In this article, a Pareto multiobjective optimization is performed to design new luminaires. The effort involves finding the optimal forward current, the number of light-emitting diodes (LEDs), and a proper heat sink by taking into account the cost, energy consumption, and environmental impact (carrying out a cradle-to-grave life-cycle analysis). Three commercial white LEDs were studied and modeled in terms of their optical, electrical, thermal, and aging performance. The multiobjective methodology was also applied to other lamps (incandescent, halogen, and fluorescent), which indicated that LED lighting has great potential for energy and cost savings, with minimal long-term environmental impact.

A Promising Technology

In a global context of rising climate change concerns and continuously increasing electricity demand [1], the use of LED solid-state lighting (SSL) with high electricity-to-light conversion efficiency is a promising development. The average efficiency of an LED is around 35%, far better than incandescent lightbulbs and fluorescent lamps (5% and 20%, respectively) [2]. A U.S. Department of Energy (DOE) report [3] studied a 2030 scenario proposing a high LED market penetration. Such a scenario would enable energy savings up to 60% compared to one without LEDs; this corresponds to 395 TWh saved annually (equivalent to the annual electricity consumption of 36 million U.S. homes). The overall environmental impact of LED lamps (e.g., resource consumption and pollution of soil, water, and air) is less than other commercial lighting technologies. The effects of these attributes are presented in studies dealing with life-cycle assessments (LCAs) [4], [5].

LED-based SSL is fully controllable and could offer many innovative functionalities, such as connected lighting applications and visible light communication. For its operation, this type of lighting is supplied by a power converter called an LED driver, which usually works in continuous conduction mode and regulates the current of the luminaire with a single current control loop [6]. Other, more complex, control schemes using additional sensors enable the accurate (spectral composition) and efficient control of LED lamps [7], [8]. This control is crucial for ensuring good performance since the current waveform has photometrical and colorimetrical impacts on the light emission [9]. Some additional practices must be followed to control LED lamps to avoid any potential health risks from flickering [10]–[12].
Despite the numerous benefits of LEDs (e.g., low energy consumption, extralong lifetime, and full controllability) compared to other technologies, their purchase price is still a hurdle to their widespread adoption. In this article, special attention is paid to LED operating conditions. The level of forward current is crucial because it affects the LED junction temperature, which defines the light output and aging behavior [13], [14]. Recent studies have reported the relationships among the photometric, electrical, and thermal aspects of LED systems [14]–[16].

The purpose of this article is to find the best tradeoff between three conflicting objectives: the luminaires’ environmental impact, cost, and energy consumption. First, based on the main results of an earlier study [17], a new LED model is proposed and experimentally validated on three types of white LEDs. To solve this multiobjective optimization problem, a method based on Pareto optimality [18] is developed that enables the comparison of all of the lighting technologies.

Optimization Methodology
This work aims to design a 3,600-lm LED luminaire corresponding to a standard lamp consisting of three fluorescent 1,200-lm tubes of 14 W, which is supposed to operate 3,744 h/year (12 h/day, six days/week, and 52 weeks/year). The key parameters of the design are the number of LEDs, the level of forward current, and the choice of heat sink.

As LEDs do not have exactly the same voltage–current characteristics, their electrical association to create a luminaire can cause some photoelectrothermal troubles. One study [19] has presented different LED associations (single string, series string, and series–parallel string) with a method to achieve current equalization. The work in [20] demonstrated a series–parallel connection of LEDs as the topology that ensures the best performance (in terms of luminous efficacy and uniformity) of an LED luminaire.

In this study, the current supplied per LED is the first parameter optimized. In an iterative and incremental way, the effect of different forward currents (from 0.1 to 700 mA) on different luminaire configurations is simulated. The LED light output and electrothermal behaviors are described in the “LED Light Output” and “Thermal Modeling of an LED” sections to propose a complete LED model depending on the forward current. As presented in Figure 1, this methodology allows the annual cost, energy consumption, and environmental impact of each luminaire configuration to be calculated.

The Pareto method is used to find the best tradeoff among the three objectives mentioned in the section “A Promising Technology.” The nonlinear multiobjective minimization problem between k conflicting objectives and n decision variables can be defined as

\[
\begin{align*}
\text{minimize} & \quad \{f_1(x), \ldots, f_k(x)\} \\
\text{subject to} & \quad x \in S,
\end{align*}
\]

(1)

where \( f_i \) are the objective functions, and \( x \) is a decision vector belonging to a feasible set \( S \subset \mathbb{R}^n \).

In multiobjective optimization, the optimal solution is not unique, and a set of nondominated solutions forms the so-called Pareto front [18], [21]. If two solutions belonging to the Pareto set are considered, one is better than the other on some objectives but also worse on at least one. A solution \( x_P \in S \) is said to be Pareto optimal if another solution does not exist where \( x \in S \), such that

\[
f_i(x) \leq f_i(x_P) \quad \text{for all} \quad i = 1, \ldots, k, \quad \text{and} \quad f_j(x_P) < f_j(x) \quad \text{for at least one index} \quad j.
\]

To help the decision maker choose one optimal solution among others, an ideal point can be set for each Pareto front. The coordinates of this ideal point correspond to the global minimum of the Pareto front on each objective. After normalization of the objectives, the optimal point of the Pareto set is the nearest point to the ideal point, according to its Euclidean distance [21]. To validate the different models described in the following sections, three different types of white LEDs with similar properties were tested. Their main characteristics, as provided by the manufacturers [22]–[24], are presented in Table 1.

LED Light Output
To determine the necessary number of LEDs to obtain the desired luminous flux, the luminous efficacy was assessed with a Keithley 2602 A SourceMeter, an integrating sphere, and a Spectbos 1201 spectrometer in a controlled temperature environment (22 °C). Experimental tests were performed with LEDs soldered on an insulated metal substrate printed circuit board (PCB). For each type of LED, three LEDs were associated in series. All measures were carried out after 40 min to ensure that the LED junction temperature had stabilized. The temperature was estimated based on the measurements of a thermocouple placed as close to the LED as possible. The section “Thermal Modeling of an LED” provides more details about the thermal aspects. The experimental results are shown in Figure 2.

The currents assessed in Figure 2 are 0.1, 1, 5, 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 600, and 700 mA. Because of possible high junction temperatures that could cause irreversible damage, currents above 700 mA were not tested. The forward current has a strong impact on the luminous efficacy, and currents from 5 to 100 mA lead to the best luminous efficacy. For each forward current, the number of LEDs, noted as \( N_{\text{LED}} \), required to achieve a 3,600-lm luminous flux, can be calculated as

\[
N_{\text{LED}} = \frac{F_d}{F_{\text{LED}}} = \frac{F_d}{\epsilon_{\text{LED}} (P_{\text{LED}}) \times P_{\text{LED}}},
\]

(2)

where \( F_d \) and \( F_{\text{LED}} \) are the desired luminous flux of the luminaire and the luminous flux of an LED, respectively,
and $\epsilon_{\text{LED}}(P_{\text{LED}})$ is the luminous efficacy of an LED for a given electrical power, noted as $P_{\text{LED}}$.

In the context of low-consumption electric appliances, the energy utilization of the luminaire must be taken into account. The different configurations are plotted in Figure 3. The configuration corresponding to a supply current of 0.1 mA per LED is not presented because hundreds of thousands of LEDs are necessary to obtain a luminous flux of 3,600 lm.

In Figure 3, the Pareto set is from 10 to 700 mA for the Cree LED, 20 to 700 mA for the Lumileds LED, and 30 to 700 mA for the OSRAM LED. The very low forward currents are not optimal because the energy consumption and the number of LEDs are both higher than other configurations. A minimum forward current value can be set to avoid a too-high number of LEDs (e.g., greater than 250 LEDs per luminaire). In this case, according to our experiments, only currents higher than 50 mA would be considered.

The light output analysis reveals the configurations that minimize both the number of LEDs and energy consumption. Currents from 50 to 700 mA lead to possible optimal configurations. The next section focuses on the influence of the forward current on the LED junction temperature. The junction temperature affects the luminous flux and lifetime of an LED [13]–[16].

**Thermal Modeling of an LED**

As with any P–N junction, the junction temperature of an LED increases when supplied. Many models are available to accurately represent the thermal behavior of an LED, such as the Shockley equation [25], [26]. In this article, a simplified steady-state thermal model is derived from [15]. The different elements of the model are represented in Figure 4(a) and (b). An LED luminaire can be modeled with a simple resistor network to define a static thermal model, as illustrated in Figure 4(c). The junction
temperature is difficult to measure and can be estimated by using a thermocouple placed as close as possible to the LED. The temperature measured by this thermocouple is called the solder point temperature.

Based on the static thermal model in Figure 4(c), the temperature of the solder point can be predicted for each forward current. Thus, if \( N_{\text{LED}} \) LEDs are mounted on the same heat sink, the solder point temperature can be computed using the following relation derived from Fourier’s law of heat conduction:

\[
T_{\text{sp}} = T_a + \left( \frac{1}{N_{\text{LED}}} R_{\text{sp-hs}} + R_{\text{hs-a}} \right) P_{\text{heat}},
\]

(3)

where \( T_{\text{sp}} \) and \( T_a \) are the solder point and the ambient temperature, respectively, in degrees centigrade, and \( N_{\text{LED}} \) is the number of LEDs mounted on the same heat sink. The thermal resistance between the solder point and heat sink and the thermal resistance between the heat sink and ambient temperature in degrees centigrade per watt are \( R_{\text{sp-hs}} \) and \( R_{\text{hs-a}} \), respectively. The amount of input power is converted by the LED as heat \( P_{\text{heat}} \), which is calculated as

\[
P_{\text{heat}} = \eta_{\text{heat}} N_{\text{LED}} V_f I_f,
\]

(4)

where \( \eta_{\text{heat}} \) is the power losses coefficient of an LED. As explained in [27], an average value of 0.85 can be considered. \( V_f \) and \( I_f \) are, respectively, the forward voltage and the forward current (in amperes) of a single LED.

The thermal resistance \( R_{\text{sp-hs}} \) corresponds to the sum of the PCB and thermal grease thermal resistances. These thermal resistances have to be calculated based on their thermal conductivity and their contact area with the LED device. Usually, a thermal resistance \( R_s \) is defined as

\[
R_s = \frac{L}{kA},
\]

(5)

where \( L \) is the thickness of the material \( x \) mm, \( k \) is the conductivity of the material \( x \) W/mK, and \( A \) is the contact area (in square millimeters) between the heating device

---

### Table 1. LEDs’ performance highlights (manufacturers data) [22]–[24]

<table>
<thead>
<tr>
<th></th>
<th>Cree XTEAWT GE5</th>
<th>Lumileds LUXEON Rebel Plus LX18-P140-3</th>
<th>OSRAM OSLON Square SL7N-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing angle (°)</td>
<td>115</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Luminous flux (lm) at 85 °C junction temperature</td>
<td>130 at 350 mA</td>
<td>103 at 350 mA</td>
<td>194 at 700 mA</td>
</tr>
<tr>
<td>Forward voltage (V)</td>
<td>3.4</td>
<td>2.85</td>
<td>2.85</td>
</tr>
<tr>
<td>Maximum junction temperature (°C)</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Maximum thermal resistance junction/solder point (°C/W)</td>
<td>5</td>
<td>9</td>
<td>3.9</td>
</tr>
<tr>
<td>Purchase price (€)</td>
<td>1.36</td>
<td>1.36</td>
<td>2.38</td>
</tr>
</tbody>
</table>

---

**FIGURE 2.** The luminous efficacy versus power for the three tested LEDs.

**FIGURE 3.** The number of LEDs versus the power supplied to the luminaire.
and the material $x$, corresponding to the gray areas depicted in Figure 4(b).

To evaluate the LED devices’ thermal behavior, a very accurate power supply (a Biologic BCS-815 battery cycler) and an ESPEC SU-221 temperature chamber were used. As previously mentioned, three strings of three different LEDs were assessed. A heat sink with a thermal resistance of 1.2 K/W was selected, and a silicone thermal grease with a conductivity of 0.9 W/mK was used to increase the thermal conduction between the PCB and the heat sink. The LED strings were powered separately in a controlled environment of 25 °C, with 30-min current pulses from 50 to 700 mA by 50 mA. Rests of 30 min were allowed between two pulses. A very low dispersion between LEDs from the same manufacturer is noted. Figure 5 illustrates the voltage across each LED.

The temperature at the solder point can be predicted with the previous voltage measurements and a good estimate of $R_{sp-hs}$ by using (3). Note that a small voltage drop occurs across a heating LED, a phenomenon that can be neglected if the LED junction temperature is lower than 80 °C.

The experimental and modeled evolutions of the solder point temperature are illustrated in Figure 6. Only one temperature was plotted for the Cree and Lumileds LEDs because they had exactly the same temperature during the experiments. The temperature of the OSRAM LED is very low compared to the others. To have a model that fits well with the data, an abnormal, very low $\eta_{heat} (\eta_{heat} = 0.45)$ was computed.

To evaluate the LED junction temperature, the relationship between the junction temperature and the LED solder point is defined as

$$T_j = T_{sp} + \frac{1}{N_{LED} \times R_{sp-sp}} P_{heat},$$

where $T_j$ is the junction temperature of the LED in degrees centigrade, and $R_{sp-sp}$ is the thermal resistance of the LED between the junction and solder point in degrees centigrade per watt. According to Figure 3, the luminaire needs to be powered between 20 and 60 W, so large heat sinks with a thermal resistance of 0.4, 1.2, and 2 K/W were selected to dissipate the generated heat. Figure 7 estimates the junction temperature for the different heat sinks.

The LED thermal management is crucial. According to our experiments, the drop in luminous flux due to the temperature rise can be limited to 10% if the junction temperature remains below 80 °C. In this case, the drop in luminous flux can be ignored because it is not visible to the human eye [28]. Figure 7 shows that several configurations with the 2-K/W and the 1.2-K/W heat sinks must be removed because the junction temperature is too high.

**LED Aging Model**

The study of LED aging, also called *lumen maintenance*, focuses on lumen depreciation. The lifetime of an LED is defined by the number of operating hours before the luminous flux decreases below 70% of its initial value. This lifetime is often designated $L_{70}$. According to the
Illuminating Engineering Society of North America, the TM-21 standard provides a method to assess the lumen maintenance of LEDs.

A simplified LED-lifetime model was computed based on [28], as illustrated in Figure 8. The model assumes that the aging of an LED is related to the junction temperature and the forward current. The lifetime is shorter for warmer junction temperatures. This simplified model considers that currents below 350 mA exhibit 350-ma behavior, whereas higher currents will follow the 700-ma aging model.

The number of years of LED operation can be estimated for different junction temperatures and forward currents:

\[
T_{\text{LED}} = \frac{\text{Lifetime}(T, I)}{I_{\text{op.year}}}. \tag{7}
\]

where \(\text{Lifetime}(T, I)\) is the maximum number of operating hours for a given junction temperature and forward current, as described in Figure 8, and \(I_{\text{op.year}}\) is the number of operating hours per year. Now that LED luminous, thermal, and aging behaviors have been discussed, the luminaire cost model and life-cycle analysis needs to be developed.

**LED Luminaire Cost Analysis and LCA**

This study determines the energy consumption and the cost of the luminaire separately, so no assumption on the price of electricity is made, which is arbitrary and varies from one area to another and throughout the year. As this method compares different LED luminaire configurations that need roughly the same supplied power, the cost of LED drivers is assumed to be identical, and, consequently, it will not be considered in this analysis. No maintenance cost is needed as the LED luminaire will be replaced according to its L70 lifetime. The annual cost (euros per year) of the luminaire can be defined as in [29]:

\[
C_{\text{year.lighting}} = C_{\text{purchase}} \times \text{CRF}, \tag{8}
\]

where \(C_{\text{purchase}}\) (in euros) is the initial capital cost (purchase price) of the luminaire, corresponding to the cost of the LEDs and heat sink, and

\[
C_{\text{purchase}} = N_{\text{LED}} \times (C_{\text{LED}} + C_{\text{heat sink}}), \tag{9}
\]
where \( C_{\text{LED}} \) is the price (in euros) of a single LED (see Table 1), and \( C_{\text{heatsink}} \) is the additional cost per LED of 0.6 €, 0.35 €, and 0.2 €, respectively, corresponding to the 0.4-, 1.2-, and 2-K/W heat sinks.

The capital recovery factor (CRF) enables the calculation of the equivalent uniform annual worth over the lifetime of the luminaire \( n_{\text{life}} \) in years, with a given initial capital cost and an interest rate \( i \) (this study considered 5%). It is defined as in \([29]\), \([30]\)

\[
\text{CRF} = \frac{i(1+i)^{n_{\text{life}}}}{(1+i)^{n_{\text{life}}}-1}. \quad (10)
\]

The annual energy consumption of the lamp is

\[
E_{\text{year,lighting}} = T_{\text{op,year}} P_{\text{Lum}}. \quad (11)
\]

As illustrated in Figure 9, one Pareto front per LED type (solid line) is obtained. For the Cree and OSRAM components, each heat sink leads to an optimal configuration for a given range of power. When the power supplied to the luminaire increases, more expensive and highly dissipative heat sinks are optimal. For Lumileds LEDs, the lowest dissipative heat sink does not lead to an optimal configuration because of its high junction-to-solder-point thermal resistance.

In Figure 9, all of the configurations leading to a junction temperature higher than 80 °C were removed. For each type of LED, the optimal configuration is the solution that minimizes its distance to the ideal point, as illustrated in Figure 1 and explained in \([21]\). The optimal configurations are 42 Cree LEDs at 200 mA, 57 Lumileds at 200 mA, and 45 OSRAM LEDs at 250 mA. A 2-K/W heat sink is sufficient for OSRAM devices, whereas one of 1.2 K/W is needed for Cree and Lumileds equipment.

The last objective to minimize is the LCA, which is often used to quantify the environmental impact of industrial devices. To equitably compare lighting devices, a functional unit has to be set. The most relevant one is the quantity of luminous flux over a given time, expressed in megalumen hours \([4]\), \([5]\), \([31]\). In this article, the functional unit is the annual lighting service of a 3,600-lm luminaire that is assumed to operate 3,744 h/year; so the functional unit is close to 13.5 Mlm·h. The results of the LCA are given in terms of primary energy consumption and expressed in megajoules per functional unit.

Four main stages were studied to calculate the energy consumed over the entire life of the products.

- **Manufacturing stage**: Because of the many confidential industrial processes, the calculation of this LCA stage is uncertain and includes numerous assumptions. Following the method in \([5]\) for LED lamps, it appears that this stage can represent a large part of the total LCA, as illustrated in Figure 10.

- **Transportation stage**: This stage can be ignored in this study because it represents less than 1% of the total LCA \([5]\).

- **Use stage**: As explained in \([4]\), \([5]\), and \([31]\), the environmental impact of any type of lamp is due to the energy consumed in using it. In this calculation, the lumen output depreciation of LED devices, a nonlinear phenomenon, has not been considered \([32]\).
energy consumption (in megajoules per functional unit) of the use stage is given by [5]

\[ E_{LCA} = \frac{3.6}{1,000} \times P_{LED} \times \text{Lifetime}(T_{LED}, I_f) \times C_{\text{mix}} \times N_{\text{equ}}, \]  

(12)

where \( C_{\text{mix}} \) is the secondary-to-primary energy conversion factor, based on the electricity production mix. In this study, \( C_{\text{mix}} = 2.45 \), corresponding to the European Union’s 2010 electricity production [5]. This factor is extremely important for assessing the real environmental impact of the use stage. \( N_{\text{equ}} \) is the number of equivalent LEDs satisfying both the luminous flux and lifetime requirements to obtain the desired luminaire

\[ N_{\text{equ}} = \frac{F_a \times t_d}{P_{LED} \times \text{Lifetime}(T_{LED}, I_f)}, \]  

(13)

where \( t_d \) is the desired number of lighting hours. In this article, \( t_d \equiv T_{\text{op.year}} \), because the LCA is assessed for one year of service. According to (2) and (12), a linear relation between the energy of the LCA use stage and the annual consumption of the luminaire can be written as

\[ E_{LCA} = \frac{3.6}{1,000} \times C_{\text{mix}} \times t_d \times P_{\text{lum}}. \]  

(14)

When fewer than 100 LEDs are needed to make a luminaire, the LCA use stage is the main consuming stage of LED life, as shown in Figure 10.

- **End-of-life stage**: Waste management is a major issue, especially when toxic materials are involved. Principi and Fioretti have assessed three scenarios [4]: complete recycling, landfill disposal, and incinerator disposal. The energy consumed during the end-of-life stage represents only up to 3% of the entire LCA, and the difference between the three approaches accounts for less than 1%. This shows that recycling is the most efficient method [4], [31].

The transportation and end-of-life stages have been ignored because of their low impact on the final results. The results of the LCA study are represented in Figure 10. The minimum primary energy consumption is obtained for a current per LED around 200 mA. By taking into account the manufacturing stage, the energy consumption of the configurations that need a large number of LEDs increases significantly. The results given in Figure 10 are similar to the predictions in [5] about LED technology from 2015. The LCA for LED devices is quite difficult to manage because of the fast development of this technology in comparison with conventional lamps. These advances involve changes in manufacturing processes and rising performance (in luminous efficacy and CRI) that strongly affect the final LCA results.

In Figure 11, the three Pareto fronts are represented. For each forward current value, the different heat sinks do not influence either the energy consumption of the luminaire (assuming that the power does not change when the junction temperature increases until 80 °C) or the different LCA (the LCA is assumed to be the same for the three heat sinks). In this case, for each LED, the Pareto front is not a surface but a line. Thus, the nondominated solutions are the ones previously described in Figure 9. When the LCA is taken into account (especially the manufacturing stage), the configurations involving a high number of LEDs and a low annual energy consumption are far from the ideal point.

According to Figure 11, the optimal configurations for the Cree and OSRAM LEDs are those presented in Figure 9. But for Lumileds LEDs, taking the LCA into account shifts the optimal configuration to a higher forward current (250 mA instead of 200 mA) and a lower number of LEDs (47 instead of 57).

The LED optimal configurations are subject to annual cost, annual energy consumption, and LCA (see Figure 11). In the next section, comparative study with conventional lighting—the halogen lamp, incandescent lamp, and compact fluorescent lamp (CFL)—will be carried out.

![Figure 10: The LCA manufacturing and use stages for different LED configurations.](image-url)
Comparison with Conventional Lamp Technologies

Table 2 lists data gathered from a report of the U.S. DOE [32] corresponding to A19 conventional light bulbs. Ballast cost will not be considered, as it is assumed that the different ballasts and LED drivers have the same price. In Figure 12, the optimal configurations obtained in the previous section are compared to the commercial lamps described in Table 2. As stated in the “Optimization Methodology” section, the results are given for a luminaire operating 3,744 h/year (12 h/day, 312 days/year).

Because of their high luminous efficacy, LED lamps and CFLs both have a low annual energy consumption and low energy needs throughout their life (LCA). Today, CFLs are the least expensive devices, but if a cost of 0.1 €/kWh is considered, the energy consumption gap between LEDs and CFLs is sufficient to make LED lamps the most economic lighting technology (considering both purchase and energy consumption costs). The same analysis can be performed on halogen lamps, which are nearly three times less expensive than LED lamps but consume more than three times the energy. Incandescent lamps are, by far, the least-effective lighting technology.

Models of LED driver failure and optical components degradation, which may reduce the L70 lifetime [32], must be introduced to fairly compare all of the lighting technologies. In addition, assessments of LED lumen depreciation under standardized operating conditions should also be analyzed more thoroughly to describe LEDs in real-life environments.

Conclusions

In this article, a new methodology to find the optimal design of a luminaire was proposed. The forward current, number of LEDs, and heat sink were selected to minimize purchase cost, energy consumption, and the ecological footprint. This method takes into account the luminous output, thermal management, lifetime prediction,
purchase cost, and LCA. For the three selected LEDs, the optimal forward currents are between 200 and 250 mA. The use of LCA reveals the significant energy consumption related to the manufacturing stage. A comparison with other lighting technologies shows that LED lights exhibit better performance than CFL, halogen, and incandescent lamps in terms of energy consumption and LCA. The overall cost based on purchase price and annual energy consumption is also optimal for LED devices.

Because of the modularity of this methodology, the LED models used in this article can be improved or adapted to any type of lamp. Other models can be added to improve the relevance of this analysis in terms of the reliability of the LED configuration (string, series string, and series-parallel string modules), the failure distribution of LED drivers, and LED lumen depreciation.

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