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LCA Assisted Design as Approach to the Sustainable Product Development: Case Study of Acrylic Lamp

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Abstract

The case study developed and presented is related to a cult object of Italian Design: the “Acrilica” lamp by Joe and Gianni Colombo.

In order to achieve a sustainable product, another lamp has been designed with the aim to reach three main results: weight reduction, environmental performance improvement and lighting performance improvement.

An integrated, adaptive and evolutionary approach has been adopted. Different aspects such as virtual simulations of functioning, life cycle assessment, reverse engineering, prototyping, innovation and creativity have been considered, not in a linear and sequential manner, but throughout the whole design process.

This design process has led to a new lamp which provided a shape redefinition of PMMA (Polymethylmethacrylate) convector, a reduction of its thickness, a change of the direction of the whole lighting apparatus. Every evolutionary step of the product development has been aimed to reduce the dispersion of the light and the environmental impact. This approach led to an optimization on multiple levels which gave improvements in terms of the use of materials, functioning, processing technologies and duration of the life of the lamp.

At the end of the process, to validate the new product and its environmental performance, a comparative LCA (Life Cycle Assessment) between the “Acrilica” lamp and the new lamp has been made. For the Life Cycle Assessment ISO14040-ISO14043 standards have been complied, to communicate the data, instead, the EPD certification scheme (Environmental Product Declaration. ISO14025) [2].

The weight of the convector for the new lamp decrease from 3.755 kg to 2.020 kg. By the environmental point of view, instead, the Global Warming Potential (GWP 100years) decreases from 388.806 kg CO2 equiv. to 62.859 kg CO2 equiv.

The final product has a higher lighting efficiency with an implementation of the illuminated area of 50%, a weight reduction of 46% and a GWP reduction of 84%.

Keywords: Design Process, LCA, Sustainability

Acknowledgments: Thanks to “Plart Foundation”, Museum of Plastic and Art. Naples, Italy.

Forewords

The research developed is related to the sustainable product development of a table lamp designed starting from the analysis of a case study: the "Acrilica" lamp by Joe and Gianni Colombo.

The design process follows criteria, methodology and tools adopted for LCA (Life Cycle Assessment), a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

For the design process an integrated, adaptive and evolutionary approach has been adopted, with three main aims to get: weight reduction, environmental performance improvement and lighting performance improvement.

The design process development has regarded different aspects: the thickness of the convector, the surface of the polymethylmethacrylate, the choice and the positioning of the light source, the shape and the end cut of the convector, the shape of lamp base. The main tools to ensure the best design evolution have been the virtual simulations of functioning and the life cycle assessment methodology.

This approach, giving improvements in terms of the materials used, functioning, processing technologies, lamp lifetime and environmental impact, brings to have an implementation of illuminated area of 50%, a weight reduction of 46% and a GWP(Global Warming Potential) reduction of 84%.

Study of Acrilica Lamp

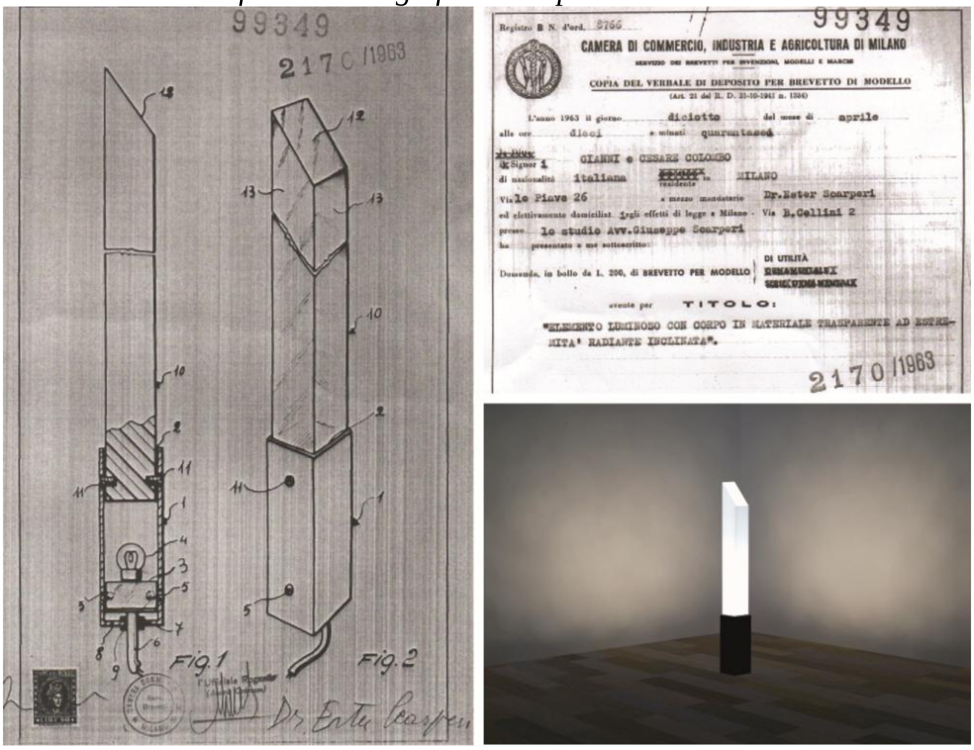
Study and Description of Shape

The "Acrilica" is a table lamp that gives indirect and diffused light, composed by a metal base and a Perspex convector. The lamp, designed by Joe and Gianni Colombo in 1962 and still manufactured by Oluce, got the Golden Metal Prize at the thirteenth Triennale of Milan in 1964. It is exhibited at MOMA (Museum of Modern Art) of New York and in many other important museums. The "Acrilica" o "Colombo 281" lamp occupies a space of 250X270X240 mm and consists of two main components: a bent convector, made of polymethylmethacrylate with a thickness of 30 mm and a metal base (divided in 2 parts), made of aluminium, where a small fluorescent tube light source is placed. The assembly of the components takes place through the use of five screws. Three screws are fixed into the light source casing and the remaining two are directly fixed into the PMMA convector [1, 9].

Study of Patent

A key moment for the design process and the reverse engineering is related to the acquisition of a patent, not directly linked to the "Acrilica", but deposited by its designers at the UIBM (Italian Patents and Trademarks Office). The research ended with the finding of the utility model number 99349 (title: Luminous component with the body in transparent material and radiant end), kept in the ACS (Central Archives of the State), granted to Colombo brothers on 9th October 1965 [12]. The project represents the anticipation of the "Acrilica". The shape of the lamp, according to the utility model, is linear and has no bends; this aspect, as verified with the virtual simulations of functioning (Figure 1), improved the functionality and efficiency of the lamp. Then the Colombo brothers have gone further and they have tried to convey the light through curved components in polymethylmethacrylate [11]. This attempt represented a considerable step backwards from the functional point of view and it contrasts with many other aspects related to the project (for example the manufacturing process is more difficult, the production costs become higher, the environmental impact rises).

Figure 1. *Utility Model n° 99349 (Italian Patent and Trademark Office) – Virtual Simulation of Functioning of the Lamp*



Physicochemical Characterization Analysis

In order to analyze from a chemical and physical point of view the "Acrilica" and to define which parts of PMMA suffer a higher photodegradation, a physico-chemical characterization of the convector was realised by means of two tools: RAMAN FLEX 400F and DSC822 METTLER TOLEDO. The Raman is a technique used for the identification and the analysis of molecular types and the Raman spectroscopy is based on the observation of the scattered light. Usually, when the light interacts with a substance, it occurs in three different ways:

- It can be absorbed
- It can be transmitted
- It can be scattered

Raman spectroscopy is the result of the dispersion of the light. The radiation can be resiliently scattered without any variation of its wavelength (Rayleigh scattering), or it can be inelastically scattered, producing the consequent Raman Effect. There are two types of Raman transitions: “Stokes radiation” (the photon collides with a molecule and loses some energy) and “anti-Stokes radiation” (the photon collides with a molecule and gains energy). Both “Stokes” and “anti-Stokes” radiations consist of lines that correspond to the molecular vibrations of the substance in analysis. Every compound is characterized by its own and unique Raman spectrum, which can be used as a sort of digital fingerprint for the identification. The experiments are aimed to understand the material photo aging, interpreting the influence that the light source has on it. For this reason a series of tracepoints along the body of the PMMA curve (Figure 2) to analyze with Raman spectroscopy, have been identified. A protocol for Raman analysis was created and implemented, including 13 trace-points and the analysis was repeated 3 times for each of them, in order to guarantee the accuracy of the result. The trace-points were identified depending on their distance from the light source and everyone was associated to a letter from A to O; the letter A corresponds to the closest point and the letter O corresponds to the farthest point. An analysis of 4 seconds (0.5 sec. per 8 esp.) was planned for each point and, before it, the sample (the convector in PMMA) had been cleaned with a special cloth [6, 10].

The results of the analysis shows that the peak of photodegradation, pointed out by the presence of the carboxyl groups (C=O, 1730 cm-1), in correspondence with the area identified by the points E, F, G , H and L (table 1). This area corresponds to the area that, for the virtual simulations of functioning, represents the maximum light dispersion. Virtual simulations of functioning made with 3D rendering software, setting the PMMA optical properties (refractive index in particular) and positioning the light source [8]. On the other hand the area identified by the N and O points near the light source, but shielded from external light, do not show a considerable degradation. This indicates that we have a higher photodegradation where a combined effect of natural and artificial light exists.

Figure 2. *Example of Raman Spectra and Analysis Points Identified*

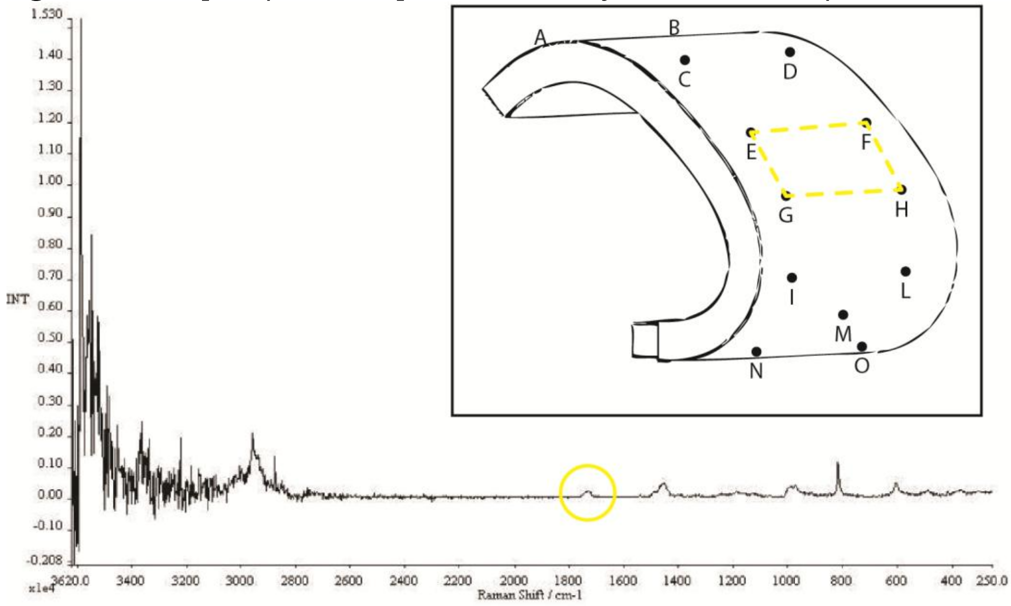


Table 1. *Results of Raman Spectroscopy*

Point *	B, 3360 cm-1	C, 2940 cm-1	D, 2870 cm-1	E, 1470 cm-1	F, 800 cm-1	CO, 1730 cm-1
A	0.23	0.23	0.18	0.06	0.12	0.02
B	0.28	0.4	0.19	0.07	0.25	0.046
C	0.2	0.53	0.23	0.12	0.30	0.063
D	0.26	0.48	0.19	0.13	0.42	0.058
E	0.31	0.63	0.14	0.16	0.41	**0.074**
F	0.26	0.87	0.38	0.26	0.57	**0.112***
G	0.36	1.4	0.29	0.36	0.91	**0.161***
H	0.29	0.55	0.11	0.13	0.34	**0.074**
I	0.23	0.32	0.35	0.1	0.19	0.036
L	0.2	0.54	0.31	0.14	0.31	0.070
M	0.23	0.65	0.21	0.17	0.39	0.067
N	0.28	0.17	0.22	0.22	0.11	0.023
O	0.33	0.17	0.21	0.1	0.12	0.022

Acrilica Weak Points

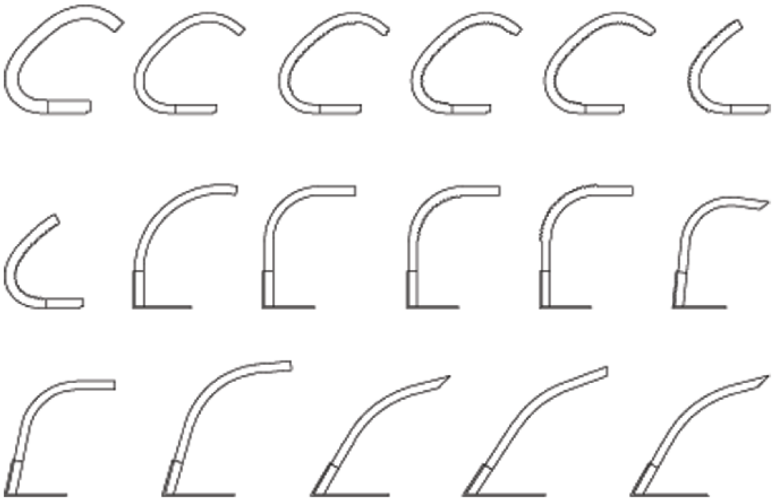
The “Acrilica” lamp has been chosen as a case study for the potentialities related to the use of PMMA as a light guide. Although it was a pioneering product for the 60s however it is characterized by many weak points, especially by a functional point of view and by the point of view of the environmental impact. The particular shape of the convector, with a sharp curve at its beginning and other curves along it, causes a significant light dispersion and so a poor lighting. For example, observing the “Acrilica” turned on in a dark room, it is possible to notice that a considerable amount of the light, generated by the light source, is not conveyed; but it illuminates the rear of the lamp (Figure 3). This corresponds to an inefficiency because the performance of the unit is not close to the maximum attainable. On the basis of this first analysis, the use of a 30mm PMMA convector could be a possible solution, because a greater thickness permits a greater capacity to convey light. However, this kind of solution collides with environmental issues and manufacturing technology; in fact, the overabundance of material (PMMA) leads to a higher environmental impact (it will be showed in one of the next sections). Moreover, by the technological point of view too, because the use of a material with a high thickness induces more problems of PMMA heating and curving during the thermoforming process.

Figure 3. *Acrilica Photo, Light Dispersion*

Design Process: Evolutionary Steps

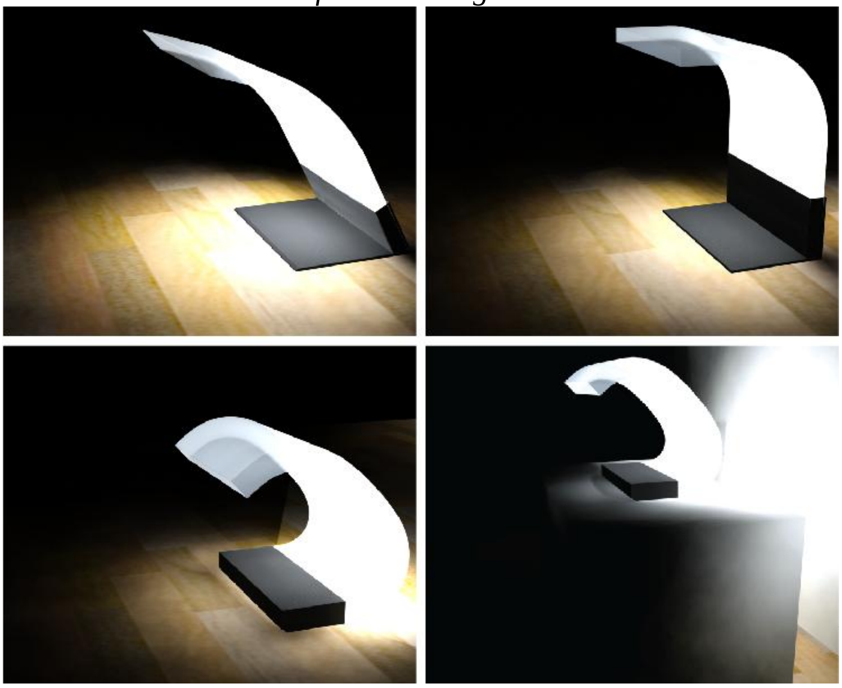
This section shows the main evolutionary stages of the lamp (Figure 4). The re-design process concerns different aspects such as: convector thickness and shape, PMMA surface, lamp direction, casing of the light source, end part of the convector, base shape, etc. The evolution is not exclusively aesthetical, but it is characterized by a technical and functional development too. The validation of design choices is done using virtual simulation of functioning (Figure 5), made with rendering software and considering, step by step, every effect of each evolutionary stage on the environmental impact. The validation and LCA tools have been the key to understand the right choices to get a product characterized by a low weight, good environmental and lighting performances [3, 7].

Figure 4. *Evolutionary Stages of Design*



The prototype of the lamp base is made of aluminum and it is manufactured using the technological process of numerical control curvature and through the realization of 4 countersunk holes. The support of lamp is made of aluminum and it is produced by means of the curvature processing with numerical control; its shape is similar to a box open on the rear side, inside which there is placed a house by the shape of a "V" for the light source (LED). After these processes, the base can be painted with the defined colors. The convector, instead, is made of PMMA and it is manufactured, starting by a linear sheet, using the thermoforming process technology. Later, a cutting process with numerical control is necessary in order to create the part to insert in the metal base and the end cut.

Figure 5. *Virtual Simulations of Functioning*



Life Cycle Assessment: A sustainable Product Development

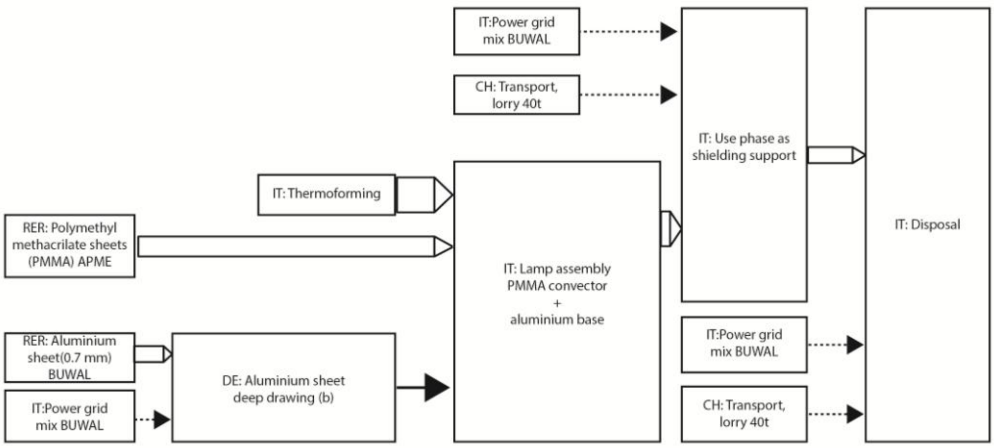
A fundamental tool to assist the design process and get a sustainable product development has been the LCA (Life Cycle Assessment). A comparative LCA between the "Acrilica" and the new table lamp has been made to assess the environmental impact of each lamp and to understand the implications of each design choice on the environment.

Table 2. *LCA Hypothesis*

LCA HYPOTHESIS	Acrilica lamp, new lamp
MATERIALS	Recycled aluminium + PMMA
MANUFACTURING TECHNOLOGIES	CNC bending + thermoforming
MOLD FOR THERMOFORMING	Impact not included
USE OF LAMP(LIGHT SOURCES)	Impact not included
PRODUCT END LIFE	Disposal in landfill

For the LCA, hypothesis aimed to get a strict and reliable analysis has been defined (Table 2). The functional unit has been defined as the "support and shield of the light source", in order to do a focus on the environmental benefit related to the structural re-design, avoiding to overshadow the results with the considerable gap existing between the environmental impact of fluorescent light source (used for the "Acrilica") and LED light source (used for the re-designed lamp). Although the use of LED light represents an eco-friendly design choice for the product life cycle anyways.

Figure 6. *Definition of Life Cycle Stages, GABI Software*



In fact with the use of LED we have a lower consumption of kWh/lm and a higher life time, consequently for the new lamp we have also a slower degradation of the polymer because of the minimal dispersion of heat per lumen. For the LCA ISO14040-ISO14043 standards have been complied, to communicate the data, instead, the CML 2001 method of assessment [2, 5].

At the end of the LCA, using a specific software (Figure 6), we can appreciate that for the new lamp the environmental impact is lower. In particular, for the Global Warming Potential (GWP 100years) it decreases from 388.806 kg CO2 equiv. to 62.859 kg CO2 equiv. (Table 3) and, in general, there is a significant weight reduction for the convector, from 3.755 kg to 2.020 kg.

Summarizing the final product has a higher lighting efficiency with an implementation of illuminated area of 50%, a weight reduction of 46% and a GWP reduction of 84%.

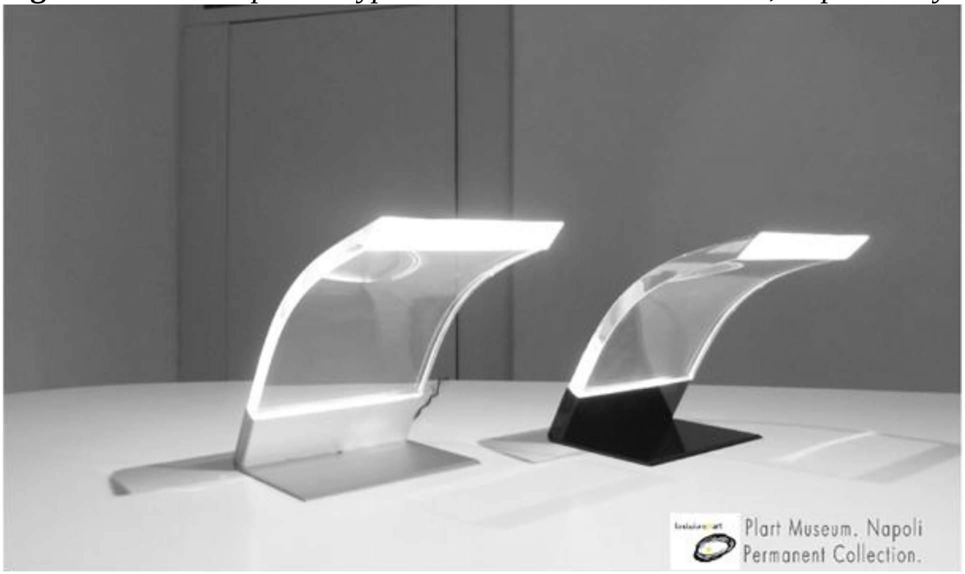
Table 3. *Environmental Impacts of Lamps, CML2001 Method (GABI Software)*

	ACRILICA LAMP	**NEW LAMP**
CML2001, Acidification Potential (AP) [kg SO2-Equiv.]	3.364	0.509
CML2001, Eutrophication Potential (EP) [Kg Phosphate-Equiv.]	0.135	0.025
CML2001, Global Warming Potential (GWP 100 years)[Kg CO2- Equiv.]	388.806	62.809
CML2001, Ozone Layer Depletion Potential (ODP, steady state) [Kg R11-Equiv.]	0.001	2.430
CML2001, Photochem. Ozone Creation Potential (POCP) [Kg Ethene-Equiv.]	0.379	0.056

Concluding Remarks

The research presented is oriented to an approach based on an evolutionary and adaptive design method. This design method is aimed to get an evolutionary stage for the lamp able to survive, taking into account functional, environmental, manufacturing, economic and cultural aspects. The design process is not separated in different phases, but the stages are enclosed in a spiral which turns on itself several times, retracing and stopping at different times on the same aspects. Determining at the end a “holistic” design approach [3] that considers aspects such as “Acrilica” analysis and reverse engineering (shape, part disassembly, study of materials and technologies, physico-chemical analysis of the PMMA convector, identifications of design weak points), innovation and creativity, CAD, virtual simulations of functioning, life cycle assessment, lighting and prototyping technologies [4]. In this way, through the correct use of materials, technologies and integrated design tools, we get a new lamp (Figure 7) with most advanced environmental and functional performance.

Figure 7. *Two Lamp Prototypes Exhibited at Plart Museum, Naples. Italy*



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