REPRO-LIGHT

08 October 2018

D2.3 User insights briefing report

WP2 – Luminaire Manufacturing and Characteristics Specification

Repro-light:
Re-usable and re-configurable parts for
sustainable LED-based lighting systems

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Introduction

Purpose

This report summarizes the most relevant technical aspects the Repro-light luminaire should have in order to fulfil the requirements. Requirements can be formulated by users, customers, legal issues or as a strategic target by the development team. It describes the correlation between design attributes of the Repro-light luminaire and requirements for the luminaire. Those design attributes that are most important to create customer satisfaction have been identified using a method out of the “Design for Six Sigma – toolbox”.

The document shall provide a guideline for development of design specifications of the Repro-light luminaire. It shall help to distinguish between features that provide real customer benefit and features that are only “nice to have”.

Besides pure customer requirements we have decided to add legal requirements (given by standards and directives) and requirements to create reconfigurable customised LED luminaires. These latest requirements should be seen as strategic requirements that will foster the innovative approach of the Repro-light project.

House of Quality

It was one goal of WP2 “Luminaire Manufacturing and Characteristics Specification” to ensure that the luminaire characteristics are based on requirements that add customer value to the Repro-light luminaire. We used a special creative technique – Quality Function Deployment (QFD) – to find the correlation between requirements and design attributes of the luminaire. The technique is based on a correlation matrix which is also called due to its graphic representation the “House of Quality (HoQ)”.

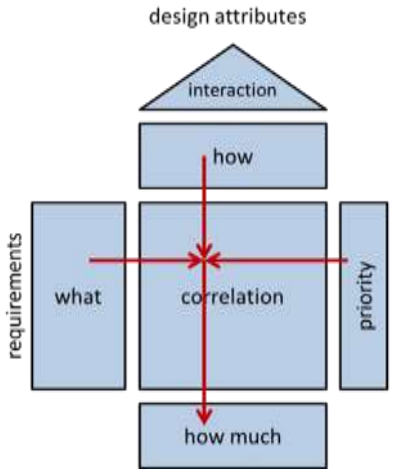


Figure 1: Schematic of the House of Quality

As can be seen in Fig. 1, on the left side (“*what*”) is the list of Requirements, on the right (“*priority*”) a number (1 to 9) indicates, how important fulfilment of the specific requirement is for customer satisfaction. 1 indicates low importance, 9 indicates very high importance.

Above the matrix (“*how*”) is a list of Design Attributes that help to fulfil Requirements. For each Design Attribute one or more targets are given which shall help to find the right characteristic for the Design Attribute. If applicable also a direction is given (larger is better or smaller is better). The “roof”

("*interaction*") describe the interaction between Design Attributes (getting closer to the target of one Design Attribute helps or avoids getting closer to the target of another Design Attribute).

The correlation matrix is filled with correlation parameters which indicate "*how much*" one Design Attribute contributes to fulfil one Requirement. 0 indicates no contribution, 9 indicates high contribution.

A final rating for each Design Attribute is calculated by multiplying the priority of a Requirement with the corresponding matrix element and summing up over the whole column for the specific Design Attribute. The higher the final rating is, the higher the importance of the specific Design Attribute is for fulfilment of customer requirements.

HoQ design procedure

The following is a presentation of the development of the Repro-light Lamps, House of Quality. The following approach was chosen:

- Recording of Requirements by the project partner
- Specifying the Requirements: Rephrasing the requirements to better fit the "customer's language": Eliminating multiple entries
- Prioritizing the Requirements by the project partner
- Investigating Design Attributes that can completely or partially fulfil the Requirements; alternative Design Attributes are allowed
- Creating a Correlation Matrix and calculating an evaluation of the Design Attributes

Requirements

Introduction

For development of a new product it's essential to know what the customer really wants to have or - especially for innovations - what is proposed to generate customer benefit. Standard Quality Function Deployment often generates the list of Requirements by directly asking customers or users of the product to develop. This can be done using questionnaires or by interviews with key customers.

Unfortunately, this method will only deliver Requirements the customer already has. Requirements for breakthrough inventions will not be found by just asking customers or users. For example, Apple would never have developed an iPhone by just asking phone users.

Therefore, the Repro-light consortium decided to use a slightly different approach. We decided to collect Requirements from different sources:

- Customer requirements (source: experienced marketing and sales staff from the project partners ITZ, BART, BJB, dealing with customers for years)
- User requirements (source: End User Survey and Focus Group Spain): End User Survey and Focus Group results have been described in D2.2 of the Repro-light project.
- Requirements from other stakeholders (architects, lighting designer, electricians, planner, wholesaler) (source: Focus Groups Germany and Austria): Focus Group results have been described in D2.2 of the Repro-light project.
- Requirements from lighting experts (source: experienced technical and lighting design staff from the project partners LUGER, ITZ, BART)

- Circular economy requirements from external and internal experts (source: Focus Groups Germany and Austria): Focus Group results have been described in D2.2 of the Repro-light project.

Original Requirements

As we showed above, requirements came from very different sources. Consequently, the formulation targeted very different levels.

Examples:

"**Luminaire should have daylight adjustment**": This is a typical Requirement as it is specified by users or customers. The user/customer has a clear imagination what this means, but it's not very specific. Normally one would understand "Luminaire should dim down when there is enough daylight coming in through the windows". But it could also mean (as proposed by human centric lighting) "Luminaire should imitate natural daylight – low level and warm colour temperature in the morning and evening and high level and cold colour temperature at noon". This would be more the understanding of lighting experts.

"**Cylindrical illuminance level, modelling, directed light**": This is a Requirement formulated by a lighting expert. In fact, it means that light must be distributed in 3-dimensional space to guarantee proper object (3D) recognition.

"**Luminaire should provide container functionality (e.g. WiFi)**": in fact, container functionality is not a Requirement. This is already a Design Attribute supporting e.g. the Requirement "luminaire should be usable for additional, non-lighting functions". The Requirement should not presume, how it can be realized.

In total we started with a list of about 80 Requirements, most of them not very specific, at different levels between very open, nonspecific desire and close to Design Attribute.

Standardized Requirements

In a first step we translated these Requirements to a standardized level (same degree of technical and application abstraction for all Requirements; initially some requirements have been formulated with technical details, others described application needs very unspecific) and tried to make the Requirement explicit and precise. In the same step we divided between System Requirements (to be fulfilled by system software or system layout) and Luminaire Requirements. (A **System** consists from 2 or more luminaires, communication means and optional sensors. System control software may be located on a server or run distributed in the system but it's not responsible for a single luminaire functionality.)

In the turn of Quality Function Deployment (QFD), we focussed on Luminaire Requirements only as the intention of QFD is to rate Design Attributes for the luminaire and not for the system. The system is very flexible due to different configuration and software, QFD is not an appropriate method to evaluate flexible system design.

Table 1: This example shows (see column "Comment") that part of the original Requirement (left column) has been split off and has been transferred to system Requirements (not treated in the HoQ). The Requirement for the luminaire consists of two sub-requirements.

Requirement	Comment	Sharpened requirement
daylight adjustment	Daylight adjustment has to be implemented in the system	a) Luminaire must be capable to adjust flux b) Luminaire must be capable to adjust colour temperature
Activity adaptable	Activity adaption is system requirement	a) Same as above b) Same as above

Sharpening the Requirements in this way and focussing on Luminaire Requirements reduced the number of Requirements from 80 to 37. This is still a huge number for Quality Function Deployment, but we were able to handle it.

Prioritization

In order to find out the most important Requirements we decided to use a scale from 1 to 9, where 1 means very low importance and 9 means very high importance. In a first step the partners LUGER, ITZ, BJB and BART evaluated the priority from their perspectives. For a first step we decided not to go too far into detail and use only three values: 2 for low importance, 5 for medium importance and 8 for high importance. These steps could be refined later if necessary.

In most cases all 4 partners chose the same priority or chose priorities with small deviations (e.g. 3 partners rated the item with 8 and 1 partner rated it with 5). To find those Requirements, where the partners were not aligned very well, we calculated the standard deviation. If it exceeded a certain value (1.2), we discussed the reasons for the discrepancies in a telephone conference to agree upon a priority setting.

Examples:

Requirement: "**Luminaire must deliver enough light for specified applications**"

All partners set priority high (8), so the final priority is also 8.

Requirement: "**No flicker effects must be perceptible**"

3 partners set high priority (8), 1 partner medium (5). After a short discussion we agreed that in the course of Human Centric Lighting it's very important that no flicker can be perceived, the final priority was 8.

Requirement: "**Luminaire must be upgradeable to adopt to newest state of technology**"

3 partners set high priority (8), 1 partner low priority (2). Argument for low priority rating: "We estimated that nobody would do that, even if it's possible". In the discussion the partners agreed, that this requirement is in line with the idea of Repro-light to increase life time by upgrading. So it's not a customer requirement (today) but it's a requirement from an ecological point of view. We agreed to set priority to 7.

Design Attributes

Derivation

When deriving the Design Attributes care must be taken not to mistake them for functional or realisation attributes.

Design Attributes describe which features a product must have in order to fulfil certain requirements

Functional Attributes describe which functions need to be fulfilled through certain design attributes.

Realisation Attributes describe the technical design needed to fulfil the function.

Example:

Requirement: The firmware must be able to be updated with very little effort.

Design attribute: The luminaire is equipped with a wireless interface.

Functional attributes: The luminaire can receive commands, data and updates through the wireless interface.

Realisation attributes: The luminaire is equipped with a Bluetooth mesh interface.

When deriving the Design Attributes, it should be taken into account that the description of the characteristics is abstract enough that it won't restrict the function or the technical design to a great degree.

In Task 2.5, LUGER determined a list of Design Attributes by way of brainstorming the Requirements. The following possibilities were the result:

a) A Requirement can be assigned to a single Design Attribute.

   Example:
   Requirement "Luminaire shall provide enough light for specified application"
   Design Attribute "Luminaire flux is within specified bandwidth"

b) A Requirement can be assigned two or more Design Attributes alternatively.

   Example:
   Requirement „No flicker effects must be perceptible"
   Design Attribute „PWM LED are driven above certain frequency" or "Dimming by current control"

c) A Requirement can be assigned two or more Design Attributes that complement each other. In this case, the implementation of one Design Attribute may already satisfy the requirement. On the other hand, there is also the possibility that both must be implemented.

   Example:
   Requirement „Luminaire must be energy efficient"
   Design attribute „Luminaire power efficacy better than specified value" and "Standby power less than specified value"

These specific Design Attributes were discussed and amended in a workshop with the partners: LUGER, ITZ and BJB. For some of the Requirements from Group b) alternative Design Attributes were deleted based on experience, because implementation would have either been too elaborate or inferior.

Using this method, a total of **72 Design Attributes** for the Repro-light luminaire were determined.

Target values

For every Design Attribute, one or more Target Parameters as well as a Target Value can be determined.

For example, the Target Parameter "flux range" was determined for the Design Attribute "Luminaire flux is within specified bandwidth" and the Target Value of "3500-4500 lm" was determined. This Target Parameter should also determine whether rising or falling values show an improvement. In this example, rising values are, of course, an improvement.

These Target Parameters and Values as well as the optimisation direction are a great help when it comes to continuing product development, because they can be used as target criteria with which the achievement of the development goals can be checked.

A Target Parameter could not be determined for every design attribute. For example, a Target Parameter for the Design Attribute “The lamp is equipped with a wireless interface” has not yet been determined. A definition of the Functional Attributes (what the interface must be able to do) and the Realisation Attribute (which interface should be implemented) would be needed first. The targets are then determined by the norms that the interfaces describe.

There are also certain Design Attributes that don’t need to determine their own target parameter because it is already implicit in the design attribute (e.g. “luminaire can be opened without using a tool”).

All Design Attributes that did not correspond to the two previously named types, were determined a Target Parameter and Target Values workshop with LUGER, ITZ and BJB.

House of Quality

Influence Matrix

The Influence Matrix for the Repro-light luminaire consists of 37 lines (one line per requirement) and 72 columns (one column per Design Attribute). This adds to a total of 2664 matrix cells containing influencing factors.

Each factor is evaluated by answering the question: “If Design Attribute X is realized in the Repro-light luminaire, how much does it contribute to fulfil Requirement Y.

The Influence Factors can take values between 0 (no contribution) and 9 (high contribution). We decided to use

- **Influence Factor 0** if realization of a design attribute does not influence fulfilment of a requirement

  Example:
  Design Attribute “Luminaire flux is within specified bandwidth” does not influence Requirement “No flicker effects must me perceptible”

- **Influence Factor 1** if realization of a Design Attribute influences fulfilment of a Requirement only to a small amount

  Example:
  Design Attribute “Luminaire power efficacy better than specified value” influences Requirement “Luminaire shall provide enough light for specified application” only little (with high power efficacy it’s easier to achieve a certain illuminance level as the LED stays colder and emits more light. But it’s mainly a question of LEDs’ flux)

- **Influence Factor 3** if realization of a Design Attribute influences fulfilment of a Requirement to a medium amount

  Example:
  Design Attribute “Luminaire power efficacy better than specified value” influences fulfilment of the Requirement “Luminaire must be usable at ambient temperatures up to specified value” to a medium amount (If the LEDs generate less heat, luminaire may be used at higher ambient temperature. But the main influence comes from cooling design)

- **Influence Facor 9** if realization of a Design Attribute influences fulfilment of a Requirement to a high amount

  Example:
  Design Attribute “Luminaire flux is within specified bandwidth” influences fulfilment of the Requirement “Luminaire shall provide enough light for specified application” very much (The main thing to get enough light is to put enough flux into the luminaire)

To use a more granular scale would give the illusion of higher accuracy, but it would use much more time and discussions to fill the matrix. Practise has shown that major trends can be recognized even using only a 4 step scale.

The idea laying behind to use a scale 1-3-9 instead of a linear scale 3-6-9 is the following: A linear scale would rate two Design Attributes with minor influence equally to one Design Attribute with medium influence and two Design Attributes with medium influence even higher than one Design Attribute with high influence. This would give Design Attributes with high influence not enough weight.

With the non-linear scale it needs three design attributes of lower importance to have the same weight as one Design Attribute with the higher influence. This gives Design Attributes with higher importance enough weight.

Evaluation

Evaluation was done by LUGER in an internal workshop. The best way to proceed was as follows: Requirements with close relationship were grouped (Requirements on photometry, on luminaire appearance, on physiological effects, on controllability, on environmental impact, on lifetime and performance and on life cycle). Putting related Requirements together in the matrix is convenient because it supports mental focussing during evaluation.

Design Attributes were grouped according to luminaire subassemblies the attribute is connected with (Design Attributes connected with LED, driver, connectivity, firmware, mechanics, optics, sensors, modularity). Again, this was done to facilitate focussing during evaluation.

The evaluation itself was done column by column. The Design Attribute for each column was discussed.

Example: What does “Luminaire flux is within specified bandwidth” mean? What features, advantages, disadvantages are connected with this Design Attribute? Results from discussion:

- There is enough light for certain application
- Light can be distributed according to the needs of the application
- Luminaire will produce a certain amount of heat
- If flux does not exceed the upper limit, it helps to avoid glare

These arguments then helped to go through the Requirements (line by line) and evaluate the influence of the Design Attribute on fulfilment of the Requirement. As during the discussion no connection of the flux with life-cycle topics was found, the process could be accelerated by stepping through the life-cycle Requirements very fast.

After determination of all Influence Factors in the matrix a check for consistency had to be performed. All lines had to be checked whether there is a line with all influence factors equal to zero. This would

mean, that there is a Requirement and none of the design attributes would contribute to fulfil this requirement. No such line was detected.

Also all columns had to be checked, whether there was one with all Influence Factors equal to zero. Such column means that there is a Design Attribute that doesn't help to fulfil any of the Requirements. Six of these columns could be detected. Discussing the Design Attributes we discovered that these Design Attributes are connected with luminaire production. As there are no Requirements for production in the HoQ, it is clear that they don't contribute to any of the Requirements in the HoQ.

Although these Design Attributes will not be evaluated by the HoQ, they are nevertheless important for development of the Repro-light luminaire.

Finally, the rating for each design attribute was calculated:

$$R_i = \sum_{j=1}^{n_r} P_j \cdot I_{i,j}$$

Where

R_i	Rating for Design Attribute i
P_j	Priority of Requirement j
$I_{i,j}$	Influence Factor of Design Attribute i to fulfilment of Requirement j
n_r	Number of Requirements

The higher the rating of a Design Attribute is, the more it will contribute to Requirement fulfilment.

Results and output for other WPs

List of Requirements

The prioritized list of Requirements is an important tool for the whole luminaire design process. It is not only helpful for the evaluation of Design Attributes during the process of Quality Function Deployment but it can also help to evaluate Functional Attributes or Realisation Attributes. Two solutions based on different functionality or different technical solutions can be evaluated during the design process as they can be drawn back to basic needs using this list of Requirements.

These results will be useful in WP3 (design) and WP6 (assessment).

List of design attributes

Design Attributes are the starting point for product specifications. The list of Design Attributes has been derived systematically. In addition, the HoQ delivers ratings for the Design Attributes that reflect the importance of Design Attributes in fulfilment of Requirements. The results will be directly used in WP3.

QFD results

Major trends for Design Attributes for a Repro-light luminaire have been derived from the QFD:

- **Connected lighting is very important** to realize a Repro-light system. Both wired connectivity and wireless connectivity got the highest ratings as Design Attributes. The rating for wireless connected lighting is slightly higher than for wired connected lighting. This has been expected

as all System Requirements lead to the necessity to have connectable luminaires. The higher rating for wireless systems can be derived from Requirements for adaptable lighting due to changes in environment.

- **Dynamic lighting** for changing light in all dimensions (intensity, colour, direction) has been rated also with significant high values. These ratings result from Requirements for Human Centric Lighting, personalized lighting and adaptable lighting due to changes in environment.
- **Exchangeable and upgradable components and firmware.** The rating for these Design Attributes are caused by Strategic Requirements for circular economy of Repro-light systems. It covers drivers, LED modules and optical modules. These Design attributes will make it easier to adopt luminaires to personalized usage of light and adopt luminaires to changing environment and changing technology.
- **Efficiency** is not the most important Design Attribute but it's got still a medium high rating. It was not expected in that way (estimated to be higher). In the following we will give an explanation for this discrepancy.

The interpretation of QFD results also shows the limits of this method. The Requirement "The luminaire must avoid direct glare" is a "*Must*" according to legislation. Design Attribute that contributes mostly to this Requirement is "Light distribution with defined cut-off matches the specified target distribution". But this Design Attribute is only rated in the mid-field. Reason: prioritization of the Requirement does not reflect the "*Must*". Similar applies for Efficiency.

QFD results can be treated as a useful guideline for finding the important Design Attributes. But it can't replace an intelligent interpretation. There are always Requirements that are so obvious, that they are not even stated (e.g. luminaire must not disturb radio). And, in accordance to these, there are Design Attributes that are not listed (e.g. EMC must comply to legal regulations). There will always be basic Design Attributes, that will not be reflected by the HoQ. In these cases HoQ will only reflect the incremental innovation that exceeds the basic Requirements.

Summary

Quality Function Deployment (QFD), a tool out of the "Design for Lean Six Sigma"-toolbox has been used to derive Design Attributes for a Repro-light luminaire from the requirements elaborated in D2.2: "Requirements Specification".

The main issue was to use a standardized method to evaluate the importance of Design Attributes for contributing to the fulfilment of the Requirements.

As the Requirements developed from different sources (user, customers, experts, …) and with different target fields (Personalization Requirements, Visual and Photometric Requirements, Technical Requirements) that have been collected in D2.2 are not easy to compare and can't be treated the same way in QFD, they had to be "standardized" first. This means, they had to be brought to the same degree of technical and application abstraction made explicit and precise.

Requirements were divided into System Requirements and Luminaire Requirements. In the QFD model only Luminaire Requirements were analysed. The Requirements were the prioritized giving them priorities between 1 (little importance to achieve customer satisfaction) and 9 (very important to achieve customer satisfaction).

From the set of (finally) 37 Requirements Design Attributes were derived. This was done by answering the question "*Which Design Attribute might contribute to fulfil a specific Requirement?*". In this way a set of 72 Design Attributes was developed. Target Parameters and Target Values for the Design Attributes were defined.

Finally the Influence Matrix was defined by asking for the influence of each Design Attribute on fulfilment of each Requirement. Ratings for each Design Attribute can be simply calculated using the coefficients of the Influence Matrix and the Requirement's priorities.

Interpretation of the Rating for the Design Attributes show, that Connected Lighting, Dynamic Lighting, exchangeable and upgradable components and firmware and Efficiency will have the highest influence on customer satisfaction.

These results, but also the prioritized list of requirements will be an important tool for the whole luminaire design process. Design attributes, that are the starting point for product specifications, have been derived systematically and will be direct input for WP3.

Appendix (confidential)

Original Requirements and sharpened Requirements

The original Requirements have been collected by ITZ internally, are output from MU-ENG workshops Personalization/Office, Personalization/Industry, Personalization/Care, Personalization/Retail and are output from the TRILUX Client Lab. These (78) Requirements were used without sorting or selection. Output of the BART focus groups have been brought into the already sharpened Requirements list later.

Requirements for the luminaire and for the lighting system have been mentioned. For the Repro-light project these Requirements have been reduced to luminaire requirements. System Requirements often imply also a Requirement for the luminaire. In the following table only the Luminaire Requirements will be sharpened.

Sharpening is used as a term that means “to find the true kernel of the Requirement and formulate in the language of the customer (not the lighting expert)”. Sharpening also includes bundling Requirements if they mean basically the same or splitting Requirements, if they include two separate Requirements (see for example line 9).

Table 2: Requirements

	Requirement	Comment	Sharpened requirement
	Trilux collection		
1	illuminance level and homogeneity	Requirement for the room. Transform into luminaire requirement using know how. Illuminance level and homogeneity depends and luminaire flux and LDC	a) Luminaire flux must be within specified bandwidth b) LDC must match the specified target distribution
2	luminance distribution	Requirement for the room. Transform into luminaire requirement using know how. Luminance distribution depends on luminaire LDC	Same as 1b)
3	direct glare rating (UGR)		UGR (standard table) must be better than specified value
4	reflex glare reduction (BAP, e.g. 3000 cd/m² above gamma 60°)		Light emitting surface mean luminance must be below specified value for angles above specified gamma
5	cylindrical illuminance level, modelling, directed light	Requirement for the room. Transform into luminaire requirement using know how. Parameters depend on luminaire LDC	Same as 1a) Same as 1b)
6	aesthetic appearance of the luminaire and LES	“Aesthetic” is an individual feeling and cannot define a customer requirement. Try to specify the design: should it be trendy, timeless, smooth, … ? Is appearance more than design?	Luminance distribution of the light emitting surface must be perceived as “smooth” (reduced gradients, no hot-spots)
7	natural shadowing	“Natural” is not a good term: cast shadows are common in nature but are unwanted in office/industrial applications. Unwanted are for example als multiple shadows	Luminaire must not create unwanted shadowing
8	Flicker (Pst)		No flicker effects must me perceptible
9	Stroboscopic effects (SVM)		No stroboscopic effects must me perceptible
10	melanopic illuminance Level @ eye level	Room requirement. Can be transformed in luminaire requirements (similar to 1)	a) Luminaire melanopic flux must be within specified bandwidth b) same as 1b)

	Requirement	Comment	Sharpened requirement
11	circadian dynamics	Circadian dynamics have to be implemented in the system.	a) Luminaire must be capable to adjust flux b) Luminaire must be capable to adjust colour temperature
12	energy efficiency	System efficiency (energy consumption/year) can't be considered From customer view energy efficiency is the ratio between luminaire flux and total electrical input power. Standby power has also to be considered	a) energy efficiency must be better than specified value b) Standby power must be less than specified value
13	lifetime and minimum flux level (L80=…. h)	For the user an initial flux value and therefore an L80 lifetime is not relevant. Using intelligent in-luminaire controls the luminaire flux can be kept constant for the whole lifetime (dimming the initial LED flux to 80% and slightly increasing over lifetime to 100%)	Luminaire flux must not drop below specified value over specified lifetime
14	ambient temperature		Luminaire must be usable at ambient temperatures up to specified value
15	switching cycles		Luminaire switching cycles must be higher than specified number
16	energy monitoring (?)		Luminaire must be capable monitoring and transmitting real (or computed) energy consumption
17	monitoring of visual aspects (?)		Luminaire must be capable monitoring and transmitting real (or computed) values for actual flux and CCT
18	predictive maintenance (?)		Luminaire must be capable predicting and transmitting necessary maintenance actions (when and what)
19	services beyond lighting (heatmap, indoor navigation) (?)	Services are system requirements. Services have to be defined	Luminaire must be capable to incorporate modules to support defined services
20	Constant light output		Luminaire flux must be kept at specified value over specified lifetime
21	daylight adjustment	Daylight adjustment has to be implemented in the system	a) Same as 11a) b) Same as 11b)
22	presence control	Presence control has to be implemented in the system or Local presence control	a) Same as 11a) b) Same as 11b) c) Luminaire must be equipped with presence detector that controls flux (and CCT)
23	swarm functionality (?)	Swarm functionality has to be implemented in the system. I assume that luminaire has to send information about its current status into the system	a) Same as 17 b) Same as 11a) c) Same as 11b)
24	emergency light	There can be several options: - It is possible to equip some of the luminaires with emergency lighting functionality	Luminaire must be able to work in emergency lighting mode

	Requirement	Comment	Sharpened requirement
		- It is possible that the customer adds an emergency lighting module to arbitrary luminaires - Every luminaire is capable to work with emergency lighting functionality and ha to be activated (re-configuration) Customer requirement may target a special solution (e.g. customer wants to implement/change functionality without the need of hardware intervention) or may be open for two or more possible solutions (e.g. customer needs emergency lighting no matter how it's realized)	
25	container function (adaptation of additional modules, e.g. wifi, VLC, Bluetooth)	There are various possibilities to make the luminaire adaptable (see also comment to requirement 24)	The functionality of the luminaire has to be adaptable with specified options
26	easy installation		It must be "easy" to install the luminaire
27	easy commissioning	Commissioning is system requirement	
28	easy control	Control is system requirement	
29	easy refurbishment		It must be "easy" to change modules or components in the luminaire
30	easy replacement		It must be "easy" to dismount/replace a luminaire
31	flexible usage in changing environments		Luminaire must be adaptable to changes of environment with minimal effort
32	adaptation of light intensity to age of end-user	Not only age of the end-user. Also to personal preferences, visual performance, …	Flux must be adaptable (scalable) to personal preferences of the end-user
33	homogeneity of the light emitting surface	Maybe 6 is better as perfect homogeneity may not be what's desired or achievable	Replaced by 6
34	avoid multi-shadowing		Replaced by 7
	MU-ENG Workshop	**Personalization/Office**	
35	Adaptable (physically) e.g. Height, orientation…	I guess this applies mainly for desk lighting.	Luminaire must be mechanically adaptable by changing position and orientation
36	Individual lighting	Individual control has to be implemented in the system	a) Same as 11a) b) Same as 11b)
37	Intensity adaptation		Same as 11a)
38	Intelligence control (auto-regulation)	Intelligent/auto control is system requirement	a) Same as 11a) b) Same as 11b)
39	Light-control based on user patterns (machine learning)	Control based on learned user pattern is system requirement	a) Same as 11a) b) Same as 11b)
40	Adaptable to the mood	Mood adaption is system requirement	a) Same as 11a) b) Same as 11b)
41	Activity adaptable	Activity adaption is system requirement	c) Same as 11a) d) Same as 11b)
42	Avoid visual fatigue (workload/stress)	Requirement for lighting design and system	
43	Day/night adaptation (daylight cycle)		Replaced by 21

	Requirement	Comment	Sharpened requirement
44	Enable privacy (Polarized luminaire, shared workplaces)	No idea, how we can realize this with light. (sitting in the dark would provide privacy ☺)	
	MU-ENG Workshop	**Personalization/Industry**	
45	Manually adaptable		Replaced by 35
46	Autonomous lighting control for each worker		Replaced by 36
47	Adaptable to work shifts	This is close to adaption to circadian rhythms. System requirement	a) Same as 11a) b) Same as 11b)
48	Focused lighting for detailed task performances	Lighting design requirement	
49	Light-control based on user patterns // Predesigned lighting features		Replaced by 39
50	Avoid visual fatigue		Replaced by 42
51	Stress reduction		Replaced by 42
52	Adaptable to the mood		Same as 40
53	Avoid task performance errors Illumination for notifications, process information and incidents – not for alarms	I don't understand this	
54	Accessible for deaf people or noisy environments	I don't understand this	
	MU-ENG Workshop	**Personalization/Care**	
55	Separate room spaces by light	Lighting design requirement	
56	Intelligence control (auto-regulation)		Same as 38
57	Light-control from the bed	System requirement	
58	Avoid disturbing the patient	Requirements to flux and LDC	Same as 1
59	Activity adaptable (reading, eating, when receiving visitors)		Same as 41
60	Adaptable according to patient state or severity	System requirement	a) Same as 11a) b) Same as 11b)
61	Reminder for taking medicine	How should this look like?	
62	Treatment accompaniment	How should this look like?	
63	Empathy with the patient	How should this look like?	
	MU-ENG Workshop	**Personalization/Retail**	
64	Filters in fitting room to provide real light environments	This is already a technical solution. I guess the requirement behind is to adopt CCT System requirement	Same as 11b)
65	Intelligence control - Direction adaptable depending on user and products distribution	System requirement	Luminaire must be capable to adjust LDC or its orientation
66	Daylight simulation		Same as 21
67	Light to call attention (sales, new season…)	How should this look like? System requirement	a) Same as 11a) b) Same as 11b)
68	Different light environments depending on the sections	Lighting design requirement	
	TRILUX Client Lab		

	Requirement	Comment	Sharpened requirement
69	Customer suggests exchangeable LEDM with plug system, spring clamps, for non-electrician	Requirement must not contain the solution	LED modules must be exchangeable in a simple way, also by non-electricians
70	Customer requires long-term compatibility and spare parts (> 10 years)	Supply chain requirement	
71	Long-term view: Repairable luminaires maybe not necessary today, but in hard times (economically)	If reparability is required, is 70 enough?	
72	Exchangeability of outer surfaces (scratches, dirt) useful		Outer surface parts of luminaire must be exchangeable
73	Keep the carrier rail system, exchange whole gear tray	What is required?	
74	Interested in analysis&monitoring of luminaire components (also optics – yellowing, dirt accumulation) over DALI/WiFi	Similar to 18	Luminaire must be capable monitoring ageing parts and transmitting necessary maintenance actions (when and what)
75	Exchangeable optics for LDC would be helpful (like in former times:exchangeable reflectors)		Optics must be exchangeable to adopt LDC
76	Protection foil on luminaire will allow installation within single visit of the site (even before painting)	Requirement must not contain the solution	Luminaire has to be protected to allow installation within single visit on site
77	some projects require Cradle to Cradle certification		Cradle to cradle certification required
78	variable LDC is useful for industry applications in case of rezoning of work area		Same as 75 (?)

Requirement priorities

This leads to a new (sharpened) requirement list. These Requirements have been grouped and rearranged to a new list. The partners ITZ, BJB, BART and LUGER set priorities for each of the Requirements. The consent priority was set during a telephone conference in agreement with all partners.

Table 3: Requirement priorities

No.	Requirement	Priority TRILUX	Priority BJB	Priority BART	Priority LUGER	consent Priority
1	enough light for specified applications	8	8	8	8	**8**
2	Flux must be adaptable (scalable) to personal preferences of the end-user	5	5	8	2	**5**
3	light shall trigger melanopic processes	5	3	5	8	**7**

No.	Requirement	Priority TRILUX	Priority BJB	Priority BART	Priority LUGER	consent Priority
4	Light distribution must facilitate comfortable vision in compliance to standards or better	8	8	8	8	**8**
5	Avoid direct glare	8	7	8	8	**8**
6	Avoid veiling reflections	5	3	8	5	**6**
7	Luminaire must not create unwanted shadowing	5	5	5	5	**5**
8	Luminance distribution of the light emitting surface must be perceived as “smooth” (reduced gradients, no hot-spots)	5	6	5	5	**5**
9	No flicker effects must me perceptible	5	8	8	8	**8**
10	No stroboscopic effects must be perceptible	5	8	6,5	8	**8**
11	Luminaire must be capable to adjust flux continuously and dynamically	8	8	8	8	**8**
12	Luminaire must be capable to adjust colour temperature dynamically	8	6	5	5	**6**
13	Luminaire must be capable to enhance colour impression of illuminated goods (switchable, static)	2	1	0	2	**2**
14	Luminaire must be capable to adjust LDC or its orientation (dynamic)	5	3	8	2	**5**
15	Local presence control	5	5	8	2	**5**
16	Luminaire must be energy efficient	8	6	8	8	**8**
17	sustainable usage of materials	8	8	8	5	**8**
18	Lifetime must reach specified value	8	8	8	8	**8**
19	Luminaire flux must be constant over specified lifetime	5	8	8	5	**5**
20	Luminaire must be usable at ambient temperatures up to specified value	8	8	8	8	**8**
21	Luminaire must be capable monitoring and transmitting energy consumption	8	8	8	5	**6**
22	Luminaire must be capable monitoring and transmitting visual parameters	5		5	2	**5**

No.	Requirement	Priority TRILUX	Priority BJB	Priority BART	Priority LUGER	consent Priority
23	Luminaire must be capable to acquire and transmit parameter influencing ageing of luminaire or components	5	2	5	2	**4**
24	Luminaire must be capable to incorporate modules to support defined services	5	8	8	5	**5**
25	The luminaire must be able to incorporate modules to extend functionality	5	4	8	5	**5**
26	It must be “easy” to install the luminaire	5	8	5	8	**7**
27	Luminaire must allow installation within single visit on site	2	5	2	2	**3**
28	Luminaire must be adaptable to changes of environment with minimal effort	5	3	8	5	**6**
29	Luminaire must be upgradeable to adopt to newest state of technology	8	8	8	2	**7**
30	Luminaire must be upgradeable to implement new features	8	8	8	2	**7**
31	It must be easy to update luminaire software/firmware to adopt luminaire functionality	5	8	8	8	**8**
32	It must be “easy” to change modules or components in the luminaire	5	7	5	5	**5**
33	Exchanged modules must be adjustable to "defined age"	5	2	2	2	**3**
34	Outer surface parts of luminaire must be exchangeable	5	8	5	2	**5**
35	It must be “easy” to dismount/replace a luminaire	5	8	8	2	**5**
36	It must be "easy" to disassemble a luminaire	8	8	8	5	**8**
37	Cradle to cradle certification required	2		2	5	**2**

Design Attributes

Design Attributes were derived from the Requirements list. Alternative Design Attributes are marked with # or * (* is only used if there are for a Requirement already alternative Design Attributes marked with # to differentiate). If there is a Requirement with no Design Attribute, the Design Attribute is defined during the specification process.

Table 4: Derivation of Design Attributes

Requirement	Design Attributes
enough light for specified applications	Luminaire flux within specified bandwidth
Flux must be adaptable (scalable) to personal preferences of the end-user	Luminaire has implemented individual flux gain (SW)
light shall trigger melanopic processes	# Luminaire melanopic flux within specified bandwidth
	# Extra LES to emit melanopic effective light under flat angles
Light distribution must facilitate comfortable vision in compliance to standards or better	LDC matches the specified target distribution
Luminaire must be mechanically adaptable by changing position and orientation	
Avoid direct glare	LDC with defined cut-off matches the specified target distribution
	large area LES
	direct/indirect light distribution
Avoid veiling reflections	LDC with sharp cut-off matches the specified target distribution
	large area LES
Luminaire must not create unwanted shadowing	high number of (mid to low power) LED evenly distributed over LES
	# diffuser to disperse single LED shadows
	# waveguide to mix light of LEDs
	# (white) reflector to mix light of LEDs
Luminance distribution of the light emitting surface must be perceived as “smooth” (reduced gradients, no hot-spots)	high number of (mid to low power) LED evenly distributed over LES
	# diffuser in LES to disperse single LED image
	# waveguide to mix light of LEDs
	# (white) reflector to mix light of LEDs
No flicker effects must me perceptible	# PWM LED are driven above certain frequency

Requirement	Design Attributes
	# Dimming by current control
No stroboscopic effects must be perceptible	# PWM LED are driven above certain frequency
	# Dimming by current control
	# randomly changing frequency PWM LED
Luminaire must be capable to adjust flux continuously and dynamically	# luminaire equipped with bus interface
	# luminaire equipped with wireless interface
	* LEDs are dimmable using PWM
	* LEDs are dimmable using current control
Luminaire must be capable to adjust colour temperature dynamically	Luminaire equipped with two (or more) groups of different colour LED
	# luminaire equipped with bus interface
	# luminaire equipped with wireless interface
	* LED groups are dimmable in opposite direction using PWM
	* LEDs are dimmable in opposite direction using current control
	optical system to mix light from different groups
Luminaire must be capable to enhance colour impression of illuminated goods (switchable, static)	# special spectrum LED modules, exchangeable
	# multi-spectral LED module, switchable
	# optical filter, exchangeable
Luminaire must be capable to adjust LDC or its orientation (dynamic)	# 2 groups of LED with different optics independently controlled
	# Mechanically adjustable optical systems (like zoom)
	# Electro-optical adjustable optical system
	# change position, orientation, tilt of optical system (LDC unchanged)
Local presence control	luminaire equipped with presence detector directly coupled to light output (and/or dynamic LDC)
Luminaire must be able to work in emergency lighting mode	luminaire equipped with emergency lighting driver (low output)
	# luminaire equipped with battery

Requirement	Design Attributes
	# luminaire connected to emergency power supply
Luminaire must be energy efficient	Luminaire power efficacy better than specified value
	Luminaire melanopic power efficacy better than specified value
	Standby power less than specified value
sustainable usage of materials	
Lifetime must reach specified value	All components (LED, driver, optics) must reach specified lifetime
	All components (LED, driver, electrical contacts) must reach specified switching cycles
Luminaire flux must be constant over specified lifetime	Self adjusting driver for constant light output
Luminaire must be usable at ambient temperatures up to specified value	Passive cooling of LED and driver
	high number of (mid to low power) LED evenly distributed
	Components positioned to distribute heat
Luminaire switching cycles must be higher than specified number	
Luminaire must be capable monitoring and transmitting energy consumption	# Integrated Power measurement
	# Integrated look-up table and power computation
	* luminaire equipped with bus interface (bidirectional)
	* luminaire equipped with wireless interface (bidirectional)
Luminaire must be capable monitoring and transmitting visual parameters	# Integrated flux and CCT measurement
	# Integrated look-up table for flux and CCT
	* luminaire equipped with bus interface (bidirectional)
	* luminaire equipped with wireless interface (bidirectional)
Luminaire must be capable to acquire and transmit parameter influencing ageing of luminaire or components	Integrated ageing sensors (dust on reflector, optics yellowing, …)
	* luminaire equipped with bus interface (bidirectional)

Requirement	Design Attributes
Luminaire must be capable monitoring ageing parts and transmitting maintenance parameters	* luminaire equipped with wireless interface (bidirectional)
Luminaire must be capable to incorporate modules to support defined services	Standard interface for additional sensors Standard interface for additional modules Firmware upgradeable
LDC must be adoptable to application needs	
The luminaire must be able to incorporate modules to extend functionality	Standard interface for additional sensors Standard interface for additional modules Firmware upgradeable
It must be “easy” to install the luminaire	# Luminaire can be mounted without tools # Luminaire can be mounted with (few) standard tools Luminaire can be mounted by single person (weight and size) Luminaire mounting is self-explaining Large distance between ceiling mounting points (carrier rail system) Luminaire delivered fully assembled and configured (without carrier rail system)
Luminaire must allow installation within single visit on site	# Luminaire equipped with protective film. Can be removed before initial operation # Luminaire equipped with removeable protective cover # No protection against dust required
Luminaire must be adaptable to changes of environment with minimal effort	Exchangeable optics Adjustable optical systems (like zoom) Exchangeable LED module (with optics) Reprogramming driver Accessory to change IP protection Plug-in sensors Exchangeable LED module

Requirement	Design Attributes
Luminaire must be upgradeable to adopt to newest state of technology	Exchangeable driver module Exchangeable communication module Firmware upgradeable Exchangeable optics Exchangeable sensors
Luminaire must be upgradeable to implement new features	Firmware upgradeable Plug-in sensors
It must be easy to update luminaire software/firmware to adopt luminaire functionality	Upgrade via standard interface Reconfiguration of firmware to release additional features
Defect luminaires must be repairable with little effort	fault-critical parts are mounted on replaceable modules defect modules can be located by a simple step by step procedure luminaire can be opened without tool or with standard tool modules can be replaced without soldering modules can be replaced without tool or with standard tool new modules cannot be inserted in wrong position or wrong orientation
It must be “easy” to change modules or components in the luminaire	luminaire can be opened without tool or with standard tool modules/components can be replaced without soldering modules/components can be replaced without tool or with standard tool new modules/components cannot be inserted in wrong position or wrong orientation LED must be protected against ESD during change
Exchange modules must be adjustable to "defined age"	integrated sensor to adjust flux
Outer surface parts of luminaire must be exchangeable	luminaire is built up as a frame or carrier with all components attached to it surface parts are attached to the frame/carrier with no other components attached to it

Requirement	Design Attributes
	surface parts can be dismounted and remounted without tool or standard tools only
It must be “easy” to dismount/replace a luminaire	# Luminaire can be dismounted without tools
	Luminaire can be dismounted by single person
	Luminaire dismounting is self-explaining
It must be "easy" to disassemble a luminaire	Luminaire can be disassembled into basic fractions (metal, plastic, glass, wires, …) without tool or only few standard tools
	No soldering is needed to disassemble luminaire
	no composite materials are used
	Luminaire disassembling is self-explaining
Cradle to cradle certification required	

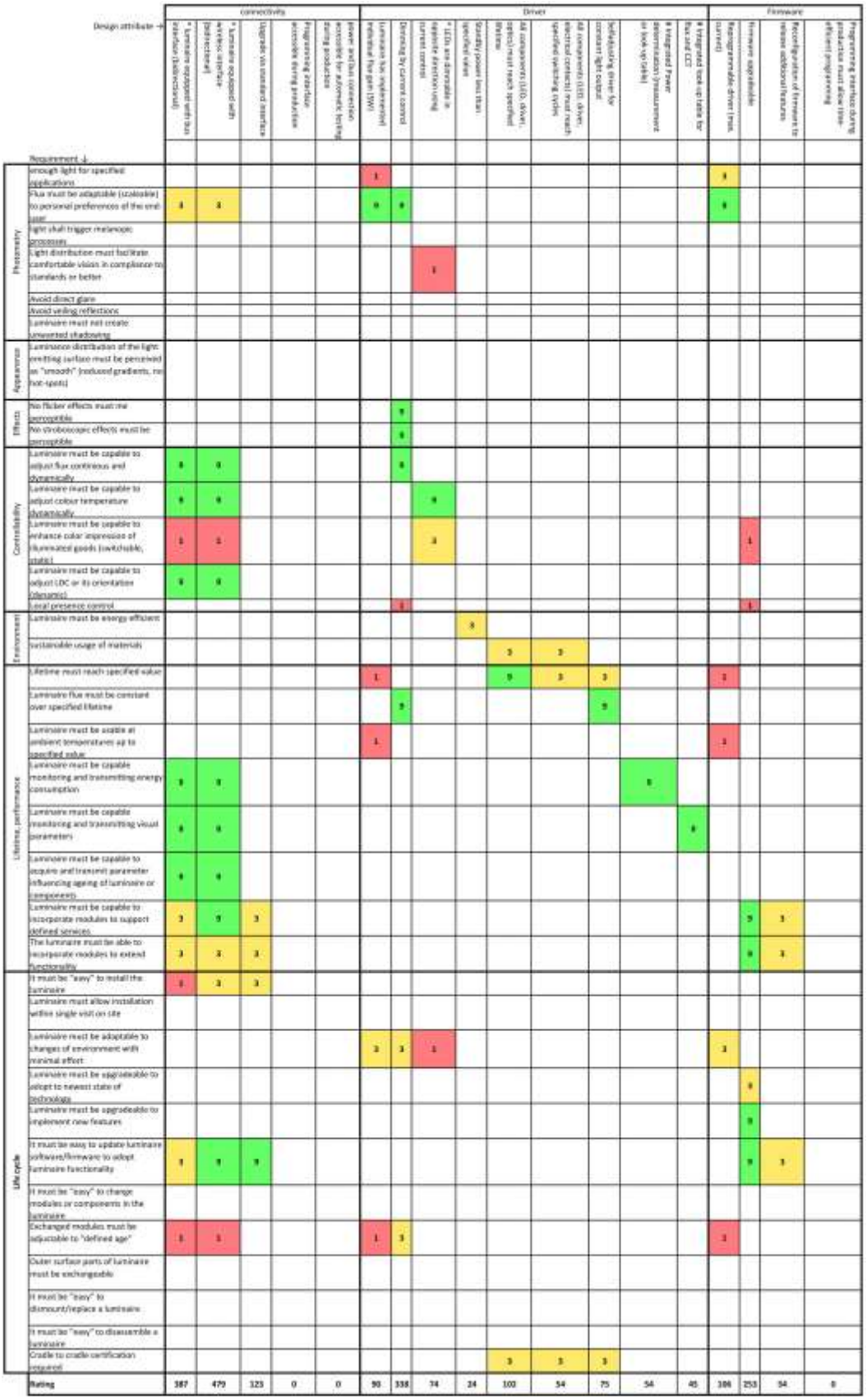
House of quality

To generate the HoQ, the Design Attributes have been condensed. Design Attributes derived from different Requirements but with the same content have been merged to one. Finally, Design Attributes have been sorted according to luminaire subassemblies (although firmware and modularity are not really a subassembly they are treated the same way).

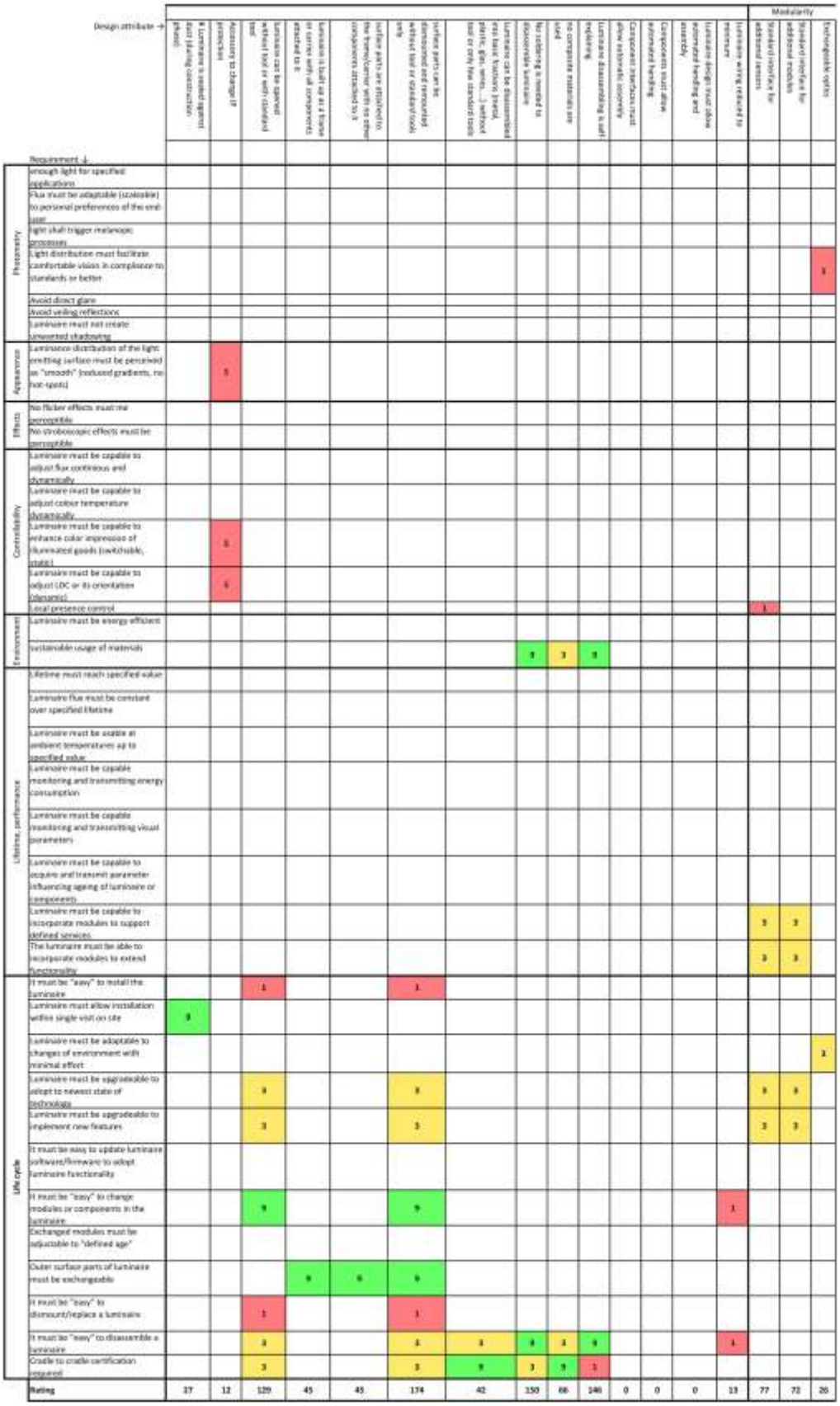
The HoQ matrix (split into 4 parts) is shown on the next pages. The Influence Factors in the matrix describe how strongly a Design Attribute (head of the column) influences the fulfilment of a Requirement (head of the row). For example the Design Attribute “luminaire is equipped with a bus interface (bidirectional)” in column 1 has no influence on fulfilment of the Requirement “enough light for specified application” in row 1 (because the flux depends on the LEDs in the luminaire but not on being equipped with an interface). The same Design attribute has an medium impact on the Requirement “Flux must be adaptable (scaleable) to personal preferences of the end-user” in row 2 (the luminaire flux can be scaled locally, so the bus interface is not essential, but it makes things easier). Therefore the influence factor has been set to 3.

The rating for a Design Attribute is calculated by multiplying the priorities of the Requirements with the corresponding influence factor and the summing up the whole column. The calculated ratings for the Design Attributes can be found in the last row.

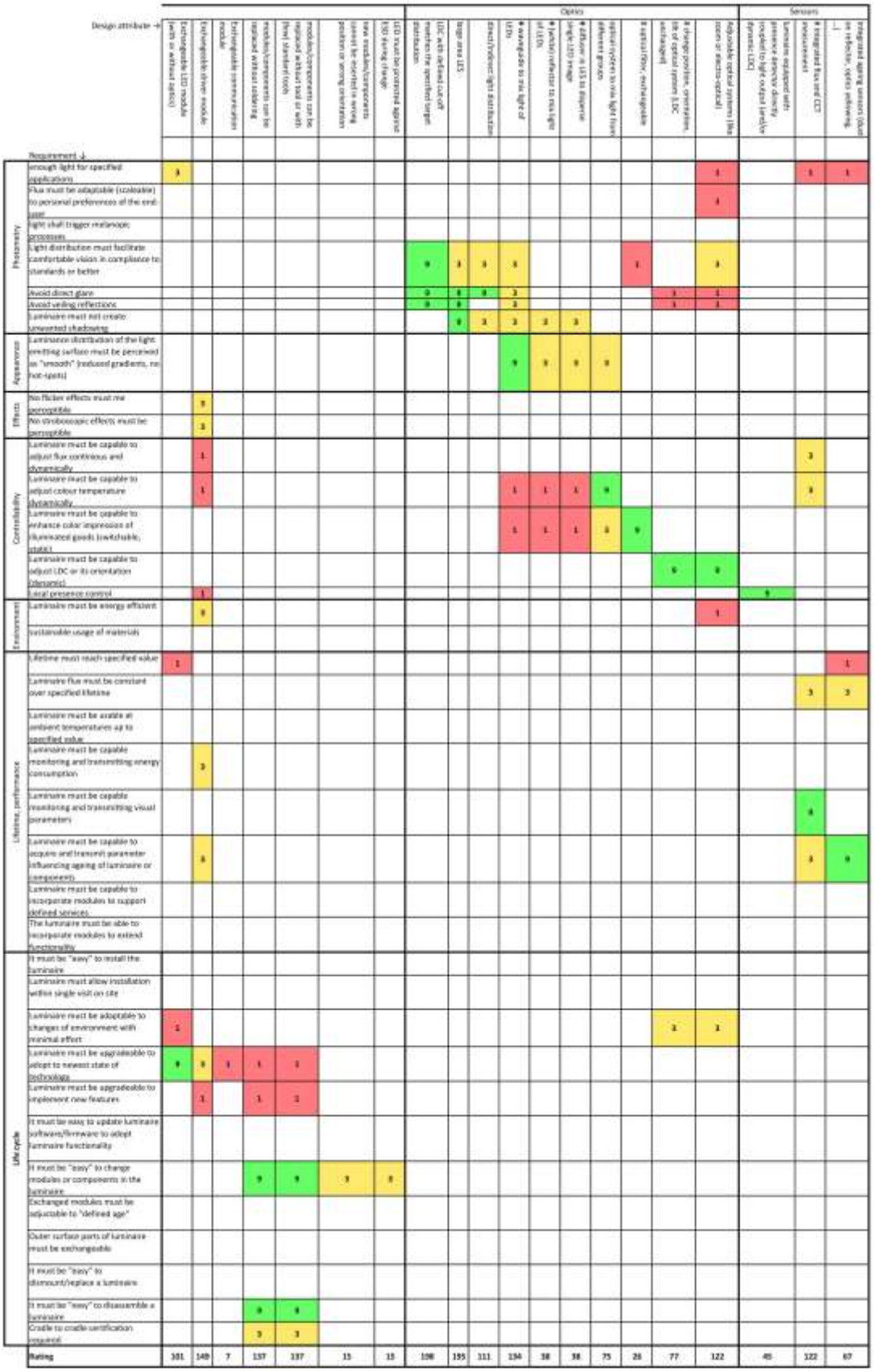
Table 5: House of Quality Matrix



	Design attribute →	LED									Mechanics							
		Luminaire flux within specified bandwidth	Luminaire exchange flux within specified bandwidth	High number of (mid to low power) LED evenly distributed over LES	Luminaire equipped with two (or more) groups of different color LED	Special spectrum LED modules	Dual spectral LED module, switchable	2 groups of LED with different optics independently controlled	Luminaire power efficacy better than specified value	Luminaire exchange power efficacy better than specified value	Passive cooling of LED and driver	Components positioned to distribute heat	# Luminaire can be mounted and dismounted with (few) standard tools in short time	Luminaire can be mounted and dismounted by single person	Luminaire mounting and dismounting is self-explaining	Large distance between ceiling mounting points (carrier rail system)	Luminaire delivered fully assembled and configured (without carrier rail system)	# Luminaire equipped with removable protective cover
	Requirement ↓																	
Photometry	enough light for specified applications	9							1									
Photometry	Flux must be adaptable (scaleable) to personal preferences of the end user																	
Photometry	light shall trigger melanopic processes		9		3	1				1								
Photometry	Light distribution must facilitate comfortable vision in compliance to standards or better	3		3	1	1		1										
Photometry	Avoid direct glare	1		3				1										
Photometry	Avoid veiling reflections	1		3				1										
Photometry	Luminaire must not create unwanted shadowing			3														
Appearance	Luminance distribution of the light emitting surface must be perceived as "smooth" (reduced gradients, no hot-spots)			9														
Effects	No flicker effects must me perceptible																	
Effects	No stroboscopic effects must be perceptible																	
Controllability	Luminaire must be capable to adjust flux continious and dynamically																	
Controllability	Luminaire must be capable to adjust colour temperature dynamically				9													
Controllability	Luminaire must be capable to enhance color impression of illuminated goods (switchable, static)				9	3	9											
Controllability	Luminaire must be capable to adjust LDC or its orientation (dynamic)							9										
Controllability	Local presence control																	
Environment	Luminaire must be energy efficient			1					9	9	3	1						
Environment	sustainable usage of materials								9	9	1							
Lifetime, performance	Lifetime must reach specified value										9	3						
Lifetime, performance	Luminaire flux must be constant over specified lifetime																	
Lifetime, performance	Luminaire must be usable at ambient temperatures up to specified value			1					3	3	3	1						
Lifetime, performance	Luminaire must be capable monitoring and transmitting energy consumption																	
Lifetime, performance	Luminaire must be capable monitoring and transmitting visual parameters																	
Lifetime, performance	Luminaire must be capable to acquire and transmit parameter influencing ageing of luminaire or components																	
Lifetime, performance	Luminaire must be capable to incorporate modules to support defined services																	
Lifetime, performance	The luminaire must be able to incorporate modules to extend functionality																	
Life cycle	It must be "easy" to install the luminaire												9	9	3	9	3	
Life cycle	Luminaire must allow installation within single visit on site																9	9
Life cycle	Luminaire must be adaptable to changes of environment with minimal effort				1	1	3	3										
Life cycle	Luminaire must be upgradeable to adopt to newest state of technology																	
Life cycle	Luminaire must be upgradeable to implement new features																	
Life cycle	It must be easy to update luminaire software/firmware to adopt luminaire functionality																	
Life cycle	It must be "easy" to change modules or components in the luminaire																	
Life cycle	Exchanged modules must be adjustable to "defined age"																	
Life cycle	Outer surface parts of luminaire must be exchangeable																	
Life cycle	It must be "easy" to dismount/replace a luminaire												9	9	9	1		
Life cycle	It must be "easy" to disassemble a luminaire																	
Life cycle	Cradle to cradle certification required																	
	Rating	110	83	142	107	27	36	85	176	175	128	40	108	108	68	68	48	27



Requirement ↓ / Design attribute →	Modularity		
	Standard interface for additional sensors	Standard interface for additional modules	Interoperable cycles
Photometry			
enough light for specified applications			
Flux must be adaptable (scalable) to personal preferences of the end user			
light shall trigger melanopic processes			
Light distribution must facilitate comfortable vision in compliance to standards or better			1
Avoid direct glare			
Avoid veiling reflections			
Luminaire must not create unwanted shadowing			
Appearance			
Luminance distribution of the light emitting surface must be perceived as "smooth" (reduced gradients, no hot-spots)			
Effects			
No flicker effects must me perceptible			
No stroboscopic effects must be perceptible			
Controllability			
Luminaire must be capable to adjust flux continous and dynamically			
Luminaire must be capable to adjust colour temperature dynamically			
Luminaire must be capable to enhance color impression of illuminated goods (switchable, static)			
Luminaire must be capable to adjust LDC or its orientation (dynamic)			
Local presence control	1		
Environment			
Luminaire must be energy efficient			
sustainable usage of materials			
Lifetime, performance			
Lifetime must reach specified value			
Luminaire flux must be constant over specified lifetime			
Luminaire must be usable at ambient temperatures up to specified value			
Luminaire must be capable monitoring and transmitting energy consumption			
Luminaire must be capable monitoring and transmitting visual parameters			
Luminaire must be capable to acquire and transmit parameter influencing ageing of luminaire or components			
Luminaire must be capable to incorporate modules to support defined services	1	1	
The luminaire must be able to incorporate modules to extend functionality	1	1	
Lifecycle			
It must be "easy" to install the Luminaire			
Luminaire must allow installation within single visit on site			
Luminaire must be adaptable to changes of environment with minimal effort			1
Luminaire must be upgradeable to adopt to newest state of technology	1	1	
Luminaire must be upgradeable to implement new features	1	1	
It must be easy to update luminaire software/firmware to adopt luminaire functionality			
It must be "easy" to change modules or components in the luminaire			
Exchanged modules must be adjustable to "defined age"			
Outer surface parts of luminaire must be exchangeable			
It must be "easy" to dismount/replace a luminaire			
It must be "easy" to disassemble a luminaire			
Cradle to cradle certification required			
Rating	77	72	26


Design attribute →
Optics
Sensors
Requirement ↓
Photometry
Appearance
Effects
Controllability
Environment
Lifetime performance
Lifecycle
Rating

Design Attributes and rating

In the following table rated Design Attributes are shown. The table is sorted in falling order. Design Attributes which contribute most to fulfilment of the Requirements are on top in the table.

Setting up the Repro-light project, the consortium envisioned the Repro-light luminaire to possess the following features. The top rated Design Attributes (see Table 6, top 15) are in good agreement with these features:

- **Sustainable modular architecture**: Design Attributes 9, 11, 14 and 15 are connected with a modular architecture. The driver module is most important to be exchangeable to increase luminaire lifetime and to facilitate adoption to technology changes. It is also important to support (nearly) tool-less change of components. For sustainability the luminaire has to be dismountable in its basic components at the end of lifetime (Design Attribute 10, 12).
- **Human Centric Lighting**: Connected with human centric lighting are melanopic processes and light quality. These will be supported by Design Attributes 3, 5, 6, 8 and 13.
- **Extended IoT Connectivity**: The top rated Design Attributes 1 and 2 both support the IoT connectivity. They have to be seen as alternatives (wired and wireless connectivity). The rating for wireless is higher as the capabilities for extended IoT (beyond lighting) are higher.
- **Industry 4.0 compatible**: As the HoQ is based on external requirements (user, customer, legal, environment) and not on internal (production), Industry 4.0 is not reflected by the Design Attributes. We discussed this topic when developing the HoQ and decided not to cover internal requirements here as it is not proved that Quality Function Deployment would work.
- **Avoiding the programmed obsolescence**: Outdated soft- and firmware and defect electronic parts (mainly capacitors) are main causes for programmed obsolescence. Design attributes 4 and 11 are connected with avoidance of programmed obsolescence.

Table 6: Design Attributes with ratings

	Design attribute	Rating
1	* luminaire equipped with wireless interface (bidirectional)	479
2	* luminaire equipped with bus interface (bidirectional)	387
3	Dimming by current control	338
4	Firmware upgradeable	253
5	LDC with defined cut-off matches the specified target distribution	198
6	large area LES	195
7	Luminaire power efficacy better than specified value	176
8	Luminaire melanopic power efficacy better than specified value	175
9	surface parts can be dismounted and remounted without tool or standard tools only	174
10	No soldering is needed to disassemble luminaire	150

	Design attribute	Rating
11	Exchangeable driver module	149
12	Luminaire disassembling is self-explaining	146
13	high number of (mid to low power) LED evenly distributed over LES	142
14	modules/components can be replaced without soldering	137
15	modules/components can be replaced without tool or with (few) standard tools	137
16	# waveguide to mix light of LEDs	134
17	luminaire can be opened without tool or with standard tool	129
18	Passive cooling of LED and driver	128
19	Upgrade via standard interface	123
20	Adjustable optical systems (like zoom or electro-optical)	122
21	# Integrated flux and CCT measurement	122
22	direct/indirect light distribution	111
23	Luminaire flux within specified bandwidth	110
24	# Luminaire can be mounted and dismounted with (few) standard tools in short time	108
25	Luminaire can be mounted and dismounted by single person (weight and size)	108
26	Luminaire equipped with two (or more) groups of different color LED	107
27	Reprogrammable driver (max. current)	106
28	All components (LED, driver, optics) must reach specified lifetime	102
29	Exchangeable LED module (with or without optics)	101
30	Luminaire has implemented individual flux gain (SW)	90
31	2 groups of LED with different optics independently controlled	85
32	Standard interface for additional sensors	77
33	# change position, orientation, tilt of optical system (LDC unchanged)	77
34	Selfadjusting driver for constant light output	75
35	optical system to mix light from different groups	75
36	* LEDs are dimmable in opposite direction using current control	74

	Design attribute	Rating
37	Standard interface for additional modules	72
38	Large distance between ceiling mounting points (carrier rail system)	68
39	Integrated ageing sensors (dust on reflector, optics yellowing, …)	67
40	Luminaire mounting and dismounting is self-explaining	66
41	no composite materials are used	66
42	Luminaire melanopic flux within specified bandwidth	63
43	All components (LED, driver, electrical contacts) must reach specified switching cycles	54
44	# Integrated Power determination (measurement or look-up table)	54
45	Reconfiguration of firmware to release additional features	54
46	Luminaire delivered fully assembled and configured (without carrier rail system)	48
47	# Integrated look-up table for flux and CCT	45
48	luminaire is built up as a frame or carrier with all components attached to it	45
49	surface parts are attached to the frame/carrier with no other components attached to it	45
50	luminaire equipped with presence detector directly coupled to light output (and/or dynamic LDC)	45
51	Luminaire can be disassembled into basic fractions (metal, plastic, glas, wires, …) without tool or only few standard tools	42
52	Components positioned to distribute heat	40
53	# (white) reflector to mix light of LEDs	38
54	# diffuser in LES to disperse single LED image	38
55	dual-spectral LED module, switchable	36
56	special spectrum LED modules	27
57	# Luminaire equipped with removeable protective cover	27
58	# Luminaire is sealed against dust (during construction phase)	27
59	Exchangeable optics	26
60	# optical filter, exchangeable	26
61	Standby power less than specified value	24

	Design attribute	Rating
62	new modules/components cannot be inserted in wrong position or wrong orientation	15
63	LED must be protected against ESD during change	15
64	Luminaire wiring reduced to minimum	13
65	Accessory to change IP protection	12
66	Exchangeable communication module	7
67	Programming interface accessible during production	0
68	power and bus connection accessible for automatic testing during production	0
69	Programming interface during production must allow time-efficient programming	0
70	Component interfaces must allow automatic assembly	0
71	Components must allow automated handling	0
72	Luminaire design must allow automated handling and assembly	0