages, intended as the bridge from current fine-pitch to true Micro LED.
- COG** (Chip on Glass) and flip-chip: emerging for ultra-fine pitch and transparent applications.
- Encapsulant:** epoxy, silicone, or hybrid resins; critical for mechanical, optical and environmental performance.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Package luminous intensity	Goniophotometer at rated current	Within manufacturer spec, ±5% across a reel
Viewing angle (FWHM)	Goniophotometer	DIP 100–120° • SMD 140–160° • COB ≥ 170°
Solder joint integrity	IPC-A-610 Class 2 or 3 inspection	Class 2 indoor min • Class 3 mission-critical & rental
Encapsulant moisture resistance	MSL rating per JEDEC J-STD-020	MSL 2a or better indoor • MSL 1 outdoor
Anti-collision rating (COB)	Pendulum impact or controlled drop test	≥ 2× SMD equivalent, vendor-stated joules
Colour consistency within reel	Spectroradiometer sample of n ≥ 30 packages	$\Delta u'v' \leq 0.003$ for premium grades

COMMON FAILURE MODES

- ! "Dead pixel" or "dead sub-pixel" failures from cold solder joints or wire-bond fractures (SMD).
- ! Encapsulant yellowing under UV exposure, shifting white point and lowering perceived brightness (outdoor SMD).
- ! Delamination between die and encapsulant under thermal cycling, producing localised dim or dark spots.
- ! Moisture ingress in non-hermetic packages, producing cluster failures in humid environments.
- ! COB resin gloss inconsistency producing visible "patchiness" at low grayscale, even when LED dies are bin-matched.

RELEVANT STANDARDS

- JEDEC J-STD-020
- JEDEC JESD22 series
- IPC-A-610
- IEC 60810

OSI analogue: OSI Layer 1 (electrical & mechanical implementation), with embedded driver behaviour analogous to a PHY chip.

The module layer is where individual LED packages are arranged into the regular grid that defines pixel pitch, mounted onto a PCB, driven by a constant-current driver IC, and protected by a front mask. A module is the smallest field-replaceable unit in most SMD systems and the smallest non-replaceable unit in most COB systems. The module sets the electrical, thermal, and optical micro-architecture: how power is distributed, how heat exits the assembly, how the driver IC controls grayscale and refresh, and how the mask manages contrast and viewing geometry.

COMPONENTS & SUB-LAYERS

- **PCB:** typically 4-, 6-, or 8-layer FR-4. For fine pitch and high power, copper-core or aluminium-backed substrates dramatically improve thermal performance.
- **Driver IC:** constant-current LED drivers (MBI, ICN, SUM series) controlling PWM grayscale; key parameters include grayscale bit depth (typically 16-bit), GCLK frequency, and ghost suppression.
- **Pixel pitch & arrangement:** centre-to-centre distance between RGB pixels, ranging from below P0.5 (Micro LED) to P20+ (outdoor).
- **Power distribution:** typically 5 V or 4.2 V DC at the module from a cabinet-level PSU, with copper-plane design critical to avoid voltage droop at high duty cycle.
- **Front mask:** matte black plastic or rubber that defines the optical aperture for each pixel and controls contrast under ambient light.
- **Connectors:** HUB75 / HUB75E (most common), or proprietary high-density alternatives at fine pitch.
- **Module-level calibration EEPROM:** stores per-module factory coefficients on premium products.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Pixel pitch tolerance	Optical inspection or coordinate measuring	±0.05 mm of nominal across module
Grayscale bit depth	Driver-IC datasheet, verified by signal analyser	≥ 14-bit indoor • ≥ 16-bit broadcast/HDR
Refresh rate (visual)	High-speed camera at 1/8000 s shutter or scan-line analyser	≥ 1,920 Hz general • ≥ 3,840 Hz camera-facing • ≥ 7,680 Hz XR
Power consumption — peak white	Calibrated DC power meter at full 100% white	Per spec, max ≤ vendor-stated W/m²
Power consumption — typical content	Same instrument at 30% APL test pattern	Indoor SMD ≤ 200 W/m² • Outdoor ≤ 600 W/m²
Module flatness	Surface gauge across module corners	≤ 0.1 mm fine pitch • ≤ 0.3 mm outdoor
Solder joint quality	X-ray inspection sample basis + IPC-A-610 visual	Class 2 minimum • Class 3 rental & broadcast

COMMON FAILURE MODES

- ! Solder-joint cracking under repeated thermal cycling ("thermal fatigue") – most common at the corners of large SMD packages.
- ! Driver IC saturation at high APL producing brightness clipping at peak white.
- ! Voltage droop on inadequate copper planes producing visible brightness gradient across a module.
- ! Mask discolouration or warping reducing contrast and creating uneven appearance.
- ! EMI emissions from high-frequency GCLK lines exceeding regulatory limits when not properly designed.
- ! Connector wear from repeated rental cycling causing intermittent flat-cable failures.

RELEVANT STANDARDS

- IPC-2221
- IPC-A-610
- IPC-J-STD-001
- IEC 61000-6
- FCC Part 15 / CISPR 32

OSI analogue: OSI Layer 1 (physical, mechanical envelope) plus environmental conditioning.

The cabinet layer aggregates modules into the field-installable assembly that integrators bolt, hang or rig onto a structure. It addresses everything mechanical rather than electronic: chassis stiffness and flatness, ingress protection, thermal management, weight, serviceability (front- vs rear-service), interconnect mechanics, and the seam tolerances that determine whether a wall reads as one continuous image or as a tiled mosaic. **Two cabinets with identical Layer 1 through Layer 3 components can deliver radically different installed performance because of Layer 4 decisions.**

COMPONENTS & SUB-LAYERS

Chassis: die-cast aluminium (best precision, common in rental), profile aluminium (cost-balanced), magnesium alloy (lightweight rental), or steel (outdoor heavy industrial).

Cabinet dimensions: standard rental 500×500, 500×1000, 600×337.5, 600×675 mm; fixed-install 480×540 or 960×960 mm; outdoor up to 1280×960 mm.

Service orientation: front-service (mandatory for most architectural and against-wall installs), rear-service (lower cost, deeper installs), or both.

IP rating: IP30–IP40 typical indoor; IP54–IP65 semi-protected outdoor; IP65/IP65 (front/rear) full outdoor; IP67/IP68 marine and immersive.

Thermal management: passive convection (most indoor), forced air (high-density indoor and outdoor), liquid cooling (extreme XR and outdoor at scale).

Cabinet alignment: locating pins, magnetic alignment, push-pull or hex-key tensioners; typical seam tolerance ±0.1 mm fine pitch · ±0.3 mm outdoor.

Power supply units: redundant N+1 for mission-critical; typical 5 V at 40–60 A per PSU with PFC.

Hanging hardware: certified for rigging loads with a minimum 8:1 safety factor for rental and overhead applications.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Cabinet flatness	Surface gauge or laser scanner across diagonal	≤ 0.2 mm fine pitch · ≤ 0.5 mm outdoor
Seam alignment between cabinets	Optical or feeler gauge	≤ 0.1 mm indoor fine pitch · ≤ 0.3 mm outdoor
IP rating compliance	IEC 60529 spray and dust test	As specified per environment, seal verified after thermal cycling
Operating temperature range	Climate chamber per IEC 60068-2-1/-2	Indoor 0 to +40 °C · Outdoor -30 to +50 °C
Storage temperature	Climate chamber	-40 to +60 °C minimum
Humidity tolerance	IEC 60068-2-78 damp heat	10-85% RH NC indoor · 10-95% outdoor with condensation tolerance
Vibration tolerance	IEC 60068-2-6 sinusoidal vibration	Per intended use; rental and touring grades certified
Module replacement time (front-service)	Stopwatch, average over n = 10 swaps	≤ 60 s for premium fine-pitch products
Cabinet weight per square metre	Calibrated scale	Per spec; structural design depends on this number

COMMON FAILURE MODES

-  Cabinet warping under thermal load producing visible seams that were straight at install.
-  Loss of seal at cabinet edges allowing water ingress and progressive corrosion of internal components in outdoor systems.
-  PSU failure under sustained high-APL operation when thermal headroom is inadequate.
-  Misalignment between cabinets producing parallax-visible seams at oblique viewing angles.
-  Hanging hardware fatigue and creep in rental cabinets that have undergone many touring cycles.
-  Cooling fan failure in active-cooled cabinets producing localised thermal hot spots and accelerated LED ageing.

RELEVANT STANDARDS

- IEC 60529
- IEC 60068-2 series
- UL 48 / UL 879
- IEC 60598-1
- ANSI E1.21



Receiving Card Layer

OSI analogue: OSI Layer 2 (Data Link). The receiving card is the MAC layer of the LED display.

Layer 5 is the most direct analogue to OSI Layer 2. The receiving card sits inside or directly behind a cabinet, decodes the frame data arriving over Ethernet from the sending card, applies pixel-level brightness and chromaticity calibration coefficients, manages scan timing for the driver ICs below it, and reports status back upstream. It is also **where most of the perceived "image quality" of an LED display is actually decided**: a perfect L1–L4 stack driven by a misconfigured L5 will look bad, and a mediocre stack driven by an excellent receiving card and good calibration will outperform expectations.

COMPONENTS & SUB-LAYERS

- **Receiving card:** NovaStar (MRV, A-series, DH-series), Colorlight (i-series), Linsn (RV-series), or equivalent. Loading capacity typically 256×256 to 512×384 pixels per card depending on model.
- **HUB75 / HUB75E interface:** the de facto data link to driver ICs. Carries RGB data lanes, address lines, latch, OE and clock.
- **Scan mode:** 1/2, 1/4, 1/8, 1/16, 1/32 — ratio of rows simultaneously driven, set by module design and decoded by the receiving card.
- **Pixel-level calibration coefficients:** per-pixel R, G, B gain values (and sometimes offset) stored on the receiving card to compensate for L1 binning variation; typically generated by camera-based calibration systems.
- **Gamma curve & bit depth:** typically 14- to 16-bit grayscale; per-channel gamma adjustment for accurate low-grayscale rendering.
- **Refresh rate multiplier:** receiving card configures GCLK to achieve target visual refresh, typically 1,920–7,680 Hz.
- **Mapping:** receiving card knows its position in the cabinet array, set by the upstream sending card.
- **Loop & backup:** secondary Ethernet input for redundant data path.
- **Configuration files:** .rcfg / .rcfgx (NovaStar) — vendor-specific binary blobs containing all module driver parameters.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Grayscale bit depth (delivered)	Verified via signal capture or test pattern luminance ramp	$\geq 14\text{-bit indoor}$ · $\geq 16\text{-bit broadcast/HDR}$
Visual refresh rate	High-speed camera or scan-line analyser	$\geq 1,920\text{ Hz general}$ · $\geq 3,840\text{ Hz broadcast}$ · $\geq 7,680\text{ Hz XR}$
Low-grayscale uniformity	Spectroradiometer or imaging colorimeter at 10% & 5% white	$\Delta E \leq 3$ across full panel
Pixel-level calibration accuracy	Imaging colorimeter pre and post calibration	Brightness uniformity $\leq \pm 1\%$ · $\Delta E \leq 0.03$ colour deviation
Calibration data persistence	Power cycle test, n = 100	100% retention of coefficients · verified checksum
Loop backup failover time	Sever primary fibre, measure black-frame duration	≤ 1 frame at 60 Hz output
Configuration round-trip	NovaLCT or equivalent: Read From / Send To	Verifiable hash equality of .rcfg before and after

COMMON FAILURE MODES

- ! Ghosting and afterglow from incorrect line blanking, GCLK frequency or duty cycle settings.
- ! Low-grayscale mottling from missing or corrupted calibration coefficients.
- ! Camera-visible scan lines from mis-set refresh rate when filming at high shutter speeds.
- ! "Patchiness" at black or near-black levels from inadequate calibration threshold settings.
- ! Receiving-card firmware mismatch across cabinets producing subtle colour or timing drift between regions of a single wall.
- ! Loss of calibration database when receiving cards are swapped without restoring per-card coefficients.

STANDARDISATION GAP

No formal industry standard exists for receiving-card behaviour. NovaStar's NovaLCT, Brompton's Tessera, Megapixel's Helios, and Colorlight's iSet have each become de facto reference implementations within their installed base. **This is the layer where the LDM-RM most clearly identifies a standardisation gap.**



Transport & Routing Layer

OSI analogue: OSI Layers 3 and 4 (Network and Transport).

Layer 6 is the routing and transport fabric that links the upstream signal source to the array of receiving cards. It is anchored by the sending card or video processor — devices that ingest a signal at L7, scale and map it across the physical canvas, partition it into cabinet-sized regions, and transmit those regions over Ethernet (Cat5e/6 or fibre) to each receiving card. It is the layer that defines whether a wall is one logical canvas or a tiled mosaic, and where genlock, redundancy and sync are guaranteed.

COMPONENTS & SUB-LAYERS

- Sending card:** hardware that converts the source signal into the proprietary protocol consumed by receiving cards (NovaStar MCTRL, Brompton SX/Tessera, Megapixel HELIOS, Colorlight Z-series).
- Video processor:** scales, switches and formats source signals before they reach the sending card; may also perform colour management, HDR tone mapping and seamless source switching.
- All-in-one controller:** sending card and processor combined into a single unit (NovaStar VX, Brompton SX series).
- Mapping configuration:** defines the position of each receiving card on the canvas; stored in the sending card.
- Genlock & frame sync:** ensures all cabinets in a wall update on the same frame; mandatory for any wall captured on camera.
- Redundancy:** dual sending cards (primary/backup) and looped Ethernet to receiving cards to survive any single point of failure.
- Latency budget:** typically 1–3 frames end-to-end for direct integration; ≤ 1 frame for broadcast and XR.
- HDR pipeline:** HDR10, HLG, Dolby Vision tone mapping; processor-level decision.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
End-to-end latency	Photodiode and signal capture, source-to-emit	≤ 1 frame (16.7 ms) broadcast/XR • ≤ 3 frames general
Genlock accuracy	Multi-cabinet high-speed camera capture	All cabinets within 1 line of each other
Redundancy failover	Sever primary input, measure visible disturbance	≤ 1 frame black or no visible disturbance
Source switching transition	Camera capture of cut/fade between sources	Clean cut at frame boundary, no tearing
Mapping accuracy	Test pattern across canvas, visual inspection	100% correct cabinet position; no rotation or mirror errors
Output bandwidth utilisation	Sending-card diagnostic readout	≤ 80% of port maximum at peak content; HDR headroom

COMMON FAILURE MODES

- ! Tearing across cabinet boundaries when genlock is not properly distributed.
- ! Frame-drop or judder when bandwidth is over-committed across a sending card's gigabit ports.
- ! Black frames during source switching when seamless switching is not configured.
- ! Visible mapping errors (rotation, offset) after firmware update or cabinet replacement.
- ! Loss of redundancy without operator awareness when secondary input has been physically disconnected.
- ! HDR colour shift when source EOTF and processor output do not match downstream receiving-card gamma.

RELEVANT STANDARDS

- SMPTE ST 2110
- SMPTE ST 2059 (PTP)
- Vendor-specific (gap)

OSI analogue: OSI Layers 6 and 7 (Presentation and Application interface). This is the AV-industry boundary.

Layer 7 is where the LED system meets the rest of the AV world. It is the boundary at which the source signal — from a media server, broadcast switcher, scaler, computer or IP-video decoder — is presented to the LED system in a defined format with defined colorimetry, bit depth, and frame rate. The signal layer determines what "4K" and "HDR" actually mean for a particular installation, and is the layer at which colour management succeeds or fails.

COMPONENTS & SUB-LAYERS

- Source signal types: HDMI 2.0/2.1, DisplayPort 1.4/2.0, 12G/6G/3G-SDI, ST 2110-20/-30/-40 IP video, NDI, fibre-optic transport variants.
- Resolution: from 1920×1080 through 3840×2160, 7680×4320, and arbitrary canvas resolutions limited only by processor bandwidth.
- Frame rate: 24, 25, 29.97, 30, 50, 59.94, 60, 100, 119.88, 120, and beyond for XR.
- Bit depth: 8, 10 or 12 bits per channel at the source; the LED stack should preserve at least 10-bit through to L5.
- Colour space: sRGB, Rec. 709, DCI-P3, Rec. 2020; broadcast and XR require explicit colorimetry handling.
- EOTF: gamma 2.2/2.4 (SDR), PQ (HDR10 / Dolby Vision), HLG (broadcast HDR).
- EDID: the negotiated capability handshake between source and processor; misconfigured EDIDs are a leading cause of "why doesn't this look right" complaints.
- Audio: where applicable, SDI embedded or AES67 over IP.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Signal lock stability	Source disconnect/reconnect, n = 50	Lock within 1 s • no green/black frames
Bit-depth preservation	10-bit gradient test pattern, imaging colorimeter	No banding visible at calibrated viewing distance
Colour space accuracy	Rec. 709 colour checker, imaging colorimeter	$\Delta E \leq 2$ average • ≤ 4 max across 24 patches
EOTF compliance (SDR)	Gamma sweep from 0% to 100% in 5% steps	Within ± 0.05 of target gamma curve
EOTF compliance (HDR PQ)	PQ sweep, photometer	Within $\pm 10\%$ of PQ curve up to display peak
EDID negotiation	Source-side EDID readout vs processor capability sheet	Match • preferred timing matches canvas resolution

COMMON FAILURE MODES

- Crushed blacks or clipped whites from incorrect EOTF assignment.
- Colour cast from Rec. 709 / Rec. 2020 mismatch between source and processor.
- Banding visible at low-grayscale ramps from 8-bit truncation in the signal chain.
- Audio loss or sync drift in installations that depend on embedded SDI audio.
- Resolution downscaling artifacts when source resolution does not match canvas native and scaler is mediocre.
- EDID handshake failures producing intermittent "no signal" after wake-from-sleep events on PC sources.

RELEVANT STANDARDS

- ITU-R BT.709
- ITU-R BT.2020
- ITU-R BT.2100
- SMPTE ST 2110
- HDMI 2.1 / DP 2.0
- CTA-861



Application & Content Layer

OSI analogue: OSI Layer 7 (Application).

Layer 8 is where the content that will eventually be rendered as photons by L1 is authored, scheduled and delivered. Its concerns are largely software and operational: what plays when, who can change it, how brightness adapts to time of day, how compliance is enforced (e.g. brightness curfews in residential overlay zones), and how content is repurposed across heterogeneous canvases. Much falls outside the manufacturing scope of an LED vendor, but the layer must be acknowledged because **an LED display is only as good as the content it shows**.

COMPONENTS & SUB-LAYERS

- Content management system (CMS):** cloud-hosted (BrightSign, Scala, Yodeck, signagelive, Aurora's own platforms) or on-premise.
- Content authoring:** still imagery, motion video, web content, real-time data feeds, generative content, broadcast feeds.
- Scheduling & dayparting:** time-, location- and trigger-based playlists.
- Brightness automation:** ambient-light-sensor-driven brightness adjustment to balance visibility and viewer comfort.
- Audience analytics:** anonymised camera-based audience measurement (where lawful and disclosed).
- Compliance enforcement:** brightness curfews, content blacklists, region-specific advertising rules.
- Multi-canvas content adaptation:** same content rendered correctly across canvases of different aspect ratios, pitches and brightness.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Brightness automation responsiveness	Step-change ambient light, measure response	≤ 30 s to new target with no visible flicker
Schedule adherence	Audit trail of scheduled vs played content	100% match for compliance-critical content
Content rendering accuracy	Compare authored vs displayed colour and detail	ΔE ≤ 2 against authored reference on calibrated wall
CMS uptime	SLA monitoring	≥ 99.5% advertising · ≥ 99.95% transit/life-safety
Content delivery latency	Author commit to all-screens-displaying	≤ 60 s advertising · immediate for emergency overrides

COMMON FAILURE MODES

- Brightness left at calibration default, producing eye-strain at night or invisible content in midday sun.

❗ Schedule conflicts producing default-content fallback that violates contractual obligations to advertisers.

❗ Content authored at 1920×1080 stretched onto a non-16:9 canvas without aspect-ratio handling.

❗ Failure to disclose audience analytics in jurisdictions where disclosure is required.

❗ CMS cloud outage producing fallback to last-cached content for unknown duration.

RELEVANT STANDARDS

DSF best practices

OAAA guidelines

AVIXA / ISE

Local ordinances



Operations & Lifecycle Layer

OSI analogue: Spans OSI's notional management plane; comparable to FCAPS (Fault, Configuration, Accounting, Performance, Security).

Layer 9 is orthogonal to the data path. It does not move pixels; it observes them and the systems that produce them, and it manages the asset across its operational life — from commissioning through routine maintenance, calibration refresh, partial replacement, and eventual decommissioning. **It is the layer at which total cost of ownership is actually controlled.** A specification that addresses Layers 1 through 8 but is silent on Layer 9 will deliver a wall that looks excellent for two years and unmaintainable thereafter.

COMPONENTS & SUB-LAYERS

- **Commissioning records:** as-built drawings, calibration baseline, photometric acceptance test results.
- **Telemetry:** per-cabinet temperature, voltage, fan speed, error counters, hours-on logs.
- **Calibration management:** scheduled re-calibration (typically annually for premium installations), coefficient archive, version history.
- **Spares strategy:** on-site spares quantity, vendor stock commitments, end-of-life notice period.
- **Module-replacement workflow:** serial number tracking, calibration coefficient transfer, field-tool requirements.
- **Firmware management:** signed firmware, rollback capability, change-log audit trail.
- **Cybersecurity:** management network segmentation, authenticated access to sending cards and CMS.
- **Warranty and SLA:** response time, replacement time, brightness-at-end-of-warranty commitment.
- **Sustainability and end-of-life:** WEEE compliance, materials disclosure, take-back programmes.

PERFORMANCE KPIS & TEST METHODS

KPI	MEASUREMENT	ACCEPTANCE CRITERION
Mean time between failures (MTBF)	Vendor-stated MTBF verified by field data	$\geq 100,000$ hr indoor · $\geq 50,000$ hr outdoor
Brightness at end of warranty	Spectroradiometer at acceptance and at warranty end	$\geq 70\%$ of commissioning brightness
Colour stability over warranty	Imaging colorimeter spot checks	$\Delta u'v' \leq 0.005$ from commissioning
Module failure rate per year	Field record audit	$\leq 0.1\%$ indoor SMD · $\leq 0.5\%$ outdoor · $\leq 0.5\%$ COB
Telemetry coverage	Audit of monitored vs deployed cabinets	100% mission-critical · $\geq 95\%$ general
Time to restore from outage	Drill exercise or field record	Per SLA – typically ≤ 4 hr indoor · ≤ 24 hr outdoor
Calibration data backup integrity	Restore-from-backup test	100% restorable to bit-identical state

COMMON FAILURE MODES

- ! Module replacement without coefficient transfer producing visibly different brightness in the replaced location.
- ! Firmware drift across cabinets after partial in-service updates.
- ! Loss of vendor support for receiving cards before the rest of the system reaches end-of-life.
- ! Cybersecurity incidents on management networks producing content takeover or denial of service.
- ! Calibration drift due to phosphor and resin ageing not being addressed by scheduled re-calibration.
- ! Loss of as-built and calibration documentation after personnel turnover.

RELEVANT STANDARDS

- ISO 55000 series
- IEC 62321 / RoHS
- WEEE Directive
- ISO/IEC 27001
- ITIL

Quality attributes that no single layer owns.

Some quality attributes are properties of the stack as a whole. The LDM-RM does not place these in any one layer, but specifies which layers must collaborate to deliver them — preventing the common error of holding a single supplier responsible for an outcome collectively produced by several.

4.1 • Colour Accuracy

Delivered colour accuracy depends on Layer 1 (binning), Layer 2 (encapsulant consistency), Layer 5 (calibration coefficients and gamma), Layer 6 (processor colour management) and Layer 7 (source colorimetry). A wall that fails an end-to-end ΔE test cannot be diagnosed at any one layer in isolation.

- L1
- L2
- L5
- L6
- L7

4.2 • Brightness Uniformity

Surface uniformity (typically $\leq \pm 3\%$ premium, achievable to $\pm 1\%$ with rigorous calibration) is produced by Layer 1 binning, Layer 3 power-plane design, Layer 4 thermal uniformity across the cabinet, and Layer 5 pixel-level calibration. A non-uniform wall is rarely a single-layer defect.

- L1
- L3
- L4
- L5

4.3 • Lifetime & Degradation

L70 / L90 lifetime is set by Layer 1 (chip quality, drive-current headroom) and Layer 2 (thermal path, encapsulant stability), but is heavily moderated by Layer 4 (cabinet thermal management) and Layer 9 (operating duty cycle, content brightness profile). Two identical walls running on different content can age at materially different rates.

- L1
- L2
- L4
- L9

4.4 • Serviceability

Time-to-repair and continuity of appearance after repair depend on Layer 2 (whether COB modules are field-replaceable at all), Layer 3 (modularity and connector design), Layer 4 (front- vs rear-service), Layer 5 (whether per-pixel coefficients survive a module swap) and Layer 9 (spares availability and field tooling). Specifying "front-serviceable" without addressing L5 calibration transfer produces a wall that is mechanically serviceable but visually patched after every repair.

- L2
- L3
- L4
- L5
- L9

4.5 • Cybersecurity

LED display systems are increasingly network-attached. Sending cards, CMS instances and management dashboards present attack surface across Layers 6, 8 and 9. The model recommends explicit segmentation between content delivery (L8), control (L6) and management (L9), with authenticated access at each boundary.

- L6
- L8
- L9

// 05 • APPLYING THE LDM-RM

Writing layered specifications.

A specification document organised by LDM-RM layers forces explicit choices at each level rather than relying on headline numbers. The recommended format is a per-layer requirement section, with KPIs drawn from Section 03, accompanied by a per-layer evidence requirement (test report, certificate, or witnessed test).

LAYER	KEY SPECIFICATIONS TO STATE EXPLICITLY	EVIDENCE REQUIRED
L1 — Photonic	Die manufacturer, bin specification, LM-80 data, projected L90	LM-80 report · TM-21 projection · binning certificate
L2 — Packaging	Package type, MSL rating, expected viewing angle, anti-collision class	Datasheet · MSL certificate · anti-collision test report
L3 — Module	Pixel pitch, driver IC family, grayscale bit depth, refresh rate, W/m²	Module datasheet · IPC-A-610 inspection report
L4 — Cabinet	IP rating, service orientation, operating temp range, weight, seam tolerance	IEC 60529 certificate · IEC 60068 climate test · drawings
L5 — Receiving Card	Bit depth, refresh rate, calibration method, coefficient persistence	Receiving-card datasheet · calibration acceptance report
L6 — Transport	End-to-end latency, redundancy topology, genlock method	Latency measurement · network topology · genlock test report
L7 — Signal	Supported sources, colour space, EOTF, bit-depth preservation	Source compatibility matrix · ΔE acceptance report

Layer	Key specifications to state explicitly	Evidence required
L8 — Application	CMS, brightness automation policy, schedule audit	CMS specification · dayparting policy document
L9 — Operations	Warranty, MTBF, spares strategy, telemetry, end-of-life	Warranty document · MTBF data · spares contract

Applied Benefit

Writing a tender to the LDM-RM forces vendors to disclose what they would otherwise be free to leave ambiguous — no hiding a low-bin wafer behind a 6,500 K calibrated white-point claim, and no hiding an unmaintainable wall behind a glossy datasheet hero number.

// 05.2 · Diagnostic Workflow

Top-down isolation, network style.

When a problem is observed on a deployed wall, the LDM-RM provides a top-down diagnostic order. The principle is the same as networking: start at the layer where the symptom is first observable and descend until the failing layer is isolated.

Step 1 · Classify

Symptom: content, signal, mapping, image quality, mechanical, or operational?

Step 2 · Map

Map the symptom class to candidate layers using the table below.

Step 3 · Test cheapest

Test the lowest-cost-to-verify candidate layer first.

Step 4 · Descend

Descend (or ascend) only after the current layer is cleared with evidence.

Step 5 · Document

Document the failing layer and root cause for L9 records.

Observed Symptom	Most Likely Layers (in order)	First Test
Wrong content playing	L8L7	Check CMS schedule and source assignment
No image, all black	L7L6L5L4	Check signal at processor input · check sending-card status
Tearing across cabinets	L6	Verify genlock and frame-sync configuration
Visible scan lines on camera	L5L3	Increase visual refresh rate at receiving card
Patches at low grayscale	L5L1	Re-run pixel-level calibration · check binning records
Single dead pixel cluster	L2L3	Identify module · inspect for solder or encapsulant failure
Visible seam between cabinets	L4	Measure seam tolerance · check thermal warping

OBSERVED SYMPTOM	MOST LIKELY LAYERS (IN ORDER)	FIRST TEST
Brightness drop over time, uniform	L1L9	Compare to baseline LM-80 expectation · assess duty cycle
Brightness drop over time, patchy	L1L5	Re-calibrate · investigate hot spots in cabinet thermal records
Colour cast across whole wall	L7L6	Verify source colour space and processor colour management

// 06 · STANDARDISATION GAPS & RECOMMENDATIONS

Where the industry should collaborate next.

The LDM-RM mapping in Section 02 highlights that several layers are well-served by existing standards while others remain almost entirely vendor-defined. The most acute gaps — and the recommended areas for industry collaboration — are below.

GAP 6.1 · LAYER 5

Receiving-Card Interoperability

The receiving-card layer is the single largest standardisation gap. Calibration-coefficient formats, configuration files and management protocols are entirely vendor-proprietary. A wall built with NovaStar receiving cards cannot be migrated to Brompton, Megapixel, or Colorlight equivalents without complete recalibration and reconfiguration.

RECOMMENDED ACTION

An industry-defined open exchange format for per-pixel calibration coefficients, comparable to ICC profiles in the printing industry.

GAP 6.2 · LAYER 6

Transport Protocol Documentation

Sending-card-to-receiving-card protocols are vendor-proprietary and undocumented. SMPTE ST 2110 has begun to address the upstream signal interface but stops at the sending card.

RECOMMENDED ACTION

Documented, royalty-bearing-or-free protocol specifications for the sending-to-receiving link, allowing third-party diagnostics and management tools.

GAP 6.3 · LAYER 9

Lifecycle Telemetry

Each vendor exposes telemetry in a different schema. Aggregating telemetry across a multi-vendor estate currently requires custom integration.

RECOMMENDED ACTION

A common telemetry schema, plausibly aligned with existing IT monitoring practice (Prometheus / OpenTelemetry style) so that LED estates can be observed alongside other digital infrastructure.

GAP 6.4 · CROSS-LAYER

Acceptance Testing

There is no widely-adopted equivalent of the broadcast industry's QC test patterns and acceptance methodology for LED walls. AVIXA's display performance standards are a starting point but do not yet cover the full LDM-RM stack.

RECOMMENDED ACTION

An LDM-RM-aligned acceptance testing standard, with pattern packs and measurement procedures defined per layer.

// 07 · CONCLUSION

An opening proposal, not a finished standard.

The LED Display Manufacturing Reference Model is offered as a contribution to the discipline of an industry that has long since outgrown its informal vocabulary. The nine layers — Photonic, Packaging, Module, Cabinet, Data Link, Transport, Signal, Application, and Operations — describe how every direct-view LED display in service today actually works, whether or not its manufacturer has named the layers.

A specifier who writes to the LDM-RM forces vendors to disclose what they would otherwise be free to leave ambiguous. A QA engineer who diagnoses to the LDM-RM resolves problems faster and assigns responsibility correctly. A manufacturer who builds to the LDM-RM produces a product that is comparable to its competitors on all axes that matter, not only the headline ones.

The model will be improved by industry critique, by working-group refinement, and by the addition of the test method packs and certification regimes that other industries took decades to build. The first task is for the industry to agree that a layered model is needed at all. The OSI model took a decade to be universally adopted; in the meantime, it disciplined every conversation in networking. **The LDM-RM aspires to do the same for direct-view LED.**

// APPENDIX A · GLOSSARY OF KEY TERMS

Vocabulary used throughout the model.

APL Average Picture Level — the average brightness of the displayed content, used to calculate typical (not peak) power draw.	Binning Sorting of LED dies by wavelength, voltage, and luminous flux into tight tolerance groups before assembly.
COB Chip on Board — packaging in which bare LED dies are bonded directly to the PCB and encapsulated together.	DIP Dual In-line Package — legacy through-hole LED packaging.
EOTF Electro-Optical Transfer Function — the mathematical curve relating signal value to displayed luminance (e.g. gamma 2.4, PQ, HLG).	GCLK Grayscale Clock — the high-frequency clock inside the driver IC that produces grayscale via PWM.
HUB75 / HUB75E The de facto pinout for LED module input from a receiving card.	IMD Integrated Matrix Device — multi-pixel SMD-style packaging combining COB-class consistency with SMD-class repairability.
IP rating Ingress Protection rating per IEC 60529; e.g. IP65 = dust-tight and protected against water jets.	L70 / L90 Lumen maintenance metrics: the operating hours at which the LED has dropped to 70% or 90% of initial luminous flux.
MIP Micro LED in Package — Micro LED dies pre-bound into SMD-format packages.	MSL Moisture Sensitivity Level (JEDEC J-STD-020) — classification of how susceptible a package is to moisture-induced damage during reflow.
MTBF Mean Time Between Failures.	Pixel Pitch The centre-to-centre distance between adjacent pixels, in millimetres (e.g. P1.5 = 1.5 mm).
PQ Perceptual Quantizer — the EOTF used in HDR10 and Dolby Vision (SMPTE ST 2084).	Receiving Card The board inside a cabinet that decodes upstream Ethernet frames and drives the modules below it.
Refresh Rate (visual) The full-frame rewrite frequency of the LED panel itself, distinct from the source frame rate; relevant for camera capture.	Scan Mode The fraction of rows energised simultaneously (e.g. 1/16 means one in sixteen).
Sending Card The board (or all-in-one controller) that converts source signal into the receiving-card protocol and distributes it across the canvas.	SMD Surface Mounted Device — the dominant individual-package LED format from 2010 onward.

Appendix B • Document Revision Notes

This is Version 1.0 of the LDM-RM. The model is intentionally vendor-neutral. Where vendor names appear (NovaStar, Brompton, Megapixel, Colorlight, Linsn), they are cited as representative of a class of equipment, not as endorsements. The model accommodates equivalent equipment from any manufacturer. Comments, critique, and proposed amendments from manufacturers, integrators and end-user organisations are explicitly invited. The intent is for the LDM-RM to evolve through industry contribution into a working reference, ultimately lodged with an appropriate standards body (candidates include AVIXA, SMPTE, IEC TC 110, or a purpose-formed working group).

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