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# DEVELOPMENT OF THE DIGITAL STORAGE FUON

**Hesamedin OSTAD-AHMAD-GHORABI (1), Thomas SCHÄFER (2), Alexander SPIELAUER (2), Gerold ASCHINGER (2), Daniel COLLADO-RUIZ (3)**
1: Magna Steyr Engineering Deutschland, Germany; 2: Vienna University of Technology, Austria; 3: Technical Universidad Politécnica de Valencia, Spain

## ABSTRACT
This paper ties to Fuon Theory, where functional icons are suggested to phrase standardized functional units. Having functional unit parameters at hand, products that can be described by these parameters can be put into one family. This further helps to compare the environmental performances of products that fall into the same family.
In this paper, a fuon for digital storage devices is developed and tested. The fuon can be used to phrase the functional units of a variety of products such as magnetic hard-discs, USB flash drives, SD cards or SSD drives. The functional unit parameters are derives for the fuon and its applicability is tested through different statistic tests.

*Keywords: eco design, functional unit, life cycle assessment, product families, sustainability*

Contact:
Dr. Hesamedin Ostad-Ahmad-Ghorabi
Magna Steyr Engineering Deutschland
Interiors
Sindelfingen
71063
Germany
hessam.ostad@gmail.com

# 1 INTRODUCTION

Environmental product evaluation and in particular Life Cycle Assessment (LCA) is being recognized by more and more companies as a relevant tool to achieve a green product design. In most literature, LCA is considered to be one of the most relevant tools for integrating environmental aspects in design (Jeswiet and Hauschild,2005; Germani et al., 2004; Nielsen and Wenzel, 2002 amongst others). However, it is far away from being an efficient tool to be used within design processes. Many authors have pointed out the barriers of implementing LCA into design and product development: its complexity which requires special training, its requirement of much information which is not available in the early stages of design or its complex modeling which differs to the models used during design are some to be named here (Millet et al., 2007; Sousa and Wallace, 2006; Ernzer and Birkhofer, 2003; Jönbrink et al., 2000). There have been many attempts to bring LCA into design, leading to various approaches given names such as simplified LCA or abridged LCA. A great many other tools and methods have been developed and presented in literature which were meant to assist the engineering designer with environmental evaluation (e.g. Ostad-Ahmad-Ghorabi et al., 2006; Goedkoop et al., 2004; Goedkoop and Spriensma, 2001 amongst others).

Regardless of its complexity, LCA is still considered in most methodologies as the standard to measure environmental impact (Millet et al., 2007; Collado-Ruiz, 2007; Stevels et al., 1999). In some methodologies it forms the core of an environmentally conscious product development (Nielsen and Wenzel, 2002; Wenzel et al., 1997). Finnveden and Moberg (2005) point out the type of comparison in any tool for environmental assessment; comparison can be done between alternatives, between different life cycle phases or against a reference (Lenzen and Treloar, 2003; Heijungs and Suh, 2002; Wenzel et al., 1997). Comparison against a reference is rare, since the definition of a reference is complex and requires much information (Keoleian and Kar, 2003). A prerequisite for all comparisons is that products are functionally similar. In this context, ISO 14040 (ISO, 2006) refers to products with the "...same function(s), quantified by the same functional unit(s)". The functional unit is defined in ISO 14044 as "...the quantified performance of a product system for use as a reference unit" (ISO, 2006). ISO does not propose how to define a functional unit, allowing for different definitions and phrasings for one and the same product.

This fact adds to the difficulty of selecting the right products for comparison. Additionally, any variation in functionality constrains comparison of the environmental evaluation of products. To face this problem, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010a) have proposed a new way of grouping products in the scope of LCA Comparison Product-families (in short: LCP-families). The life cycle of products in an LCP-family can be described by a limited set of parameters by which reference ranges can be established. Reference ranges are defined as ranges in which products can be assessed as to their better or worse environmental performance in comparison to competing products, independently to their technology (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010a). To ensure that functionally similar products are selected to form an LCP-family, the appropriate definition of the function unit becomes essential. If the functional performance of products is different, their LCA results should be scaled according to the magnitude of the reference flows (ISO, 2006). As this requires a structured and uniform definition of the functional unit, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) have developed the concept of functional icons, in short fuons. Fuons allow for standardizing functional units, providing a set of scaling and constraint parameters for their phrasing. Further, fuons ensure that different applicants always phrase the functional unit for the same product in the same way. Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) also studied how fuons act in the phrasing of functional units and up to which point standardization was achieved. An advantage of the fuon theory is that the development of fuons and their application is decoupled. The application of fuons is just matter of their correct selection according to the product being investigated. So far, two fuons have already been developed: one is the *physical container* defined as an "…element that encloses partly or totally other physical elements, protecting them or isolating them from the external environment". This fuon is applicable for example for all kind of packaging. The other fuon is the *logistics-intensive element*, defined as "…an element with the intention to allow transportation (once or more times), protecting and allowing the necessary stacking or manipulation". Currently, the pool of available fuons to model different product types is quite shallow. The reason herefore is that the development of fuons is a time-consuming and an extremely information-intensive task. However, to make fuon theory applicable, the main strategic goal is to develop more fuons, respectively all of them. Ostad-Ahmad-Ghorabi (2010) has estimated the total number of fuons needed to describe all different product types to be around 12. Fuons are distinguished by the main flow they describe, i.e. materials (M), energy (E) or information (I) and the main function applied to the flow, i.e. storing, transmitting, transforming or converting, see Table 1.

*Table 1. Distinction of fuons by general function and flow (Ostad-Ahmad-Ghorabi, 2010)*

| Fuon | Flow | Store | Transmit | Transform | Convert | Product examples |
|---|---|---|---|---|---|---|
| 1 | M | x | | | | Bottle, container |
| 2 | M | | x | | | Lift, car jack |
| 3 | M | | | x | | Injection moulding machine |
| 4 | M | | | | x | Kneader, cement mixer |
| 5 | E | x | | | | Battery |
| 6 | E | | x | | | Cable |
| 7 | E | | | x | | Gearbox |
| 8 | E | | | | x | Engine |
| 9 | I | x | | | | Hard disc, flash disc |
| 10 | I | | x | | | Antenna, digital camera, voice recorder |
| 11 | I | | | x | | Printer |
| 12 | I | | | | x | Satellite Receiver |

In this paper, a fuon for all kind of digital storage devices like hard discs or USB flash drives is developed and presented.

## 2 STATE OF THE ART: FUON THEORY

To be able to derive practically valid conclusions from an LCA, its results have to be used in relative terms (ISO, 2006). Should functionalities have been added to a new product, extrapolation and scaling from previous products is necessary for comparison. On the other hand, comparison of products is only possible when products have the same functional unit. Comparison and scaling must be done in a functional domain (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b,a). In the scope of fuon theory, the functional unit can be phrased by a set of parameters, called Functional Unit Parameters, in short FUp's (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b).

This assures that for the phrasing of the functional unit of a particular product all parameters are provided and no relevant aspect is overlooked. Further, it helps to derive the same phrasing of the functional unit for the same product. The parametric phrasing of the functional unit is the basis for selecting and scaling among products whose LCA share common traits. Products with same or similar parameters in their functional units are candidates to be grouped into the same LCP-family (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010a). With the help of LCP-families, reference ranges can be established in which products can be assessed as to their better or worse environmental performance in comparison to competing products. Through LCP-families and reference ranges it is possible to set benchmarks for a new product's environmental performance. The current environmental impact of a new product being developed can be compared to the performance of the LCP-family. By reference ranges established for the LCP-family it is then possible to judge whether a new product is doing same, better or worse than competing products and alternatives in the LCP-family. Further, the definition of target values for environmental impacts is facilitated. To facilitate selecting and scaling of products through parameterization of functional units, two types of FUp's have been distinguished:

1. *Physical FUp's*, indicated as $FUp^p$s, describe the main functions of a product. $FUp^p$s have a physical magnitude and can thus be used for scaling purposes.
2. *Functional constraints*, indicated as $FUp^c$s. They constitute a constraint to design, or an additional function or performance specification that the product must fulfill. Their nature can be dichotomic (true/false), or of any other which explains the phenomenon, e.g. a scale from 1-9 indicating the importance of the parameter. Dichotomic parameter are referred to as $FUp^{c1}$, the latter type as $FUp^{c2}$. $FUp^c$s serve as a filter to select and compare among those products which are most similar within an LCP-family.

The structure of the functional is then as follows:

$$\{FU\} = \{FUp^{p}{}_{i}\,,\ FUp^{c1}{}_{j}\,, FUp^{c2}{}_{k}\,\} \tag{1}$$

Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) have defined a fuon as "an abstraction of a product, based on its essential function that represents the whole set of products that share the parameters for its functions' flows". A fuon comprises of a set of FUp's (both $FUp^{p}$s and $FUp^{p}$s) which can be used to phrase the functional unit by using these parameters; it can thus be made sure that all relevant aspects of the product are represented in the functional unit.

An important trait of fuons is that their application and development is decoupled. It has been shown that the use of fuons can lead to robust phrasing of functional units (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b). The development of a fuon, however, is a time-consuming and difficult task. It requires much information about the market, about functionalities and life cycle data of different products within a product category (e.g. all different types of digital information storages) and requires a structured organization of these information. Thus, market information, Product Design Specification (PDS) lists and inventory information have to be studied forehand. In addition, information has to be parameterized correctly in order to be able to infer results.

# 3 DEVELOPMENT OF THE DIGITAL INFORMATION STORAGE FUON

To develop the digital information storage fuon, the approach proposed by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) has been followed.

The digital information storage fuon is defined as an "…element that allows the storage and recall of digital information". Through a brainstorm session, product types that are commonly in use and fall under the aforementioned definition have been selected. Thus, the fuon shall cover magnetic hard drives, Solid State Drives (SSD), Secure Digital (SD) Cards including MMS cards, USB flash drives, RAMs, CDs and DVDs and also floppy discs. For a total of 47 products, environmental and functional information was collected to further test $FUp^{p}$'s.

To assess the products environmentally, product models were built and life cycle data were collected. Thorough literature research was conducted and inventory data were derived from publications in the field of electronic products. Data sheets and publicly available data from manufacturers were also considered and taken for product modeling. Material composition of hard discs was derived from disassembly studies (Sunil Mohite, 2005). Life cycle data of printed circuit boards (PCBs) were modeled by merging data from Kramer (2006), Kunnari et al. (2009), Nagel (2003), and the Ecoinvent database (Frichknecht et al. 2007). Data for the modeling of RAMs were found in Kunnari et al. (2009), Liu et al. (2010), and in data sheets from the manufacturers. Distribution scenarios have been modeled by considering major manufacturer countries and consulting LCA studies (e.g., Duan et al. 2009; Kunnari et al. 2009; Liu et al. 2010). Additionally, data about manufacturing processes were obtained by consulting an expert at the Institute of Solid State Physics at the Vienna University of Technology who holds a patent on a similar product. The use stage was modeled by consulting an expert at the Institute of Solid State Electronics at the Vienna University of Technology who is responsible for archiving digital data and maintaining IT-systems at the institute. The end-of-life scenarios were modeled considering recycling and landfill processes (Duan et al. 2009; Kunnari et al. 2009; Sunil Mohite 2005). Cumulative Energy Demand (CED) expressed in MJ has been used to retrieve an environmental assessment result for the products considered. Table 2 lists the products considered and their variations along with some additional information for each of them.

In a next step, $FUp^{p}$'s have to be postulated and tested as to their suitability. A statistical model is needed to check whether the proposed $FUp^{p}$'s are able to describe the product and whether they are independent. A linear regression model can be established, where it will be checked whether the chosen $FUp^{p}$'s are suitable predictors for the environmental impact. The linear regression model thus will contain the environmental impact as a dependent variable and the $FUp^{p}$'s as independent (scaling) variables. The quality of the linear regression model can then be investigated by considering the following (Hackl, 2004; Bosch 2005):

1. For each variable ($FUp^{p}$) the probability of error p should remain below 0.05 ($p \leq 0.05$). This criterion implies that 95% of all cases can be described by this variable. If this criterion cannot

be fulfilled a more convenient requirement should apply: the chosen $FUp^p$ should minimize the p-value.

2. The coefficient of determination $R^2$ should be greater than 0.35 and preferably as near to 1 as possible.
3. To judge the influence of outliers, the residuals of the model will be evaluated as well. Residuals should have a normal distribution which can be checked by drawing a histogram and compare it with a normal curve as well as conducting a Kolmogorov-Smirnov test. This test delivers a p-value for the distribution. $p \leq 0.05$ would indicate a significant deviation of the investigated distribution from a normal distribution. In other words, for the residuals, $p \geq 0.05$ should be valid.

*Table 2. Products under study for the development of the digital information storage fuon*

| Type of product | Number of products | Variations [GB] |
|---|---|---|
| Magnetic hard discs | 9 | 10, 120, 500, 640, 1000, 1500 |
| CD & DVD | 7 | 0.6, 0.7, 0.8, 4.7, 25 |
| RAM | 7 | 0.12, 1, 2, 4 |
| SD & MMS Cards | 8 | 2, 16, 23, 1000 |
| SSD | 6 | 32, 60, 80, 100, 120, 256 |
| USB Drives | 9 | 4, 8, 16, 32 |
| Floppy Disc | 1 | 0.001 |

To find possible candidates for $FUp^p$'s, first, the main functional flow of the products has to be determined. According to Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b), for each functional flow, a separate fuon is needed. For the case of digital information storage, the only apparent existing flow is information in digital form. The information is stored on matter and can be recalled by the user at any time. The very simple black box model shown in Figure 1 is thus valid:


*Figure 1. Main flow of the fuon "Digital information storage"*

Mainly, digital storage devices are defined by their raw capacity, i.e. how much information they can store, usually expressed in Megabytes (MB), Gigabytes (GB) or Terabytes (TB). However, to store information, a physical platform is needed. This physical platform also determines how much information can be stored, similar to a sheet of paper where the size of the paper determines how much one can write on that piece of paper. In the case of the digital storage devices, this would be the size (area) of the disc or the chip were the information is stored. More discs would allow for more storage capacity. However, the dependency between storage area and capacity is not linear. Hard disc drives with newer technology for example, have higher capacities with the same storage area compared to older hard disc drives.

Some additional parameters were considered as potential FUp's, such as writing and reading rate (expressed in MB/s), number of storages (corresponds to lifetime of the device) or mass of the device amongst others. The statistical model showed that none of these parameters are useful as scaling parameters; all of them or any combination of them violated one of the three aforementioned requirements for the linear regression model.

To be able to better distinguish between the different products represented by the fuon digital information storage, $FUp^c$'s were defined by consulting available product descriptions, manuals and technical sheets. Table 3 shows the parameters considered for the products.

The testing of the fuon was conducted by using the statistic software SPSS. A linear regression model of the LCP-family was built for scaling purposes. The environmental impact (EI) was defined as a dependent variable and the $FUp^p$'s as independent variables. The criteria for proper linear regression models ($R^2 > 0.35$; $p < 0.005$; residuals $> 0.05$) were checked for the two $FUp^p$'s raw capacity (expressed in GB) and storage area (expressed in $cm^2$). For the analysis, all 47 products were considered. Table 4 shows the result of the analysis.

*Table 3. Parametric description of an excerpt of products considered to develop the fuon digital information storage*

| | $FUp^p$ | | $FUp^{c1}$ | | | | | | | | $FUp^{c2}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Raw capacity [GB] | Storage area [cm2] | Max. Temperature [°C] | Min. Temperature [°C] | Shock resistance [1-9] | Magnetic resistance [1-9] | Electrostatic resistance [1-9] | Radiation resistance [1-9] | Humidity resistance [1-9] | Mechanical protection [1-9] | Random Access [y/n] | External [y/n] | Volatility [y/n] |
| Magnetic hard disc 1 | 10 | 372 | 60 | 0 | 5 | 9 | 9 | 7 | 5 | 9 | - | - | - |
| Magnetic hard disc 9 | 500 | 372 | 40 | 5 | 7 | 9 | 9 | 7 | 3 | 7 | - | ✓ | - |
| DVD 1 | 4.7 | 113 | 70 | 0 | 1 | 9 | 9 | 5 | 6 | 1 | - | ✓ | - |
| RAM 5 | 2 | 22 | 85 | 0 | 9 | 9 | 1 | 9 | 1 | 1 | ✓ | - | ✓ |
| SD Card 2 | 23 | 6.1 | 85 | 25 | 9 | 9 | 9 | 3 | 3 | 3 | ✓ | ✓ | - |
| SD Card 3 | 1000 | 6.1 | 85 | 25 | 9 | 9 | 9 | 3 | 3 | 3 | ✓ | ✓ | - |
| SSD 4 | 256 | 17.2 | 70 | 0 | 7 | 9 | 9 | 3 | 2 | 5 | - | - | - |
| USB flash 4 | 32 | 0.3 | 50 | 0 | 1 | 9 | 9 | 3 | 2 | 1 | ✓ | ✓ | - |

*Table 4. Statistical analysis of the variables 'raw capacity' and 'storage area'*

| | |
|---|---|
| N = 47 | |
| $R^2 = 0.639$ | |
| | p |
| Raw capacity | 0.006 |
| Storage area | 0.000 |

Figure 2 shows a histogram of the residuals of the model and compares it with a normal curve. The second plot is a normal probability-probability plot (P-P plot) for the regression standardized residuals. In general, P-P plots are drawn to show whether data follow a given distribution. A fitting distribution for the data will have a linear P-P plot.

Additionally, a Kolmogorov-Smirnov test for the residuals is conducted in SPSS to prove their normal distribution. The test shows $p = 0.086$; the distribution is normal.

The analysis shows that indeed the selected $FUp^p$'s are suitable to be used as scaling parameters. It would be of great value to check now how the fuon behaves fur a subgroup of products, e.g. only magnetic hard disc drives or only SSD drives.

A fuon might have more $FUp^p$'s than it is necessary for the description of a linear regression model of a particular subgroup (Ostad-Ahmad-Ghorabi, 2010). The possibility to skip certain parameters for a particular subgroup is given. However, it is essential that a subgroup should not require additional $FUp^p$'s, since this would be in contradiction to the main purpose of fuons. A fuon should contain all possible $FUp^p$'s to be used to phrase the functional unit; a subgroup of products might require less. To check which of the $FUp^p$'s are necessary for the subgroup, the same approach as for the development of the fuon has to be followed.

A subgroup can be formed by determining the respective $FUp^c$'s. In other words, products that have the same $FUp^c$'s, and further the same quantities for the $FUp^c$'s are more likely to fall into the same group. Sometimes, the requirements for the linear regression model cannot fully be fulfilled. The more convenient requirement that should apply is that the linear regression model has to be approximated as much as possible. The P-P Plot also helps to group products, e.g. the products within the 0.2 grid in Figure 2 left, may forma subgroup of their own.

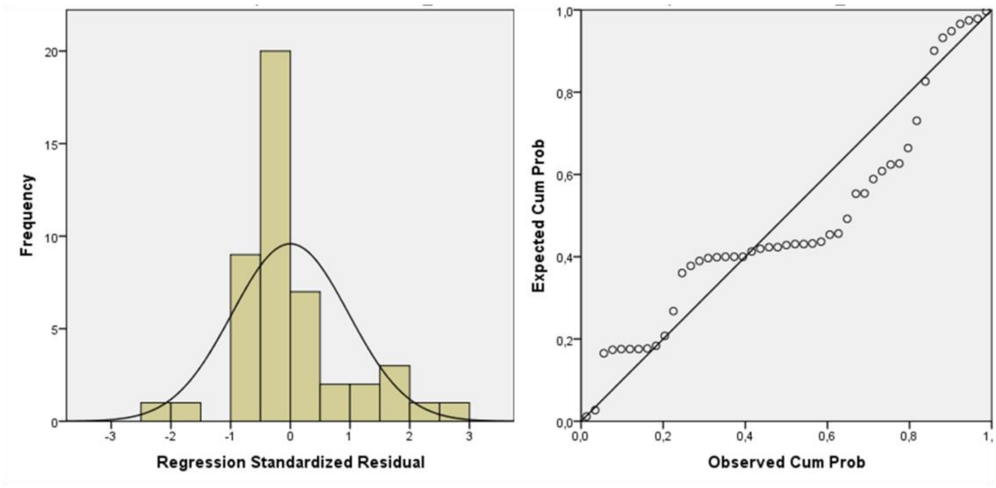


*Figure 2. Left: histogram of residuals, Right: P-P plot (independent variables: raw capacity and storage area; dependent variable: environmental impact; N=47)*

For analysing subgroups, it is important to bear in mind that the minimum number of samples should be equal to *number of $FUp^p$'s + 2* (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010a). Except for the floppy disc, this may be true for all other product categories. However, some subgroups have small sample sizes and analysis results may not be reliable.

The subgroup of RAMs has a sample size of N=7. For this subgroup, both parameters, raw capacity and storage area, were considered first. Since for storage area $p>0.05$ was valid, it was removed from the model and the analysis was run with the parameter raw capacity only. The results are listed in Table 5, first column.

SD cards and USB flash drives can be grouped together, since their $FUp^{c2}$'s are the same: both product types are meant for external use and both of them allow random access to data. Unlike RAMs, where data is stored as long as there is an external power supply, SD cards and USB flashes are able to keep data in their storage without external power too (indicated by setting the parameter volatility to "no"). This subgroup contains 17 products. The results of the linear regression model are shown in Table 5, third column. Since $R^2<0.35$ for the model and $p>0.05$ for raw capacity is valid, this parameter has been removed from the model and the analysis has been carried out again with the parameter storage area only, see Table 5 fourth column. Still $R^2<0.35$ is valid and for the parameter storage area it turns $p>0.05$. Both models are not satisfying. For the next model, the subgroup has been divided into SD and USB drives that have less than 16GB capacity and those having more. This approach is justified by two facts: first, most SD cards and USB flashes in the database have less than 16GB capacity. Second, the P-P-Plot in Figure 2 indicates that these products are to be found in the same area of the plot, indicating their similar behaviour in the regression model. 11 products fall into this category. The results are shown in Table 5, fifth column. The analysis shows that all requirements for a good linear regression model are fulfilled. For the products with higher capacities the sample size is only N=6, almost too small for the variety in the capacities to conclude to a reliable model. More samples are needed.

*Table 5. Statistical analysis of $FUp^p$'s for subgroup of RAMs, USB flashes and SD cards*

| Products | RAMs, all | SD+USB, all | SD+USB, all | SD+USB, <16GB | SD+USB, lin |
|---|---|---|---|---|---|
| *N* | 7 | 17 | 17 | 11 | 8 |
| $R^2$ | 0.684 | 0.27 | 0.106 | 0.56 | 0.882 |
| Raw capacity *p* | 0.022 | 0.538 | -- | 0.008 | 0.003 |
| Storage area *p* | -- | 0.052 | 0.161 | -- | 0.002 |

The P-P Plot can be taken to form an even more homogeneous subgroup: taking those products that are closest to the linear curve result in a subgroup of 8 products, all of the either USB flashes or SD Cards. The results of the regression model are listed in Table 6, sixth column.
This sort of analysis can be carried out for any subgroup, either pre-defined by the FUp$^{c}$'s or selected through P-P-plots by considering those spots that are close together in an own regression model. The examined cases show that the FUp$^{p}$'s of the fuon digital storage are able to describe the variety of digital storage products as well as the more specific subgroups. Figure 3 shows the final digital information storage fuon.

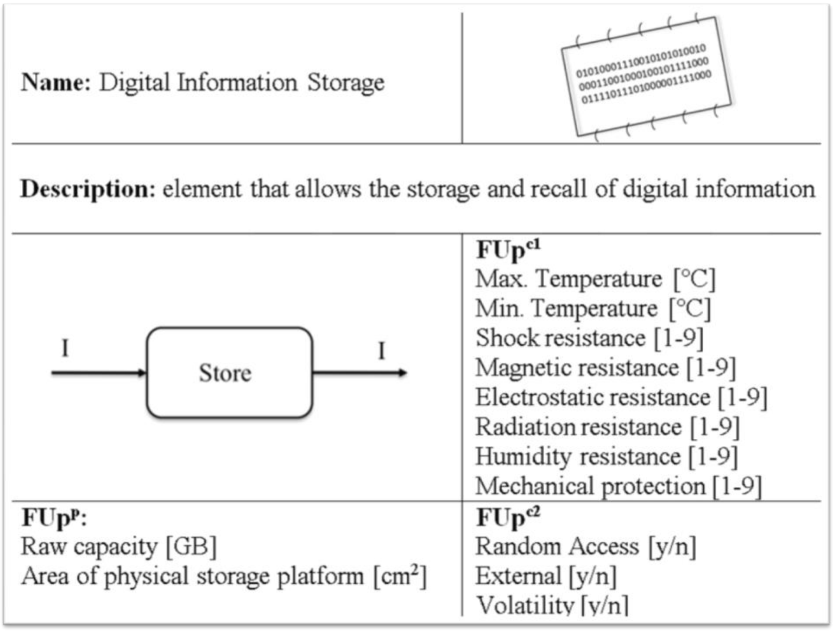


*Figure 3. Final concept of the fuon digital information storage*

## 4 CONCLUSION AND OUTLOOK

The fuon developed in this paper allows the uniform phrasing of functional units for products whose main functional flow is storing digital information. LCP-families can be established by filtering through FUp$^{c}$'s of the products. This gives a solid fundament for the comparison of environmental profiles of different products, i.e. an environmental benchmark.
The paper has shown that for the development of a fuon, detailed information of products having the same main flow and function is needed. Acquiring these information is a time- and information-intensive task. The application of the fuon however, is very convenient; once a product is defined to be e.g. a digital information storage, i.e. the main flow has been determined to be digital information that is stored, it is sufficient to take the fuon developed in this paper to phrase its functional unit.
It can be acknowledged that the area of storage is not a purely functional unit, and that different technologies might perform better or worse on this. It is, however, a good proxy of the demand in processing power that the storage system needs, and therefore of the manipulation requirements. A further development of this fuon, however, would be to analyze this relationship and to try to transform this unit into another, more functional, one, that still reflects and correlates in the way this one does
The list of FUp$^{p}$'s and FUp$^{c}$'s ensures that no relevant aspect is overseen. However, this paper indicates the difficult approach to develop fuons: for the digital information storage fuon, 47 products had to be environmentally assessed first. FUp's had to be postulated and their suitability had to be tested through statistical models. In fact, the final postulation of a suitable set of FUp's may be derived through several iterations.
What would ease the development of fuons in general is a systematic approach for their development. A systematic framework would not necessarily reduce the workload. Rather, it would help to structure and organize the information collection that is necessary for the development of a fuon and assure that

no important aspect is overseen. This intention would be similar to the framework of LCA defined by ISO: it can be read as a step by step manual to complete the task.

Some thousand of different products need to be investigated to determine the final number of different fuons and to test them. A first guide which fuons shall be developed is given in Table 1.

Once a great enough pool of different fuons are developed and available, the combination of different fuons can be studied thoroughly. Some products may have more than one main functional flow, e.g. a smartphone, which can either be regarded to be a telephone, an audio device, a digital storage device or a photo camera (information conversion) or all of them at once. The pool of fuons will consist of a limited set of elements. Their combination however, shall help to model almost any product.

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