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One of the challenging environmental issues faced by the electr(on)ic industry is the development of energy efficient products during their use. Indeed, regulations, standards, and consumers have always growing expectations on this aspect. Nevertheless, tools to support design for energy efficiency in use are scarce and do not always give an appropriate answer to the challenge. This paper presents a new methodology based on the calculation of an indicator that enables a design team to drive energy efficiency more effectively during the design process. The indicator combines the power of components with time spent by these components to do their jobs, in order to lead to energy consumption estimation. When used for design purposes, the method can provide the team with a relevant analysis of the energetic performances of the product, including modes, jobs and scenarios variations. This analysis can lead to product's hot spots and eventually to design strategies. A case study on an existing electr(on)ic equipment is proposed for illustration purposes.

Keywords: Energy efficiency; energy consumption; electric and electronic equipment; ecodesign; indicator; use phase.

1) Introduction

Energy is a growing concern for both manufacturers and the whole society. The scarcity of fuels and the contamination due to the transformation of these fuels into energy are the main issues. These can be addressed not only by switching to cleaner energy but also by reducing the pressure on energy demand (European Commission 2009).

To fulfil the objective of decreasing demand, some institutions established energy savings programmes based on the principle of energy efficiency (Calwell 2010). To achieve energy efficiency, the effort must be supported by each sector (European Commission 2006): the industry (Rahimifard *et al.* 2010), the transportation sector, but also the tertiary and the residential sectors. For the latter, an important measure is to develop and market efficient energy-using products, promoted by standards and regulations. The Energy Star program aims at labelling the most efficient products by defining protocols and thresholds for efficiency measurements (US EPA 2008). The Energy-Related Product (ErP) EU directive is the European initiative to implement best practices in energy saving of products, thus influencing the behaviours of households and industries (European Commission 2009). The European Commission assessed the potential savings from the implementation of the ErP directive, for the first nine product categories chosen in 2007, to be 12% of EU 25 electrical consumption, thus saving up to 341 TWh (European Commission 2009). The shift in 2009 from the Energy-Using Product (European Commission 2005) to the Energy-Related Product shows that energy-saving needs to be implemented for every product related to energy (e.g. windows), not only equipment directly consuming energy.

The electr(on)ic industry has been facing environmental challenges for the last two decades. End-of-life collection and recoverability (European Commission 2003b) and limitation of the use of toxic substances (European Commission 2003a) were the main topics of the environmental policies for the sector. The industry developed many design-related responses to these challenges, such as Design for Recycling and Design for Substance Management. The emerging problem of energy consumption may also be addressed during the design of products. Designers indeed agree that the energy consumption during use can be drastically reduced (Alting 1995). For the particular case of mobile devices (e.g. mobile phones), design teams have already drastically improved the energy efficiency of products: by interfacing functional needs to energy supply, mobile devices have become increasingly more self-sufficient thanks to adequate components selection and software design. This has been achieved during design because energy autonomy of mobile devices is a key functional need for this type of product.

Although efficient electr(on)ics are essential and desired to achieve large energy savings and reduce environmental concerns, most non mobile products on the market show poor efficiency combined with a high potential for energy savings (Sauer *et al.* 2002).Products, such as electric motors or television sets, can be cited (European Commission 2010). This contradiction can be explained by the lack of incentives like customer needs or regulations. This also can be explained by the absence of comprehensive methods to design energy efficient products. Our research objective is to develop a method to support the design of products that are energy-efficient during their use phase.

This paper introduces a new methodology and the associated indicator to simulate the energy consumption of a product in its use phase while the product is still under development. This "in-use energy consumption" indicator (IUE) provides a mapping of energy behaviour of the future product and helps identifying potential and significant improvements of current product design. In the first section of this paper, a review of the literature on ecodesign and product energy efficiency is presented. In a second part, a new indicator of energy consumption in use is introduced. The next section aims at illustrating the use of the indicator during the design of a product through a case study. Finally, conclusions and perspectives are given.

2) Literature review

2.1) Design potentialities to improve the environmental properties of a product

In the last decade, environmental concerns have guided many developments of new Design for Environment (DfE) tools and methods to support the design process. The ban of hazardous substances in products and their recovery at their end of life have been the main environmental aspects addressed (Gehin *et al.* 2008). It is proven that most of the environmental performances are widely influenced by decisions made while designing (Brezet 1998). The purpose of DfE methods is to relate external consequences (environmental impacts) to internal decisions (design choices) in order to decrease the former, while making the later appropriate. Legislation strongly encourages industrial practices in this direction.

Many of these tools are based on a design for X approach (X being Disassembly, Environment, Cost reduction, etc.). Design for X is usually a two-step methodology (Huang and Mak 1998). First of all, the current design should be quantitatively assessed using indicators. Then, the second step aims at supporting the modifications of the current design toward a better one. In a DfE approach, it is of critical importance to link the environmental impact indicators to the design parameters in order to challenge the designers to create greener products (Lofthouse 2006; Vezzoli and Sciama 2006). Most of the time, the proposed tools are guidelines, best practices, or procedures that guide designers by highlighting hot spots and, where possible, the design parameters associated with them.

To highlight hot spots, designers need quantitative evaluations. Indicators are a constant characteristic of DfX, including DfE (Huang and Mak 1998). Indicators are used to evaluate the situation under development according to a specific topic. They give a value of how far from the desired situation the product design is. They can take many forms: recyclability indicator of a product as a percentage of the product's weight (Mathieux *et al.* 2008), assessment of the quantity of contained hazardous substances (Lemagnen *et al*. 2009), contribution to global warming in kg of eq.CO_2 (Solomon et al. 2007), are a few examples.

Relating designer's activities and the potential environmental impact of their decision is very difficult and can explain the failure of a lot of DfE tools (Lindahl 2006). Product designers need to have access to the information about the design parameters that contribute the most to the indicator. For example, they need to relate the recycling potential of the product to the materials contained and the assembly techniques that are both specific design choices that impact the end of life performance of the product (Mathieux *et al.* 2008). Energy consumption of products is still related to design parameters: electr(on)ic product designers indeed need to know which component in their product needs energy and which design parameter influences it.

Energy efficiency is considered in some DfE tools. In the "Ten golden rules" for example, Luttropp and Lagerstedt (2006) propose the following guideline for energy: "*Minimize energy and resource consumption in the usage phase*". The same type of advice can be found in other DfE tools (Lofthouse 2006, Van Der Horst and Zweers 1994). Yet, this kind of advice, although useful for non-experts, does not efficiently support design decisions as it is only qualitative and not associated with design parameters. Recent DfEE –Design for Energy Efficiency- guidelines however overcome the latter limitations, as they give more accurate advice associated to design parameters (e.g. modes, components, etc.) relevant for various members of the design team (e.g. hardware, software, mechanical designers) (Bonvoisin *et al.* 2010). The quantitative evaluation of DfE tools is often based on environmental assessment. One of the most popular tools for environmental assessment is Life Cycle Assessment-LCA (International Standard Association 2006). Simplified LCA can provide designers with information on environmental impacts of their product design. Nonetheless, the usability of such results in design activities depends on the level of detail of input data: if energy consumption in use phase is defined as a global value in kWh, simplified LCA only provides information on the environmental impacts of

such consumption but will not highlight the product design parameters that are responsible for that.
It can be concluded that new quantitative methods of assessing energy consumption during design need to be proposed to enhance ecodesign.

2.2) Energy consumption of products during their use phase

Energy consumption has only recently been considered as a critical property of a product, property that should be monitored. Until recently, the main electric property of the electr(on)ic products was the power used to operate the system. Recent versions of standards (e.g. Energy Star (US EPA 2008)) and legislations (ErP (European Commission 2009)) focus on energy consumption as a driver for product performance. Their strategies on energy efficiency are based on two notions: restraining installed power and implementing low power modes.
Focusing on its physical definition, energy (E) is the integration of all the instantaneous power (p(t)) along the lifetime of the product (Eq. 1).

$$E = \int_t p(t)dt \qquad (1)$$

Both power and time approaches are analysed in the next sections.

2.2.1) Model of power

The value of the product power can be found using two different means: measurements based on protocols and estimations based on component and material power behaviours.
To ensure conformity with legislations and labels, products ready to be launched on the market can be tested to qualify their power (European Commission 2008b; US EPA 2008; US EPA 2009). Authors such as Bush *et al.* (2009) and Meier (1995) also used protocols for analysing the energy efficiency of coffee machines and refrigerators based on standards from several institutions (e.g. from US Department of Energy, DOE (U.S. Department of Energy 1988), International Standard Organisation, ISO, (International Standard Association 1991), Japanese International Standard Committee, JISC, (Japan Standards Association, 1986) or Swiss Agency for Efficient Energy Use, SAFE, (Bush *et al*. 2009)). Similarly, many life cycle assessments of products (for example (Kim *et al*. 2001; Moberg *et al.* 2010)) use industrial data based on direct measurements on real products.
For modelling and prospective purposes during design, electronic component characteristics are used to calculate power (Li e*t al*. 2008; Violette *et al*. 2000). Models of material, mechanic and electronic behaviours of product components can also be used (Debusschere *et al.* 2007).
Those two approaches of power valuation are actually complementary: estimation by models is possible as soon as the components and/or materials of the products are defined, but only if the elementary models already exist. Although measurements require a physical product or prototype to be operated, measurement usually gives more accurate and realistic information than models.

2.2.2) Model of time

The simplest approach to time is to average all instantaneous power in a single value, considered to be a mean value during the entire product life. This approach was used by Li *et al*. (2008) to define the energy factor for the use phase of a product. Energy in the use phase, Eq. (2), was defined as “the mean of the minimum and the maximum power consumptions" (W_{mean}) multiplied by the predicted lifespan based on a Weibull distribution:

$$Energy(Use) = W_{mean} * Lifespan \quad (2)$$

It was also used by the DOE standard (Meier 1995) for measuring the energy consumption of refrigerators, assuming that the average operating conditions could be summarized by the case of an empty fridge with door closed operating with an external temperature of 32 °C. Finally, the consumption per year was the average power used 24 hours a day 365 days a year.

This first approach was enriched defining two time periods: the product being operated and the product not doing anything. For this purpose, operating hours had to be defined, as well as their associated operating power. The rest of the time, the instant power of the product was null. This approach was used for example by the OECD (Violette *et al.* 2000) for lighting and motors and by Debusschere *et al.* (2007) for an electrical transformer. (Violette *et al.* 2000) aimed at defining a method for evaluating the greenhouse emissions related to operation of lights and motors in order to build a framework for energy efficiency policies. Eq. (3) summarises their definition of energy consumption:

$$Energy(Use) = Quantity * Power * OperatingHours * DiversityFactor \quad (3)$$

Where:
Quantity is the number of units consuming energy;
Power is the average power for the type of products;
Operating hours is the time spent in operation;
Diversity factor reflects possible geometrical variations among the same product types due to manufacturing.
Debusschere *et al.* (2007) also used two different life periods. The intrinsic energy consumption of an industrial electrical transformer is power losses during the time that the transformer operates (24 hours a day, 5 days a week, during 10 months over 12 years). The rest of the time, the transformer has no losses so it does not consume anything.

This time model was further specified. The product use phase was pictured as a chain of different time periods, called modes. Classically, two modes have been defined: the *On* mode when the task is performed and the *Off* mode when it is not. A third mode appeared in recent years: the *Stand-by* mode, where the product seems to be off (not operating) but is still performing internal tasks not visible for the user. Kim *et al.* (2001) defined three modes for computer monitors: 4 hours per day in the on mode, 4h per day in the energy saving mode (similar to the stand-by mode), the rest of the time in the off mode, each of them with its own associated power consumption (P_{on}; $P_{standby}$; P_{off}). Moberg *et al.* (2010) used three modes for the evaluation of an e-paper reader over 1 year of use: 30 minutes per day reading newspapers (on mode), 30 minutes per day for other usage (setting, downloading papers, reading e-books…- stand-by mode) and the rest of the time in the off mode. Similarly, in order to define the "best-in-class" product for espresso coffee machines, the "top ten" initiative (Bush *et al.* 2009) defined the maximum power for three different time periods: the ready mode (ie. on mode), the sleep mode (ie. stand by) and the auto-power off mode (the product switches itself off after a certain time period of no coffee-making). Energy star (US EPA 2009) used the same approach for its standard for energy efficient displays: the power level cannot be higher than a specific level defined for each of the three time periods: on, sleep and off. Some authors defined more than three modes.

For example, the on mode was separated for imaging equipments like printers (US EPA 2008) as print and communication modes, the first one covering the state during which the printer uses its mechanical part (important power needs), and the second one covering the set-up periods (product in communication with the user for parameterisation, checking of cartridge levels…) needing less power inputs.

A synthesis of all these approaches is presented in the report of the preparatory study for EuP measures on "Stand by and Off modes losses" (Nissen 2007) presenting a complementary point of view. They defined what they called "product use clusters" based on the modes available on each product. Four clusters were defined:

- PUC 0: "Always On" products. Products performing a task as soon as they are plugged in.
- PUC 1: "On/Off" products. Products, close to the first category, but with a physical off-switch, meaning that the products can be plugged but are unable to perform a task.
- PUC 2: "On/Stand by" or "On/Network stand by" products. Products having three different behaviours when they are plugged in: performing the task, keeping the product ready for performing the task on demand and unable to perform the task.
- PUC 3: "Job Based" products. Products similar to the PUC 2, except that performing the task can be separated into several "jobs" performed during a duty cycle.

Table 1 classifies the different methods to classify energy consumption from the literature presented above into the four clusters.

Table 1: PUC classification (Nissen 2007), modes and energy consumption measurement methods

Definition of Nissen (2007)	Number of modes	Energy consumption measurement methods
Always On (PUC 0)	1	(Li *et al.* 2008; Meier 1995)
On/Off (PUC 1)	2	(Debusschere *et al.* 2007; Violette *et al.* 2000)
On/ Stand by (PUC 2)	3	(Bush *et al.* 2009, Kim *et al.* 2001, Moberg *et al.* 2010, European Commission 2008a, US EPA 2009)
On/ Network Stand by (PUC 2 net)		
Job based (PUC 3)	≥ 4	(US EPA 2008)

To conclude, we can say that the most promising method to measure the energy consumption of products is the one proposed by the US EPA (US EPA 2008): the concept of the “job” is indeed a central concept that should be further developed in order to measure the energy consumption of every electr(on)ic product. The other approaches interesting for their simplicity (a single value of power during a mode) but are not explicit enough to be relevant for complex products. As an example, Mukherjee *et al.* (2007) showed that the power consumption of a datacenter depends on the CPU load, which depends on the job performed by the product.

2.3) Estimating energy consumption during design

The approaches for evaluating energy consumption were generally developed to be used as soon as the product is put on the market, i.e. at the end of design process. Only Debusschere *et al.* (2007) and Li *et al.* (2008) proposed an evaluation for the design stage when the product is still virtual. Debusschere *et al.* (2007) proposed an exhaustive description of all the design parameters that influence the power consumption of an electrical transformer. With this list of parameters, an optimised solution can be proposed, that combines the parameters based on their relative influences and on balanced tradeoffs in terms of energy efficiency. However, this model is only applicable to a given technology, in this case electric transformers.
It has been established that the product power is a function of components: Li *et al.* (2008) proposed that this function be the sum of each component’s power. However, the situation where all the components are powered-up at the same time (this can be translated as the sum of component’s power) is not always true for most electronic products: in a lot of cases, the product power is a combination, evolving through time, of its components’ individual power. The power definition proposed by Li *et al.* (2008) was a black box in which seeking for design improvements seemed difficult. A good understanding of why power is measured, is necessary to introduce energy efficiency as a systematic target for electr(on)ic product design.
The use of those methods in design activities was limited because they applied to few products or because the definition of power seems too rough to make sense to a designer.

2.4) Conclusion of literature review

This literature review highlighted the key issues for the development of a design indicator for energy efficiency in use.
Firstly, the indicator should be used during and for design activities. Designers making choices should be able to easily identify what has an influence on efficiency during the use of the product. An indicator should make a link between present design choices and future consequences such as energy consumption.
Secondly, energy is a matter of power and time. Defining an energy consumption indicator is about finding the right definition of product’s power and time periods. A promising approach to power is based on the inherent properties of the components. A promising approach to time is based on the job that the product performs.

3) In-Use Energy Consumption Indicator

It is considered in this paper that a product has two dimensions: a physical one as a tangible dimension and a functional one as a use valuation. The first one relates to power: physical parameters determine the power behaviour of a product. The second one relates to time: usage patterns will determine the lifetime pattern for a product.

The following sections introduce the In-Use Energy (IUE) indicator by presenting the combination of its power and time dimensions.

3.1) Installed and implemented powers

An electr(on)ic product is an assembly of components with their own physical characteristics. At the component level, the basic contributor to power is what we define as the installed power. The installed power is the power available for each component of the product. This power results from the inherent characteristics of the mechanical or electrical component and, most of the time, is provided for each of them by the component manufacturer in its datasheet. It is a fixed value resulting from the component choice made by the designer, and will remain on the same level over the life time of the product. It is not possible to modify, to adapt, or to limit the installed power after the component is manufactured.

We defined a component as any physical part that can be considered as a power scalable unit of a product. The level of details used to specify the number of components depends on the project goals for energy efficiency: the more detailed the specification, the smaller the identifiable energy inefficiency. For example, the following elements can all be considered as components from a micro/macro point of view: capacitor/power supply, microprocessor/motherboard, stator/motor, blade/fan.

The estimation of the installed power depends on the type of components under study. Eq. (4) and (5) give the definition of the installed power for electronic and for rotating components respectively.

$$P(i)_{install} = \vec{I}(i) * \vec{U}(i) * Eff(i) \qquad (4)$$

Where:

$P(i)_{install}$: Installed power of i component (in W);

$\vec{I}(i)$: Current entering the component (in A);

$\vec{U}(i)$: Voltage across the component (in V);

Eff(i): Electric yield (in %).

$$P(i')_{install} = \vec{C}(i') * \vec{\Omega}(i') * \eta(i') \qquad (5)$$

Where:

$P(i')_{install}$: Component i' installed power (in W);

$\vec{C}(i')$: Torque (in N.m);

$\vec{\Omega}(i')$: Revolution speed (in rad/s);

$\eta(i')$: Mechanical yield (in %).

Defining installed power at the product level as the sum of the power of all the components installed does not make sense. As argued in Section 2.3, summing all the installed powers gives information about the highest power level that the product can achieve while in a product, all the components are rarely used at the same time at their highest power level.

Even if the installed power cannot vary, Mukherjee *et al.* (2007) showed that a single component's power may vary depending on the job it performs. We call implemented power, the power that is needed by the component to perform a specific job. It is defined as a load coefficient by the installed power. This factor depends on the job to be done by the component and is defined by the software code implemented to manage the component. Practically, software manages opening, closing and the intensity of the input current of the component depending on the jobs that it have to be performed. The implemented power is defined in Eq(6).

$$P(i,j)_{imp} = P(i)_{install} * \tau(i,j) \quad (6)$$

Where
$P(i,j)_{imp}$: Implemented power of the component i for the job j (in W);
$P(i)_{install}$: Installed power of the component i (in W);
τ (i,j): Load coefficient of component i to realise job j (in %).

At an instant, t, performing a job, j, the product power is the sum of all the N_i components implemented powers, as stated in Eq. (7):

$$P(product, j)_{imp} = \sum_{i=1}^{N_i} \left[P(i)_{install} * \tau(i,j) \right] \quad (7)$$

3.2) Lifetimes of a product

Implemented power depends on the job to be done. US EPA (2008) defines the product lifetime as being a cyclic execution of jobs over its lifetime. A job starts when a user asks for a specific task to be realized by the product and ends when this task is fulfilled. Hence, the lifetime of a product can be seen as a combination of jobs.

We define a job as any actions that the product can realize in order to answer user's needs. Job definition can be based for example on value engineering (AFNOR 2007). As in the definition of a component, the finer the definition of the job, the smaller the energy inefficiency can be tracked down. For example, for printing equipment, the following action can be considered as a job from a macroscopic point of view: Printing. From a microscopic point of view, Printing can be detailed into the following jobs: ink deposition, paper rolling, cleaning cartridge, and moving paper trays.

One job can be realized several times during the product lifetime. We define $t_{job(j)}$ as the sum of all the time periods spent by the product performing the job j. We define $t_{mode(g)}$ as the sum of all the time periods spent by the product in this specific mode. Figure 1 is a representation of a product lifetime $t_{lifetime}$ and the sequencing of N_m modes and the N_j jobs over it.

Figure 1: Repartition of modes and jobs over product lifetime

Because modes occur one after another, their time units are the only time units that can be used to define the product lifetime as a sequence, as in Eq. (8). However, with our definition of jobs, no general sequential definition of the lifetime can be formalized.

$$t_{life} = \sum_{g=1}^{N_g} t_{\mathrm{mod}e(g)} \quad (8)$$

Nevertheless, we can define the lifetime in a non sequential way by saying that a product lifetime is a combination of jobs than can be performed simultaneously (for example, job(1) and job(j) at t_A in Figure 1) or sequentially (for example, job(Nj) occurring when Job(j) and Job(2) end at t_B in Figure 1).

Practically, the lifetime of the product depends on its end use. Every user will impact t_{job}, by choosing the order of the different job sequences and how long the jobs last: they will define specific use scenarios. Every product put on the market has unique energetic performances because of its own specific usage. The k user has characteristics that influence lifetime qualification of the use scenario.

We define the job duration as the time lapse between the start and the end of the job. This lag is a function of the combination of 1 to m component solicitation times to perform the j job, illustrated in Figure 2.

Figure 2: j job duration as a combination of the contribution of components 1 to m
Where
$t_{comp(i,j)}$: Time needed by the i component to perform the j job.

For the example of a printer, if j is defined as the job Print, C1 as the screen, C2 as the printhead, Ci as the driver and Cm as the paper tray, the duration of printing is the combination of the time needed by the screen, the printhead, the driver and the paper tray to realise the entire task.

We define a use scenario as a set of values $t_{comp(i,j)}$ (k) for the t_{life}(k) representing a specific use of the product. The number of defined use scenarios depends on the data available to represent the use clusters.

Defining use characteristics is not a classical task for engineering designers. Nevertheless, methods exist to refine users' profiles: marketing potential target definition, monitoring the existing user's behaviour, use-based questionnaires or interviews (Elias *et al.* 2008, Mont and Plepys 2003). The data must be processed to cluster the different users with a limited number of use scenarios. Based on these selected scenarios, specific lifetimes can be defined. Practically, it is claimed that the designers should address more than one use scenario when designing an electr(on)ic product where the use phase is certainly a large contributor to energy consumption. The purpose of the definition of scenarios is not to give a perfect representation of the future attitude of users toward the product but to flag the scope of their attitudes towards the product in order to design the most energy-efficient product that is robust to variations in use.

3.3) IUE Indicator

The IUE (In-Use Energy Consumption) indicator of a product aims at combining all the relevant parameters described in Sections 3.1 and 3.2. The IUE indicator vector is expressed in Eq. (9) for a product of N_i components, N_j jobs and N_k use scenarios.

$$IUE = \begin{pmatrix} IUE(1) = \sum_{j=1}^{N_j}\sum_{i=1}^{N_i} P(i) * \tau(i,j) * t_{comp(i,j)}(1) \\ \dots \\ IUE(k) = \sum_{j=1}^{N_j}\sum_{i=1}^{N_i} P(i) * \tau(i,j) * t_{comp(i,j)}(k) \\ \dots \\ IUE(N_k) = \sum_{j=1}^{N_j}\sum_{i=1}^{N_i} P(i) * \tau(i,j) * t_{comp(i,j)}(N_k) \end{pmatrix} \quad (9)$$

Where

IUE(k): Energy consumption indicator of the product for the k^{th} use scenario (in W.h);

P(i): Installed power of component i (in W), as specified in Eq. (4) and (5);

τ *(i,j)*: Load coefficient of component i to realise job j;

$t_{comp(i,j)}(1)$; $t_{comp(i,j)}(k)$;$t_{comp(i,j)}(N_k)$: Cumulative duration of job j for the i component over lifetime for the 1^{st}, k^{th} and $N_k{}^{th}$ use scenario(in h).

Practically, it may be difficult to attribute a duration to a job for a component- $t_{comp(i,j)}$. Eq. (9) can be simplified with the approximation of $t_{comp(i,j)}$ by the $t_{job(j)}$. The τ (i,j) can be transformed in Job(i,j) in order to illustrate at the same time the load coefficient of the component i for the j job and the duration of job j on the i component, as presented in Eq. (10).

$$IUE = \begin{pmatrix} IUE(1) = \sum_{j=1}^{N_j}(\sum_{i=1}^{N_i} P(i) * Job(i,j)) * t_{job(j)}(1) \\ \dots \\ IUE(k) = \sum_{j=1}^{N_j}(\sum_{i=1}^{N_i} P(i) * Job(i,j)) * t_{job(j)}(k) \\ \dots \\ IUE(N_k) = \sum_{j=1}^{N_j}(\sum_{i=1}^{N_i} P(i) * Job(i,j)) * t_{job(j)}(N_k) \end{pmatrix} \quad (10)$$

Where:

IUE(k) and *P(i)* are already defined;

Job(i,j) : Percentage of solicitation of component i to realise job j (in %);

$t_{job(j)}(k)$: Cumulative duration of job j during lifetime for the k^{th} use scenario (in h).

If the indicator is fed with information based on measurement, *P(i,j)* and $t_{job(j)}$ can be established and Eq. (9) can be transformed into Eq. (11):

$$IUE = \begin{pmatrix} IUE(1) = \sum_{j=1}^{N_j}(\sum_{i=1}^{N_i} P(i,j)_{imp}) * t_{job(j)}(1) \\ \dots \\ IUE(k) = \sum_{j=1}^{N_j}(\sum_{i=1}^{N_i} P(i,j)_{imp}) * t_{job(j)}(k) \\ \dots \\ IUE(N_k) = \sum_{j=1}^{N_j}(\sum_{i=1}^{N_i} P(i,j)_{imp}) * t_{job(j)}(N_k) \end{pmatrix} \quad (11)$$

Where,

IUE(k) and *P(i)* are already defined;
$t_{job(j)}(k)$: Cumulative duration of job j during lifetime for the k^{th} use scenario (in h).

4) Case study: Implementing the IUE indicator to identify redesign priorities of an equipment

4.1) Context

This case study aims at illustrating how the IUE indicator can be used during the design of efficient electr(on)ic products.
The product under study is a postage meter (also called franking machine). The meter is professional equipment addressed to medium size enterprises to frank their mail. Its main function is to stamp a letter at the adequate fees and to charge the amount to virtual purse. The meter is a typical electr(on)ic equipment, made of mechanical and electr(on)ical parts.
The design team of the company developing this equipment was associated to the analysis. It was composed of mechanical, electronic and software designers as well as marketing department and project management. The company decided to use this experimentation for industrial objectives too: redesign strategies for the next generation of products should be identified to meet corporate objectives on energy efficiency. This topic has indeed been a central issue for many years in the company and the whole mailing system range is now certified with the Energy Star label (Imaging Equipment).The research therefore benefited from industrial contributions, as real engineering decisions were discussed within a real design team.
Both types of results (research and industrial) are presented in the following sections. For confidentiality reasons, some values are not explicitly given and generic names are given to the components and jobs calculation of the In-Use Energy consumption indicator.
A five-step method was implemented for the calculation of the IUE indicator. The five steps are described in the sections below.

4.1.1) Defining the product architecture

The study started with definition of product's components: based on the last generation of the product, splitting the product into components had been done, each component presenting a measurable installed power. This task was done by electronic and mechanical designers, functional and technical architects working together.
The four modules composing the product are: the feeder, the dynamic scale, the base (with the calculating unit) and the cartridge. These 4 independent modules were used as the basis for our product-splitting. Each module is composed of several components.
Mechanical components such as motors were identified in 3 modules and electronic components such as electronic boards and power supplies were identified in the 4 modules.
The product is composed of N_i = 21 components, 6 of them being mechanic and 15 electronic (cf. Table 2).
Components are not described in more detail due to confidentiality reasons.

Table 2: List of electronic and mechanical components of each module of the postage meter.

Module	Type of components	
	Electronic	Mechanic

Feeder	Board 1, Component E1	Motor 1, Component M1
Scale	Board 2, Energy Supply 1, Components E2 to E3	Motor 2
Base	Board 3, Energy Supply 2, Components E4 to E7	Motor 3, Components M2 to M3
Cartridge	Components E9 to E11	

4.1.2) Defining jobs sequence

Job definition was the following task where project managers and software designers were the most important actors, as they detailed the functional point of view on the product.

As a first approach, the team used the list of modes that Energy Star's Standard (US EPA 2008) defined for this type of equipments (Imaging Equipment). 6 modes were thus defined: On-print, On-com, On-ready, Standby, Soft-Off, Off. A deeper analysis was however carried out to identify a list of different jobs for each of these modes. For the 3 non-active modes (Stand by, Soft off and Off), no further splitting was done because the only job performed was "Waiting for wake-up". For the 3 active modes, splitting into jobs was done based on the software routine implemented on the existing product. For example, the On-print mode was split into 7 jobs that contribute to printing (including selecting, transporting and dynamic scaling). These jobs could be defined by sequencing the different actions realised one after the other or in parallel to give the final On-print mode function, i.e. "franking a letter". 3 jobs were therefore added that are available for all the three active jobs. Table 3 gives the repartition of the N_j = 16 jobs over the 7 modes.

Jobs are not described in more details due to confidentiality reasons.

Table 3: List of jobs carried out by the postage meter along the 6 operational modes.

Mode	Jobs
On-Print	"F1 Print" to "F7 Print"
On-com	"Active com"
On-Ready	"F1 Ready" and "F2 Ready"
On	"F1 On" to "F3 On"
Stand by	"Stand by"
Soft-Off	"Soft-Off"
Off	"Off"

4.1.3) Defining use scenarios

The definition of use scenarios was done using, in particular, knowledge and data from the marketing department. Market monitoring information supplied data on the number of letters stamped per day in various types of companies and the average lifetime of the product. For one stamp, internal characteristics of the product define the job duration. With these two pieces of information, durations could be associated to all 13 active jobs (jobs performed during On print, On com, On ready and On modes) during the whole use phase of the product, based on data collected from the field. The amount of time spent realizing the 13 active jobs represent only 2% of the product lifetime.

For the 3 remaining non-active jobs, no monitoring at the customers' level was possible, so team members had to define their durations for Stand-by, Soft-Off and

Off jobs based on internal characteristics. For example, the default value of the programmed time to automatically switch to Stand-by, Soft-Off and Off was used. The marketing department was interested in illustrating the difference between N_k= 2 scenarios, i.e. “Traditional user” who does not modify default parameters for energy saving, and a user, called “Energy aware user”, who changes the product parameters according to working hours at the office (8am to 6pm), meaning that the product spends 68% of its lifetime in Soft-Off job, 2% in active jobs and the remaining 30% in Stand-by. Thus, two scenarios were defined with the following use phase time splitting (cf. Table 4).

Table 4: Time splitting of four jobs according to the 2 scenarios considered in the case study.

Jobs	Scenario 1: “Traditional user”	Scenario 2: “Energy Aware user”
Average lifetime of the product	7 years	7 years
Active Jobs	2%	2%
Stand by	98%	30%
Soft-Off	0%	68%
Off	0%	0%

4.1.4) Documenting Power

A measurement protocol was defined in order to obtain consistent power values for mechanical and electronic components. To measure the power of mechanical components, it was proposed to combine two measurements and one calculation: torque (measured by a torquemeter), rotating speed (measured by a tachymeter) and load (obtained by calculation). Similarly, in order to measure power of electronic components (except power supplies), 2 measurements (current, measured by an ammeter, and power factor, measured by a wattmeter) and one calculation based on the supply scheme (input voltage) were combined.
Table 5 shows some results of the measurement on the postage meter.

Table 5: Measured Power on 3 types of components:

Component	Measured maximum peak power (W)
Energy Supply 1	3.6
Board 1	9
Motor 1	14.14

4.2) Results

The indices of Eq. (11) were defined as follow:

- Number of components N_i =21;
- Number of jobs N_j = 16;
- Number of scenarios N_k = 2.

Using Eq. (11), Eq. (12) presents the global energy consumption in use of the product for the two considered scenarios.

$$IUE = \begin{pmatrix} IUE(Traditional) \cong 699kWh \\ IUE(EnergyAware) \cong 230kWh \end{pmatrix} \quad (12)$$

The next section analyses the results of the implementation of the indicator in the redesign of a postage meter.

4.2.1) Analysing the user influence

Figure 3 presents the value of IUE indicator for "Traditional" and "Energy aware" scenarios and the contributions of all jobs.

Figure 3: IUE indicator results and contribution of jobs for two scenarios: traditional user and energy aware user, in Wh, over the lifetime duration of 7 years

Figure 3 demonstrates the influence of the user's practices on the final value of the IUE: the Energy Aware user is saving up to 60% of the overall energy consumption compared to the traditional one only by customizing energy saving options to office working hours, switching off the machine from 6pm to 8am. This demonstrates the potential benefits for a design team to consider multiple scenarios.
A first product improvement strategy that was derived by the design team was to encourage users to customize energy savings options. The design team proposed two ways of implementing this strategy:

- First, to inform the user more efficiently on the energy savings options included in the product : this can be done by a dedicated chapter in the operating instructions;
- Secondly, to minimize the wake-up time of some key components: surveys carried out by the marketing department showed that too long wake-up times usually inhibit users to use Off and Soft-off modes of the product; improving the wake-up time delay could therefore give incentives to the "Traditional user" to adopt more "Energy Aware" practices.

Another result derived from Figure 3 is that the IUE indicator is able to identify the most consuming jobs. For example, for both users, Stand-by is the most consuming job: although the highest power is needed for the active job F6, the energy consumption is by far dominated by a non-active mode, with far lower implemented power. The next section concentrates on this mode.

4.2.2) Contributors to the stand-by mode consumption

The IUE indicator is able to identify which contributors influence the energy consumption during the job "stand-by". Results derived from the IUE indicator are presented in Figure 4(a): the repartition of components consuming energy during stand-by mode is presented. Figure 4(b) is the repartition of the maximum nominal power over the product's components, derived from the measurement of power: it is given to allow a comparison with Figure 4(a).

(a) (b)

Figure 4: Contributors to (a) energy consumption during the job "stand by" and to (b) maximum nominal power.

Figure 4(a) shows that the energy consumption during "stand-by" is mostly due to the consumption of the power supplies (77% of the consumption all together). A traditional analysis based on nominal power (cf. Figure 4(b) would have led to other key components, i.e. Motor 3, E1 to E11 and Motor 1). This shows that an energy-based approach leads to other and, above all, more relevant hot spots than a traditional power-based approach.
Another design strategy derived from this analysis by the design team should focus on decreasing the consumption of supplies. Considering that energy consumption of a supply is due to conversion losses, two ways were proposed by the company to reduce these losses:

- First, to implement more efficient technologies: with the implementation of ErP for external power supplies, manufacturers of these components are developing more efficient technologies with a reduction of the conversion losses.
- Secondly, to reduce the maximum peak power of the module: the efficiency of a power supply is mostly correlated to the difference between the minimum and maximum peak powers: the smaller the gap, the more efficient the supply. When focusing on Figure 4 (b), motors are the main contributors to maximum peak power. Therefore, an interesting way to reduce it is to find more efficient motors or working on the efficiency of kinematical chains, by reducing friction for example.

For the company, the conclusion of this study was to prioritize, not only depending on the potential savings but also on R&D efforts, the following four redesign strategies in a context of cost, quality and resource constraints:

(1) Reducing friction of mechanicals parts,

(2) Reducing wake up time from job Off and Soft-off to active jobs,

(3) Looking for more efficient supply technologies from suppliers,

(4) Efficiently informing the user about the energy saving job.

4.3) Discussion on the case study

The IUE aims at supporting and driving the design towards more energy efficient products. For this purpose, it suggests a variety of contributions starting with the proposition of a new definition of the power (installed power and implemented power), followed by the definition of jobs to represent the time spent in the modes and the use of different scenarios for the use phase.
This case study illustrates the capability to assess product energy consumption with data usually available in any electr(on)ic design company. For this redesign purpose, first-hand data were used: measurement on previous versions of a product.
By identifying contributors to energy consumption, it supports the activity of identifying the hot spots of the product in terms of energy consumption. Design team can then identify redesign principles, working either on power or time reduction, or a combination of both. The variety of redesign strategies presented in the case study shows that, despite the new energy objective, the degree of freedom of the design team remains important, as they can work on mechanical or electr (on)ic components or on the functions of the equipment.
Our proposal of using the jobs for the definition of time periods instead of modes was not really demonstrated in this case because the most consuming job is also a mode (stand-by). Nevertheless, another case study based on a set top box and presented elsewhere (Domingo et al. 2010) illustrates the interest of going beyond modes.
We found that the notion of scenario was a relevant starting point for the consideration of the user in the design. By defining several scenarios, design project team started questioning some design options that were or were not relevant from a user’s point of view.

4.4) Limitations of the indicator

The first limitation is due to the intrinsic properties of the indicator. The indicator can only be calculated if components and time are discrete parameters. Design activities and product architecture usually provide sufficient data to discretize components to the appropriate level. Yet, splitting time into appropriate discrete parameters such as modes, job or time of component used is often arbitrary and cannot always be based on reliable data.
The second limitation is its applicability to real design situations. For early design phases and innovative product development, measurements on prototypes or previous products are not feasible. In these cases, a database based on look-alike products must be defined to provide a first estimation of the indicator.
Another possible limitation to this method is the time needed to collect all the necessary data. The case study was disconnected from a design project and did not suffer from time constraints. However, in a real design situation, the time needed to collect all the necessary data to have the adequate granularity for job and component definition could hinder the deployment of the indicator.

5) Conclusion and perspectives

Like most environmental issues, product energy efficiency in use can be efficiently addressed during the design process. By relating the energy performance of the product to its design parameters, the original tool presented in this paper can give a relevant picture using jobs as markers of time and components as markers of power.

Jobs and components can be considered at different scales, mapping the energy consumption in two dimensions with the adequate accuracy.
This map can be a key element for the design team to identify hot spots in products, and to track potential improvements in product design, leading to the identification of design strategies for energy efficiency. This was in particular illustrated when identifying redesign priorities of a postage meter.
To verify that the intakes of the IUE are usable during the design process, its implementation for developing a new generation of other equipment is under study with the industrial partner. It will be used from the very beginning of a design process, in order to analyse which intakes at which moment are a leverage to achieve energy efficiency in use phase. It will be also an opportunity to test the types of difficulties that arise when using it in a real design process. Defining relevant use scenarios is also a subject of interest: constructing a robust scenario that can be used at the same time for energy efficiency and improvement of user comfort is indeed still difficult for designers. This will also be studied in the next months.

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