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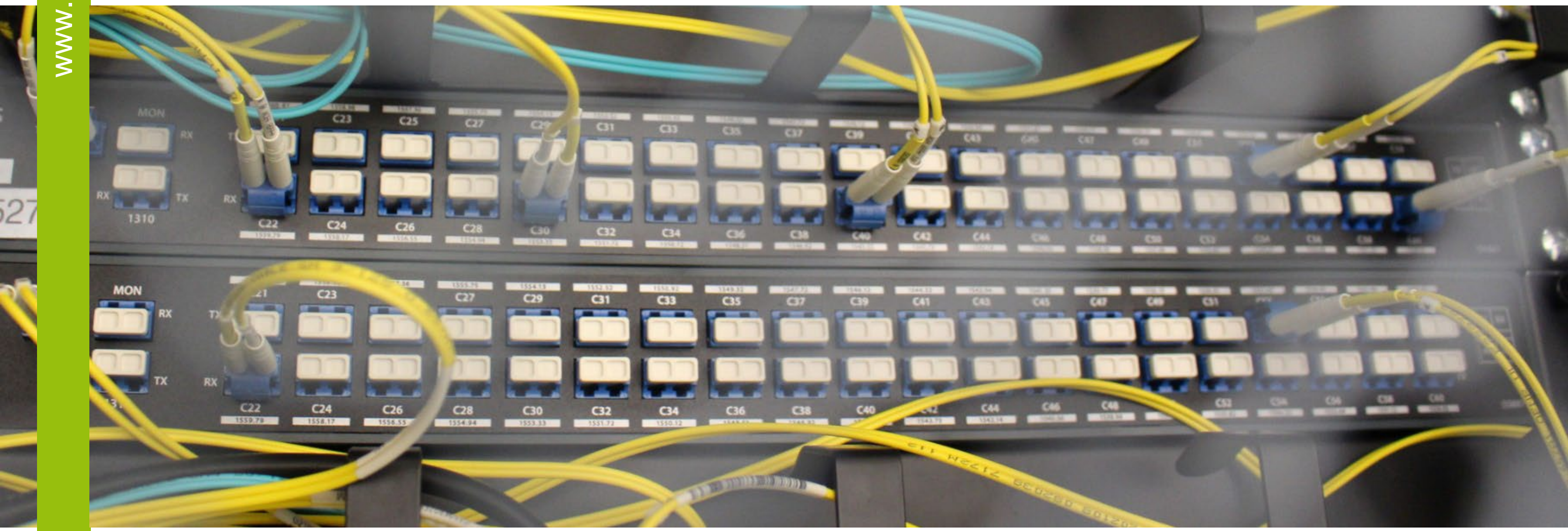

Life cycle assessment of digital services

Methodology for determining the environmental impact of software, cloud services and other digital services in distributed IT infrastructures

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The following method sketch was developed in the **eco:digit** research project funded by the Federal Ministry of Economics and Climate Protection (BMWK), which focusses on the environmental impact of software. In the research project, the participating organisations are developing a simulation environment with which software can be tested on different virtualised hardware platforms. Strategies for optimising the environmental impacts of software and hardware infrastructure can be derived from the test results. The methodology presented here for determining the environmental impact of digital services builds the methodological basis for this.

Contents

In the context of this methodology, a *digital service* is understood to be any machine work provided by digital technology. Examples are displaying content on a computer screen, processing data, transmitting data via a network, storing data in a cloud storage or, more specifically, providing a website, answering a search query or delivering a video stream. A digital service provides a quantifiable benefit.

The LCA (*life cycle assessment*) of digital services differs from the classical LCA in that the focus is not on a single physical product, but on a large number of different hardware platforms (e.g., end devices, network, servers). These platforms are not fully utilised by the service, but only for a limited time and with proportionate utilisation. This increases the complexity of the life cycle assessment, as on the one hand many different products need to be assessed and on the other hand an *allocation* must be made as to how much of the total environmental impact of the digital service is attributable to the respective products.

The *digital supply chain* is therefore introduced in the beginning of this methodological outline. The digital supply chain is made up of all hardware platforms involved in the delivery of the digital service. To prepare the LCA, all links in the digital supply chain must be assessed and appropriately allocated.

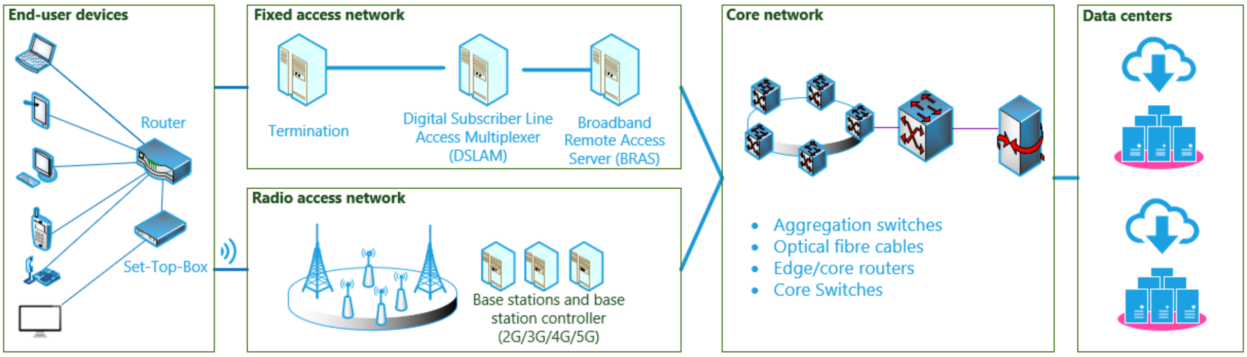
Digital supply chain

The digital supply chain describes the sum of all individual devices and infrastructure elements that are required to provide and utilise a digital service. In the simplest case, it consists of a single "chain link", for example a single end device that performs its service without external dependency (e.g., an offline computer). However, the more common case is that there is an internet connection and that many different hardware platforms are involved in the service.

For example, visiting a website requires at least one end user device, a network access point, various network nodes along the transmission path and a server with a storage system in the data centre.

The digital supply chain is shown schematically in the following diagram, whereby a distinction is made between *end-user devices*, *access network* (divided into *fixed* and *mobile*), *core network* and *data centres*.

Figure 1: Digital supply chain



Source: Öko-Institut

To assess the environmental impacts of a digital service, the environmental impacts along the entire digital supply chain must be determined and allocated proportionately to the respective service.

The above diagram shows the digital supply chain of digital services in the use phase. It does not include the "production" of the software. If developing the software involves a high use of digital infrastructure, such as is required for the training of artificial intelligence (AI) models, the digital supply chain must be supplemented by the production of the software. This could involve high-performance data centres or special server capacities with graphics processors. In that case, the impacts of developing the digital service must be allocated to the subsequently utilized digital services according to the respective service units.

Basic digital resources

Digital services basically consist of data processing, the use of random access memory (RAM), permanent data storage and data transmission. Such basic services of digital infrastructures are referred to here as *basic digital resources* (DBR).

Basic Digital Resources (DBR) are:

- Computing power (compute)
- Memory capacity (memorise)
- Storage capacity (store)
- Data transmission (transfer)

These digital services are generally provided by information and communication technology (ICT) components. All other technical devices and infrastructure components such as power distribution, fail-safe energy supply, cooled rooms, buildings, security technology and administrative expenses are postulated to be operated exclusively to provide the digital service. Their expenses can therefore also be allocated proportionately to the basic digital resources in the form of "overheads". This also applies to I/O devices e.g., mice, keyboards, monitors, display panels, etc.

Every piece of software requires a countable amount of basic digital resources. And every ICT device makes a certain amount of these available. By introducing this level of abstraction, it is possible to establish the connection between the demand (software) and the supply (hardware).

The concept of basic digital resources is presented in the white paper SDIA (2022) in more detail.

Hardware provides basic digital resources

For each digital device, hereinafter also referred to as a *platform*, the maximum basic digital resources it can provide can be determined. The computing power (compute) is determined by the performance of the CPU and GPU, the memory capacity (memorise) by the amount of RAM installed and the storage capacity (store) by SSD and HDD capacities. The maximum amount of data transfer (transfer) depends on the bandwidth of the respective network interface.

This system can be used to describe not only computing and storage systems, but also network devices. These may then exclusively provide data transfer as basic digital resources.

In addition to the maximum amount of basic digital resources (DBR) that a platform can theoretically provide, the actual operation of the hardware is decisive for its efficiency. For example, a platform that is only half utilised will only provide half of its available digital performance. The average utilisation (load) of the hardware components over their service life must therefore be determined for each device. These are the CPU and GPU utilisation, average memory utilisation, percentage hard drive utilisation and average transfer rates. This results in the average basic digital resources provided ($DBR_{average}$).

Table 1 shows examples of maximum DBR and $DBR_{average}$.

Table 1: Exemplary basic digital resources of a platform

Hardware component	Abbreviation	Digital basic resource of the platform (DBR)	Example	Unit	Average capacity utilisation or occupancy (load coverage)	Average basic digital resource provided basic digital resource ($DBR_{a\ verage}$)
CPU	co (compute)	CPU frequency * bus width	128	GHz*bit	20%	25.6 GHz*bit
RAM	me (memorise)	Working memory space	8	Gigabyte	10%	0.8 gigabyte
Storage	st (store)	Hard disc space	4.000	Gigabyte	50%	2,000 gigabytes
Network	tr (transfer)	Maximum data transmission	100	Megabit/s	2%	2 megabit/s

Source: Öko-Institut

For the sake of simplicity, *CPU frequency * bus width* was selected as the performance indicator for the basic digital resource *compute* in the table. Other performance indicators such as *floating operations per second* (FLOPS), *server-side Java operations per second* (SSJOPS) or the use of other CPU or GPU benchmarks that can be collected across platforms would also be conceivable. It must be possible to scale the benchmarks linearly via the utilisation i.e., at half utilisation, half the performance can be expected, so that the utilisation measure always refers to chosen benchmark.

If the basic digital resources (*DBR*) of a platform and their average utilisation (*load*$_{average}$) are known, the digital work (*DW*) that is provided during the entire technical lifetime of the platform (*Lifetime)* can be calculated.

Digital work (*DW*) over the lifetime of a platform:

$$DW_{co} = DBR_{CPU} \cdot Load_{average,CPU} \cdot Lifetime \qquad [\text{e.g. GHz*bit*s} = \text{Gbit}]$$

$$DW_{me} = DBR_{RAM} \cdot Load_{average,RAM} \cdot Lifetime \qquad [\text{GByte*s}]$$

$$DW_{st} = DBR_{storage} \cdot Load_{average,storage} \cdot Lifetime \qquad [\text{GByte*s}]$$

$$DW_{tr} = DBR_{network} \cdot Load_{average,network} \cdot Lifetime \qquad [\text{Mbit/s*s} = \text{Mbit}]$$

While the basic digital resources (DBR) are performance values that are available at a single point in time, the digital work (DW) contains the duration of utilisation. In the case of *co* and *tr*, the unit *seconds* is cancelled out for the selected units.

Excursus: Average capacity utilisation

To determine the environmental impact of software, it is necessary to allocate the environmental manufacturing impacts of the hardware and the energy consumption in the utilisation phase partially to the software. This method assumes an average utilisation of the hardware. Only when the hardware is actually utilised it performs digital work e.g., computing operations, memory work or data transfer. Idle states are not defined as useful in this concept, even if they are held in reserve in practice for possible load peaks.

The average utilisation is the **mean value of all utilisation states over the entire technical service life** of a piece of hardware. For hardware that is permanently in operation, for example in a data centre, this corresponds to the average values from the system monitoring log files. As these values are not usually available for the entire technical service life, the average utilisation can also be estimated using a shorter time interval.

Determining the average utilisation becomes more complicated for hardware that only runs temporarily, for example a desktop computer that is only in operation for 8 hours a day. The off state is then included in the mean value calculation for the **environmental manufacturing impacts** with utilisation of the respective hardware components of zero. During this time, the computer is of no use, but the hardware still had to be manufactured.

However, in the case of **energy consumption during** computer **use**, which is described further below in this method description, the electrical power consumption during average use and the duration of actual utilisation are included in the calculation. Energy consumption is therefore calculated using the average utilisation during the power-on state and the off state is ignored. If the off state is associated with relevant energy consumption (e.g., standby losses), these losses must be allocated to the actual operating state as overhead. However, this special case is not explained further in the method description.

Software utilises basic digital resources

When software is executed, it requires local computing capacities, random access memory (RAM) and permanent storage and causes data traffic that leaves the physical boundaries of the respective platform and is passed on to the next platform in the digital supply chain. On each individual platform, it is therefore possible to measure how many basic digital resources are utilised and to how much digital work this utilisation adds up to.

To determine the environmental impacts of a digital service, a suitable *service unit* must first be defined to which the measurement results are to be related. For a *continuous service* (e.g. audio or video streaming), this can be a unit of time (use over the period of one hour), for a *task-based service*, the respective task (e.g. answering a search query, processing a text with 1000 characters, handling a payment process) and for *quantifiable services*, the respective number together with a unit of time (e.g. use of 128 virtual CPUs over 24 hours, 1000 gigabytes of cloud storage over 1 year, 1 TB of data volume of delivered content over the period of 1 hour).

The measurement on the respective hardware platform is then carried out by using the digital service over a longer period of time or several times. By using suitable logging tools, it is possible to record how many usage units were accessed and how much digital work (DW) was performed.

In Table 2 lists the measured values that must be collected when measuring a software product or digital service:

Table 2: Measurement of the used digital work (DW) of a software product

- Service units: Number of utilisation units in the measurement period [no.]
- DW_{co}: CPU or GPU work calculated from full load seconds [Gbit/s*s]
- DW_{me}: RAM memory work [GByte seconds]
- DW_{st}: Permanent memory work [GByte seconds]
- DW_{tr}: Data transmission work [Mbit/s*s]

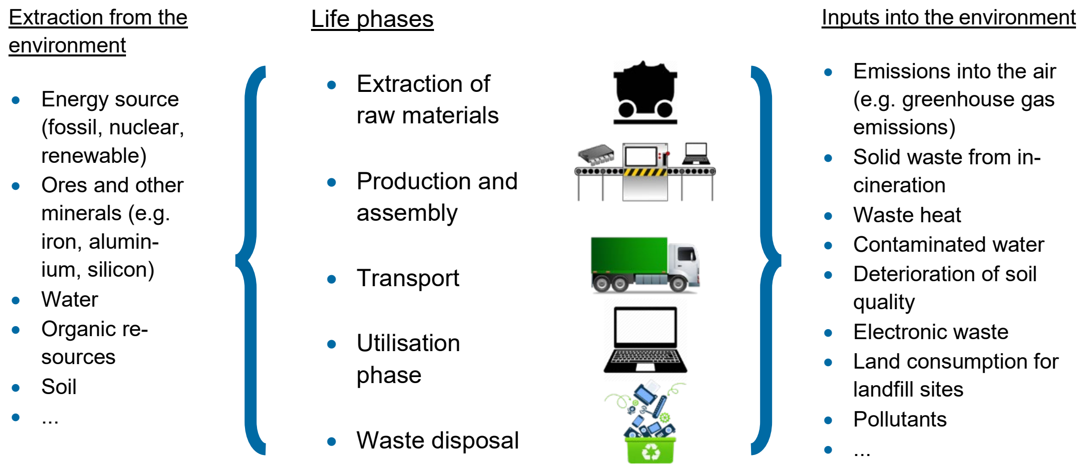
Source: Öko-Institut, note: a different measurement parameter can be selected for CPU or GPU work if required

When applying the method, the service unit must be defined depending on the context. This can be, for example, hours of use, number of calls or executions of a usage scenario, customers served or data volumes. The measurement results are then divided by the number of utilisation units so that the digital work per service unit can be communicated.

Life cycle assessment

The methodology of the product-related life cycle assessment is described in detail in ISO standard 14040/14044. A key feature of *life cycle assessment* is that a product and the materials from which it is made are analysed along their entire life cycle. From the extraction of raw materials to their transport, processing into intermediate products, production and assembly, transport to the place of use, utilisation and finally disposal or, if applicable, recycling. Along the entire life cycle, it is analysed which resources are extracted from the environment and which harmful inputs are returned to the environment. This may also involve emissions from the processes involved, for example the emissions of combustion gases from electricity production, which in turn supplies the electricity for the production and utilisation phase.

Figure 2: Inputs and outputs along the life phases



Source: Öko-Institut

The inputs into the environment are assessed in the LCA using so-called *environmental impact categories*. This makes it possible to assess and summarise different pollutants (or impacts in general) using uniform standards. For example, if there are emissions of carbon dioxide (CO_2), methane (CH_4) and refrigerant R134a ($C_2H_2F_4$), these can be weighted and summarised according to their specific global warming potential (CO_2: 1; CH_4: 28; $C_2H_2F_4$: 1,503 kg CO_2 e/kg). The unit for the environmental impact of global warming potential is then kilogrammes of carbon dioxide equivalents (kg CO_2 e).

Due to the high relevance of climate protection, life cycle assessments are often reduced to their global warming potential. For example, the product carbon footprint (PCF) according to ISO 14067 only provides for the reporting of CO_2 equivalents of a product. As part of the eco:digit project, other relevant environmental impact categories are deliberately analysed for digital services. This makes it possible to visualise further environmental impacts, such as resource consumption and pollutant emissions from software and IT infrastructure.

The following *environmental impact categories* (EI) are analysed in eco:digit using a simplified life cycle assessment approach:

- CED: Cumulated Energy Demand [J] is the primary energy demand that was used to provide a form of energy or for a process.
- GWP: Global Warming Potential [kg CO_2 e] is a measure of greenhouse gas equivalents that quantifies the environmental impact of climate change.

- ADP: Abiotic resource consumption [kg antimony equivalent] measures the mineral and metallic raw material requirements, weighted according to their availability in relation to antimony.
- Water: is a volume specification that evaluates the water consumption (taking availability into account) [m^3 world eq].

In addition, the following indicators are assessed at product level and at the level of process chemicals:

- WEEE: Waste of Electrical and Electronic Equipment [kg] measures the amount of electric and electronic waste generated when disposing of appliances.
- TOX: characterises the amount of problematic substances used in the production or use of the hardware or contained in the product, measured in kilograms of monoethylene glycol equivalents [kg MEG eq] (Bunke et al. 2024, Bunke and Graulich 2003, Liu et al. 2024).
- SVHC score [1...5]: describes the availability of information on substances of very high concern (SVHC) in a product (Bunke et al. 2024, Liu et al. 2024). The following applies:
  - 1: SVHC content specified (name, concentration, component) or none contained,
  - 2: SVHC identified (names of SVHC),
  - 3: Receive information,
  - 4: Information requested,
  - 5: No information, no activity.

Manufacturing impacts

In this method, the **environmental manufacturing impact** of hardware (often also referred to as *embedded emissions* or *embedded environmental impacts*) are determined using life cycle assessment methods. **Transport emissions**, if known, are allocated to the manufacturing emissions. However, for the assessment of electronic products, it is assumed that transport emissions contribute only insignificantly to the overall result, as the actual manufacturing impacts are very high.

A special feature of the eco:digit life cycle assessment is that the environmental impact of a product is calculated separately for the electronic components processors, main memory, permanent memory and network components. These components are the electronics that essentially provide the basic digital resources (see above). On the one hand, this approach facilitates the subsequent allocation of utilised basic digital resources to their environmental impact; on the other hand, it allows different configurations of devices to be mapped more precisely if the manufacturer data only applies to a specific configuration. The shared components that cannot be allocated to a basic resource (e.g. power supply units, housings, circuit boards) are allocated proportionally to the individual main components as overhead. This produces a differentiated presentation of results according to the scheme in Table 3:

Table 3: Breakdown of environmental impacts by hardware components

Hardware component (hw)	Net EI $_{hw}$ (example values)	Allocation factor for overhead z_{hw}	Allocated overhead	Gross EI_{hw}	Assignment to the basic digital resource
CPU/GPU	a = 150	a/(a+b+c+d) = 48%	24	A = 174	co (compute)
RAM	b = 100	b/(a+b+c+d) = 32%	16	B = 116	me (memorise)
SSD/HDD	c = 50	c/(a+b+c+d) = 16%	8	C = 58	st (store)
Network component	d = 10	d/(a+b+c+d) = 3%	2	D = 12	tr (transfer)
Other components (over-heads)	e = 50	-	-	-	-
Total	Σ = 360	Σ = 100%	Σ = 50	Σ = 360	

Source: Öko-Institut Key: EI = environmental impact category (CED, GWP, ADP, Water, WEEE, TOX)

$$z_{hw} = \frac{Netto\ EI_{hw}}{\sum Netto\ EI_{hw}\ ohne\ Overhead}$$

$$Brutto\ EI_{hw} = Netto\ EI_{hw} + z_{hw} \cdot Netto\ EI\ Overhead = z_{hw} \cdot \sum Netto\ EI_{hw}$$
$$mit\ hw = \{CPU, GPU, RAM, \ldots\}$$

In the context of the eco:digit project, a calculation tool is also being developed for the approximate life cycle assessment of digital products, which provides rough results for the manufacturing phase of hardware products with the aforementioned environmental impact categories (CED, GWP, ADP, water). The input parameters are the technical data of the most relevant electronic components (CPUs, GPUs, RAM, SSDs, HDDs), power supply units, housing materials and printed circuit board (PCB) surface area (see Table 10). If no product-specific life cycle assessments have been carried out for the hardware, this tool can be used as a workaround.

If life cycle assessments or environmental product declarations (EPDs) are already available for the respective digital product, at least the manufacturing emissions (production and transport) and the electronic waste quantities can be taken from these. For energy consumption in the utilisation phase, a standardised calculation should be made for all digital products, which can be found in the chapter Power consumption of hardware.

Utilisation phase

During the use phase of digital devices, there are generally no direct emissions from the devices themselves, but there are indirect environmental impacts from electricity consumption (e.g. greenhouse gas emissions, primary energy requirements) and from the data centre infrastructure (water consumption due to evaporative cooling, emissions of refrigerants). The focus here is therefore on recording energy consumption during the utilisation phase.

Power consumption of hardware

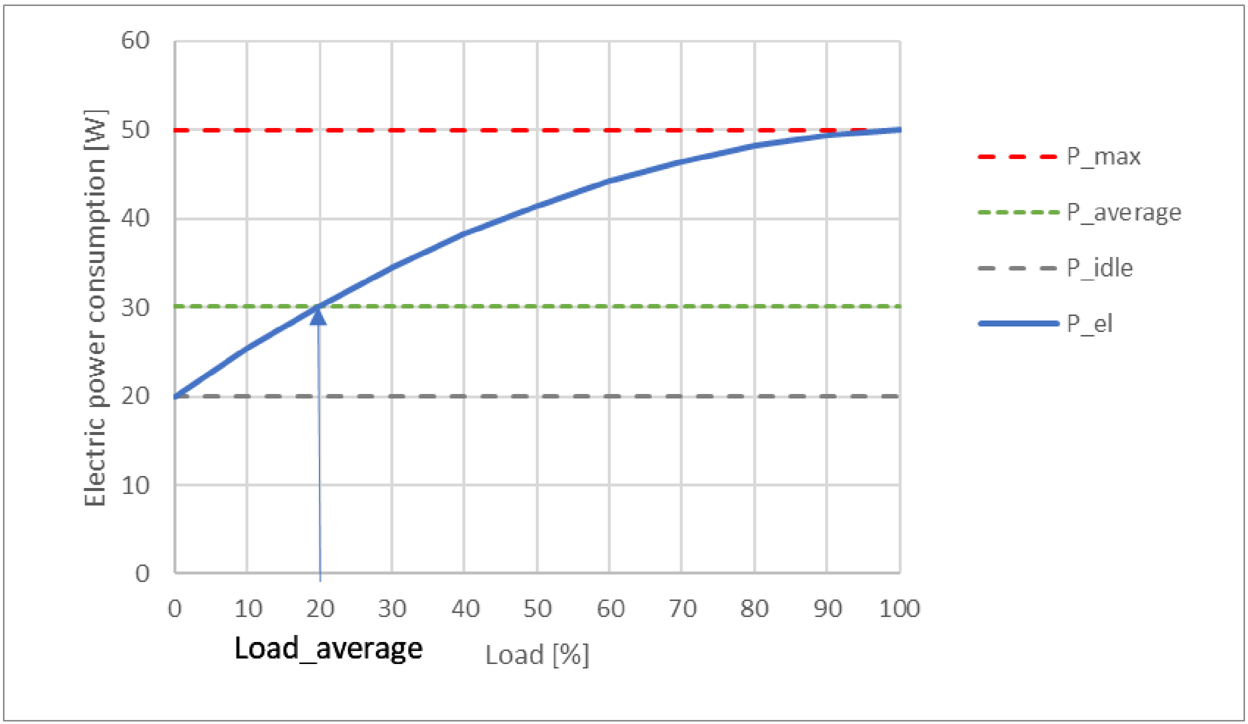
Similar to the procedure for calculating manufacturing impacts, the energy consumption of the hardware is also measured separately according to the individual hardware components involved. In contrast to the fixed manufacturing impacts, however, the energy consumption of the hardware increases depending on the intensity of use and useful life.

The electrical power consumption of each individual component can in principle be described by a fixed basic component (P_{idle}) and a variable component ($P_{variable}$) that depends on the utilisation.

$$P_{el} = P_{idle} + P_{variable}$$

In Figure 3 shows the relationship between utilisation (*load*) and electrical power consumption of any hardware component.

Figure 3: Electrical power consumption of a hardware component depending on its utilisation



Source: Öko-Institut

The curve of the electrical power consumption (P_el) in Figure 3 starts at a base value (P_idle) of 20 watts and then rises to a maximum value of 50 watts (P_max) as the load increases. The average utilisation (Load_average), which is shown here at 20 %, leads to an average power consumption (P_average) of 30 watts. The illustration is only an example. The actual curve must be determined by measurements on the respective hardware component.

As a first approximation, the power consumption curve can be described as a linear curve between P_idle (load = 0) and P_max (load = 100%), which can then be represented as a linear formula as follows:

$$P_{el}(Load) = P_{idle} + Load \cdot (P_{max} - P_{idle})$$

More realistic results are obtained if the hardware is measured under different load conditions and the curve is approximated using a quadratic formula:

$$P_{el}(Load) = P_{idle} + a \cdot Load + b \cdot Load^2$$

In Boavizta's calculation model (2024), a logarithmic formula with 4 parameters is used as an approximation for the power consumption of CPUs (see https://doc.api.boavizta.org/Explanations/components/cpu/):

$$P_{el}(Load) = a \cdot \ln\big(b \cdot (Load + c)\big) + d$$

Regardless of the accuracy with which the power consumption curve is described, a suitable formula should be found for each hardware component that provides a basic digital resource. This formula P_{el} *(Load)* must establish the relationship between the utilisation (i.e. the proportion of the maximum available basic digital resource) and the electrical power consumption of this component.

The following Table 4 shows (using arbitrary example values) what the results of a measurement of the hardware components could look like. The power consumption in idle mode (P_{idle}), the maximum power consumption of the respective component (P_{max}) and the average utilisation of the respective hardware component ($_{load}$ average) are shown.

Table 4: Breakdown of power consumption by hardware components

Hardware component (h)	P_{idle}	P_{max}	Average capacity utilisation ($load_{average}$)	Net $P_{average}$	Allocation factor for overhead z_{hw}	Gross $P_{average}$	Allocation DBR
CPU	50 W	150 W	20%	70 W	47%	81,7 W	co
GPU	20 W	100 W	5%	24 W	16%	28,0 W	co
RAM	20 W	20 W	10%	20 W	13%	23,4 W	me
SSD	10 W	10 W	50%	10 W	7%	11,7 W	st
HDD	20 W	20 W	50%	20 W	13%	23,4 W	st
NW (network component)	5 W	5 W	2%	5 W	3%	5,8 W	tr
Other components (=overhead)	25 W	25 W	100%	25 W	-	-	-
Total	$\Sigma = P_{idle}$ = 150 W	$\Sigma = P_{max}$ = 330 W		$\Sigma =$ Net $P_{average}$ = 174 W	Σ = 100%	$\Sigma =$ Gross $P_{average}$ = 174 W	

Source: Öko-Institut

Some of the components do not change their electrical power consumption, regardless of how heavily they are utilised. For example, the electrical power consumption of a hard disk drive (HDD) does not change with the storage capacity used on it. The idle power is always equal to the maximum power consumption. However, the actual utilisation makes a difference to the specific power consumption per storage capacity, as the hard disk only performs as much useful IT work as it actively provides in terms of storage space, while the energy consumption remains the same. Verifying this and substantiating it with concrete figures will be part of the measurements to be carried out.

The average utilisation is again (as with the calculation of the available DBR) a key parameter for calculating the average power consumption ($P_{average}$).

The share of the power consumption of other components (overhead) that are not allocated to a digital basic resource is added to the average net power consumption. The average gross power consumption is calculated using the *allocation factor for overhead* (z_{hw}):

$$z_{hw} = \frac{Netto\ P_{average_{hw}}}{Netto\ P_{average\ without\ overhead}}$$
$$\text{with } hw = \{CPU, GPU, RAM, SSD, HDD, NW\}$$

Whereby *net P*$_{average\ without\ overhead}$ applies to the denominator:

$$Netto\ P_{average\ without\ overhead} = \sum Netto\ P_{average_{hw}}$$

$$with\ hw = \{CPU, GPU, RAM, SSD, HDD, NW\}$$

The calculation of the gross power consumption of the DBR components is then calculated as follows:

$$Brutto\ P_{average_{hw}} = Netto\ P_{average_{hw}} + z_{hw} \cdot Netto\ P_{average_{Overhead}} = z_{hw} \cdot Netto\ P_{average_{total}}$$

$$\text{with } hw = \{CPU, GPU, RAM, SSD, HDD, NW\}$$

These average power consumption values are used to calculate the energy consumption of the respective component when running software. This is done by calculating Effort benefit ratios for utilisation phase which are determined for each of the basic digital resources (co, me, st, tr). These effort indicators are used to create a mathematical function that calculates the energy consumption of the respective computer platform as a function of the required digital work (DW):

$$E_{Software} = function(Platform, DW_{co}, DW_{me}, DW_{st}, DW_{tr}) \qquad [kWh_{el}]$$

The utilisation time of the platform by the software enters the calculation of energy consumption via the consumed digital work (DW = DBR * t) (compare Table 2). During this period, the computer platform is switched on and not in the off state. The average power consumption is therefore calculated as the power consumption in the switched-on state and not the average value together with the switched-off state. See also the notes under Excursus: Average capacity utilisation.

Conversion of electricity consumption into environmental impact

The environmental impacts in the utilisation phase must be determined for the life cycle assessment.
This is done by converting the electrical energy consumption ($E_{Software}$) into the analysed environmental impact categories (EI_{ei}) by multiplying them by an emission factor (EF_{ei}):

$$EI_{ei,usephase} = EF_{ei} \cdot E_{Software} \text{ with } ei = \{CED, GWP, ADP, \ldots\}$$

As the power consumption of the software ($E_{Software}$) is the sum of the power consumption of the individual hardware components, the environmental impacts can also be calculated component by component and the environmental impacts can also be summed up afterwards. This makes it possible to better visualise the influence of the individual hardware components.

The following Table 5 shows the emission factors (EF) of the different environmental impact categories (EI) for electrical energy from the German electricity mix of the low-voltage grid from 2020.

Table 5: Emission factors for electrical energy

Environmental impact category (EI)	Emission factor (EF)	Example value (electricity mix, DE, 2020)	Unit
CED	CED_{el}	8,37	[MJ/kWh_{el}]
GWP	GWP_{el}	0,421	[kg CO_2 e/kWh_{el}]
ADP	ADP_{el}	5,24 E-6	[kg Sb eq/kWh_{el}]
Water	$Water_{el}$	0,239	[m³ world eq/kWh_{el}]
WEEE	$WEEE_{el}$	n.a.	[kg $_{WEEE}$/kWh_{el}]
TOX	TOX_{el}	n.a.	[kg MEG eq/kWh_{el}]

Source: Öko-Institut (according to Ecoinvent 3.10) Legend: n.a. = not applicable

Special considerations for hardware in data centres

If hardware is operated in a **data centre**, there is an overhead from the building infrastructure in addition to the power consumption of the hardware. The actual power consumption of the devices then increases by the PUE (Power Usage Effectiveness).

The PUE is defined in accordance with the norm EN 50600-4-2 as:

$$\text{PUE} = \text{Power consumption of the data centre} \;/\; \text{power consumption of information technology}$$

The environmental impact of the software in the data centre therefore also increases by the PUE and can be calculated in simplified terms as follows:

$$EI_{ei,usephase\ in\ DC} = EF_{ei} \cdot PUE \cdot E_{Software} \text{ with } ei = \{CED, GWP, ADP, \ldots\}$$

In addition to the add-on of electricity consumption, direct emissions can also occur in the data centre e.g., from the backup power systems (combustion exhaust gases), from the cooling systems (loss of refrigerants) or the electrical switchgear (SF_6 protective gas emissions) as well as direct water consumption (evaporative cooling) and the generation of additional electrical and electronic waste (e.g. lead batteries from the uninterruptible power supply).

Such additional emissions can again be related to the electricity consumption of the data centre, resulting in correction values for the emission factors for electrical energy ($EF_{ei,addon}$). Instead of using the pure emission factors of the national electricity mix ($EF_{ei,grid}$) as shown in Table 5, the following formula can be used as an emission factor for electricity consumption in data centres ($EF_{ei,DC}$):

$$EF_{ei,DC} = \left(EF_{ei,grid} + EF_{ei,addon}\right) \text{ with } ei = \{CED, GWP, ADP, \ldots\}$$

For example, if the data centre has an annual e-waste quantity of 1 tonne of lead batteries with a total electricity consumption of 10 GWh/a, then the correction value for the emission factor for e-waste is $EF_{WEEE,addon}$ = 0.1 g $_{WEEE}$/kWh_{el}.

Together with the above consideration of the energy losses of the building technology via the PUE, this results in the environmental impact of the software in data centres:

$$EI_{ei,usephase\ in\ DC} = \left(EF_{ei,grid} + EF_{ei,addon}\right) \cdot PUE \cdot E_{Software} \text{ with } ei = \{CED, GWP, ADP, \ldots\}$$

Disposal phase

When **disposing** of IT equipment, raw materials could in principle be (partially) recovered and offset against credits in a life cycle assessment. Such credits are not used here, not only because the specific disposal paths of the devices cannot be predicted in most cases. Instead, the use of recycled materials within the above-mentioned manufacturing phase can be taken into account to reduce emissions.

However, the **quantities of electronic waste are** recognised here as the environmental impact of disposal, regardless of where the waste ends up. The environmental impact category WEEE (Waste of Electrical and Electronic Equipment) is used to record the amount of waste in kilograms, which in turn can be allocated to the individual software applications.

Merging life cycle assessment, DBR and digital supply chain

The three concepts described above - the digital supply chain, basic digital resources and life cycle assessment - are now being merged into a common calculation method.

Firstly, the first two concepts of LCA and DBR are combined. While the LCA describes the environmental **effort** of a hardware component, the concept of basic digital resources describes the **benefit** of the respective digital platform. Therefore, in the next methodological step, ratios of the effort and benefit are taken.

In principle, the following applies:

$$EBR = effort\ benefit\ ratio = \frac{effort}{benefit}$$

EBR is used as an abbreviation for the *effort benefit ratio*.

Effort benefit ratio for manufacturing

The environmental impacts of manufacturing the computer platform was allocated to the basic digital resources provided (gross $EI_{dbr,embedded}$), using the allocation rules described above (Manufacturing impacts). This effort is now compared with the benefit of the computer platform.

For this purpose, the digital work that is generated on average (DW_{DBR}) is calculated as described above (Hardware provides basic digital resources). This calculation takes into account the average utilisation over the entire service life of the hardware ($load_{average}$) and its technical service *life* (*lifetime*). Hardware that is used more intensively therefore provides a greater amount of digital work. Hardware that is used for a longer lifetime generates this work with a lower production effort per work unit. The calculation therefore deliberately does not assume the maximum possible work of a piece of hardware, but the work actually performed. This means that the actual operation of the IT platform also has an influence, and it makes a difference, for example, whether the server under consideration is operated in a server room with low capacity utilisation or in a data centre with high capacity utilisation.

The formula for calculating the expense ratios (EBR_EI_{DBR}) is:

$$EBR_{ei_{DBR}} = \frac{Gross\ EI_{dbr,embedded}}{DW_{dbr}}$$

$$= \frac{Gross\ EI_{dbr,embedded}}{DBR_{dbr} \cdot Load_{average,dbr} \cdot Lifetime} \text{ in } \left[\frac{\text{unit of EI}}{\text{unit of DBR} \cdot \text{s}}\right]$$

$$\text{with } ei = \{CED, GWP, ADP \ldots\} \text{ and } dbr = \{co, me, st, tr\}$$

Specifying the effort according to the environmental impact categories (EI = {CED, GWP, ADP, Water, WEEE, TOX}) and the benefit according to the basic digital resources (DBR = {compute, memorise, store, transfer}) results in a total of 6 times 4 different effort indicators:

Table 6: Effort Benefit Rations for manufacturing EBR_EI_{DBR}

Environmental impact category (EI)	compute	memorise	store	transfer
CED	EBR_CED_{co}	EBR_CED_{me}	EBR_CED_{st}	EBR_CED_{tr}
GWP	EBR_GWP_{co}	EBR_GWP_{me}	EBR_GWP_{st}	EBR_GWP_{tr}
ADP	EBR_ADP_{co}	EBR_ADP_{me}	EBR_ADP_{st}	EBR_ADP_{tr}
Water	EBR_Water_{co}	EBR_Water_{me}	EBR_Water_{st}	EBR_Water_{tr}
WEEE	EBR_WEEE_{co}	EBR_WEEE_{me}	EBR_WEEE_{st}	EBR_WEEE_{tr}
TOX	EBR_TOX_{co}	EBR_TOX_{me}	EBR_TOX_{st}	EBR_TOX_{tr}

Source: Öko-Institut

In Table 7 shows the effort benefit ratios for a fictitious computer system with the manufacturing impact from Table 3 and the basic digital resources from Table 1. A technical service life (lifetime) of 4 years was assumed.

Table 7: Example calculation of the effort benefit ratios EBR_EI_{DBR}

DBR abbreviation	Environmental impact Gross $EI_{ei,embedded}$ (e.g.: EI $)_{GWP}$	Digital work (DW_{DBR}) provided over the lifetime at average utilisation ($_{load}$ coverage)	effort benefit ratios for manufacturing $EBR\_EI_{DBR} = EI_{ei},embedded/DW_{DBR}$ (Example: EBR_GWP $)_{DBR}$
co (compute)	174 kg CO_2 e	53,821,440 Gbit	3.23 E-06 kg CO_2 e/Gbit
me (memorise)	116 kg CO_2 e	1,681,920 gigabytes*s	6.90 E-05 kg CO_2 e/(gigabyte*s)
st (store)	58 kg CO_2 e	4,204,800,000 gigabytes*s	1.38 E-08 kg CO_2 e/(gigabyte*s)
tr (transfer)	12 kg CO_2 e	4,204,800 megabits	2.85 E-06 kg CO_2 e/megabit

Source: Öko-Institut

The effort benefit ratios (EBR_EI_{DBR}) describe the respective hardware platform and its average utilisation and are the result of the life cycle assessment differentiated by component. The environmental impact of the utilisation of a platform by a software can then be calculated depending on the digital work (DW) used:

$$EI_{ei,embedded} = function(Platform, DW_{co}, DW_{me}, DW_{st}, DW_{tr})$$
$$\text{with } ei = \{CED, GWP, ADP \ldots\}$$

The respective formulas behind this function have the following structure, illustrated using the example of the environmental impact category for primary energy demand (CED):

$$EI_{CED,embedded} = DW_{co} \cdot EBR_{CED_{co}} + DW_{me} \cdot EBR_{CED_{me}} + DW_{st} \cdot EBR\_CED_{st} + DW_{tr} \cdot EBR\_CED_{tr}$$

Or in general:

$$EI_{ei,embedded} = \sum_{dbr} DW_{dbr} \cdot EBR_{ei_{dbr}}$$

$$\text{with } ei = \{CED, GWP, ADP \dots\} \text{ and } dbr = \{co, me, st, tr\}$$

These environmental impacts initially only relate to the manufacturing effort of the hardware ("embedded environmental impacts") and, in the case of electronic waste (WEEE), precisely these. They do not yet include energy consumption and any other environmental impacts that occur when the hardware is used.

Effort benefit ratios for utilisation phase

In the utilisation phase of a hardware component, environmental impacts arise in particular from the use of electric energy.

The effort benefit ratios are therefore first calculated for electric energy consumption (E) and only then converted into environmental impacts ($EI_{usephase}$). In principle, both steps could also be combined so that the basic digital resources can be converted directly into environmental impacts in the utilisation phase. However, as the emission factors for electricity production vary depending on the time of day, season, and geographical location, it is advisable for reasons of transparency to first calculate the electricity consumption and only then the associated environmental impacts.

In Table 8, the calculation of the expenditure figure for the utilisation phase is based on the average power consumption during operation, here with example values from Table 4 and the average basic digital resources provided ($DBR_{average}$) from Table 1.

Table 8: Effort benefit ratios in utilisation phase (P_{el} in relation to DBR)

DBR abbreviation	$P_{average}$ (gross)	Average basic digital resource provided basic digital resource ($DBR_{average}$)	EBR_P = $P_{average}$/$DBR_{average}$
co (compute)	81,7 W	25.6 GHz*bit	3.1932 W/(GHz*bit)
me (memorise)	23,4 W	0.8 gigabyte	29.1946 W/Gigabyte
st (store)	11,7 W	2,000 gigabytes	0.0058 W/gigabyte
tr (transfer)	5,8 W	2 megabit/s	2.9195 W/(megabit/s)

Source: Öko-Institut

The product of the average power consumption [W] and the technical service life [s] gives the energy consumption [Ws] of each component. If this energy consumption is set in relation to the digital work (DW) supplied by the component over its service life, the energy consumption per component is obtained. The technical service life cancels out in this calculation. Therefore, the power and capacity values were used in Table 8 (P and DBR) instead of the energy and work values (E and DW).

It applies generally:

$$EBR\_P_{dbr} = \frac{P_{dbr,average}}{DBR_{dbr,average}} \text{ with } dbr = \{co, me, st, tr\} \quad \text{[W/(unit of DBR)]}$$

The energy consumption of the various hardware components used by the software, including the allocated energy overhead from the other components, is then calculated as follows:

$$E_{dbr} = DW_{dbr} \cdot EBR\_P_{dbr} \text{ with } dbr = \{co, me, st, tr\} \qquad [Ws_{el}]$$

Or with the unit kilowatt hours:

$$E_{dbr} = \frac{DW_{dbr} \cdot EBR\_P_{dbr}}{1000 \cdot 3600} \text{ with } dbr = \{co, me, st, tr\} \qquad [\text{kWh}_{\text{el}}]$$

And for all basic digital resources that are required to run software:

$$E_{Software} = E_{co} + E_{me} + E_{st} + E_{tr} \qquad [\text{kWh}_{\text{el}}]$$

The energy consumption of the software ($E_{Software}$) is then converted into environmental impacts during the utilisation phase ($EI_{usephase}$) using the emission factors (EF_{grid}) for each of the impact categories analysed, as shown in Table 5:

$$EI_{ei,usephase} = EF_{ei} \cdot E_{Software} \text{ with } ei = \{CED, GWP, ADP, \ldots\}$$

In the special case that the software is operated in a data centre and the losses and additional emissions of the building technology are to be taken into account (see Special considerations for hardware in data centres), the environmental impacts are calculated as follows:

$$EI_{ei,usephase\ in\ DC} = \left(EF_{ei,grid} + EF_{ei,addon}\right) \cdot PUE \cdot E_{Software} \text{ with } ei = \{CED, GWP, ADP, \ldots\}$$

Environmental impacts of software by hardware production and utilisation phase

The total environmental impact of the software on a single platform is ultimately calculated from the share of the environmental impact that comes from the production phase ($EI_{embedded}$) and the share from the utilisation phase ($EI_{usephase}$).

$$EI_{ei} = EI_{ei,embedded} + EI_{ei,usephase} \quad \text{ with } ei = \{CED, GWP, ADP, \ldots\}$$

In order for the environmental impacts to be understandable and interpretable, the functional unit to which they relate and the computer platform for which the calculation was made should be documented together with these quantities. For example, the information could read: "Execution of a standard usage scenario of software X over a period of one hour on a desktop computer."

Accounting along the digital supply chain

The calculation presented so far for a single computer platform must be repeated for each platform involved in the digital service. Therefore, the concept of the digital supply chain is now added.

The parameters (e.g., environmental manufacturing impacts, energy consumption, average utilisation, computing power, etc.) of the platforms involved differ. The expenditure figures for production and utilisation must be determined individually for each of the platforms. In addition, the level of utilisation of the hardware capacities by the digital service, measured as digital work used (DW), must be measured or simulated for each of the platforms.

In Table 9, this is shown as an example for a digital service that runs software on a *desktop computer* and sends data to the *transmission network* via a *home router*. The transmission network is summarised here as the sum of the individual network nodes. The data reaches a *network switch* in the data centre (DC), is processed further by a *server* in the data centre and some of the data is *stored* in a *storage system*.

Table 9: Digital work (DW) along the digital supply chain

Digital work	Desktop computer	Home router	Transmission network	DC network switch	DC server	DC storage	Unit
DW_{co}	44.851	-	-	-	134.554	-	Gbit
DW_{me}	4.205	-	-	-	8.410	-	Gigabyte*s
DW_{st}	5.256.000	-	-	-	657.000	1.971.000	Gigabyte*s
DW_{tr}	21.024	21.024	21.024 *	21.024 *	31.536	10.512	Megabit

Source: Öko-Institut * the data volumes in the transmission grid and data centre are likely to be higher than the data generated by the user. Corresponding factors still need to be worked out or measured.

Distributing the digital work across the digital supply chain in Table 9, it becomes clear that not every "chain link" performs the same work. For example, all the network components listed in the table are limited to performing the digital work *transfer* (DW_{tr}). This has the side effect that all production emissions and energy consumption in the utilisation phase can be related to this one core task and a breakdown into the other basic digital resources is not necessary (see Simplifications for network components and storage systems).

The difference between software and digital services also becomes clear. The software is limited to a single platform, in this case the desktop computer on the one end and the DC server on the other. Each of these two platforms runs a different software code, which generates its own load there and thus leads to different digital work. The digital service, on the other hand, is provided by the sum of the platforms involved.

The environmental impacts for each individual platform along the digital supply chain can then be added together so that the following applies:

$$EI_{ei} = \sum_{p} EI_{ei_p}$$

$$\text{with } ei = \{CED, GWP, ADP, \ldots\}$$

$$\text{and } p = \{platform\ 1, platform\ 2, platform\ 3, \ldots\}$$

Here too, when communicating the environmental impacts, the functional unit and the platforms involved in the provision of the digital service should be specified. The information could therefore read as follows: "Delivery of a video stream over a period of one hour from a data centre in Germany via the Internet to a private DSL router and displaying it on a desktop computer."

Simplifications for network components and storage systems

Within this method description, emphasis was placed on dividing the digital work performed by hardware components into the various basic digital resources (*compute, memorise, store, transfer*) and differentiating the environmental impacts according to these (see Basic digital resources).

However, some of the systems along the digital supply chain are used specifically to provide a single basic digital resource. This applies in particular to network components, such as switches, routers, network access points, antennas or signal amplifiers, which are operated specifically to provide data transmission (*transfer*). The same applies to storage systems in data centres (storage systems) or in local networks (network attached storages), which are operated exclusively for storing data (*store*). Even if microprocessors and main memory are also involved in organising the data in these systems, these supplementary hardware resources can be seen as overheads that help to fulfil the actual core task of the system (data transfer or data storage). This overhead can be fully allocated to the basic digital resource that provides the function.

Effort benefit ratios for monofunctional systems

This results in considerable simplifications for such monofunctional systems.
The calculation of the **effort benefit ratios for manufacturing (EBR_EI$_{DBR}$)** is limited to a single basic digital resource, as shown below using the example of a network switch (transfer):

$$EBR_{ei_{tr}} = \frac{EI_{embedded}}{DW_{tr}}$$
$$= \frac{EI_{embedded}}{DBR_{tr} \cdot Load_{average,tr} \cdot Lifetime} \text{ in } \left[\frac{unit\ of\ EI}{Mbit}\right]$$
$$\text{with } ei = \{CED, GWP, ADP, \dots\}$$

Environmental impacts for manufacturing (EI$_{embedded}$) are defined here as the total manufacturing impacts for the network switch, differentiated according to the environmental impact categories analysed (CED, GWP, ADP, etc.). The digital work (DW$_{tr}$) consists of the amount of data transmitted during the technical service life of the switch. The other EBR ratios for other basic digital resources are set to zero for this switch.

The **environmental impact for the production of** the network switch, which is caused by the transmission of a certain amount of data, is then calculated in this simplified form as the product of the expenditure indicator (EBR_EI$_{tr}$) and the amount of data transmitted (DW$_{tr}$):

$$EI_{ei,embedded} = DW_{tr} \cdot EBR_{ei_{tr}} \text{ in } [(\text{unit of } ei)]$$
$$\text{with } ei = \{CED, GWP, ADP \dots\}$$

Utilisation phase of monofunctional systems

The same simplifications are used for energy consumption in the utilisation phase to calculate the environmental impacts in the utilisation phase (EI$_{usephase}$).

The average electrical power consumption of the network system (P$_{average}$) is used to calculate **the expenditure figures in the utilisation phase (EBR_P$_{DBR}$)**. The average data transmission speed (bandwidth) of the system during the technical service life is selected as the basic digital resource provided (here only *transfer*):

$$EBR\_P_{tr} = \frac{P_{average}}{DBR_{tr,average}} \qquad \text{[W/(Mbit/s)]}$$

The other key figures (EBR_P$_{co}$, EBR_P$_{me}$, EBR_P$_{st}$) of the unused basic digital resources can also be set to zero here, as the entire energy consumption has already been allocated to the data transmission.

The **environmental impacts in the utilisation phase** (EI$_{ei,usephase}$) are calculated as the product of the effort benefit ratio (EBR_P$_{tr}$), the amount of data transmitted (DW$_{tr}$) and the respective emission factor (EF$_{ei}$) of the electrical energy used:

$$EI_{ei,usephase} = EBR_{P_{tr}} \cdot DW_{tr} \cdot EF_{ei} \text{ in } [(\text{unit of } ei)]$$
$$\text{with } ei = \{CED, GWP, ADP \dots\}$$

Similarly, the same simplifications also apply to storage systems (store) and, in principle, to the other basic digital resources (compute, memorise) if they are only accessed individually and their energy consumption and environmental impact can be isolated (e.g., individual RAM memory banks).

Data collection

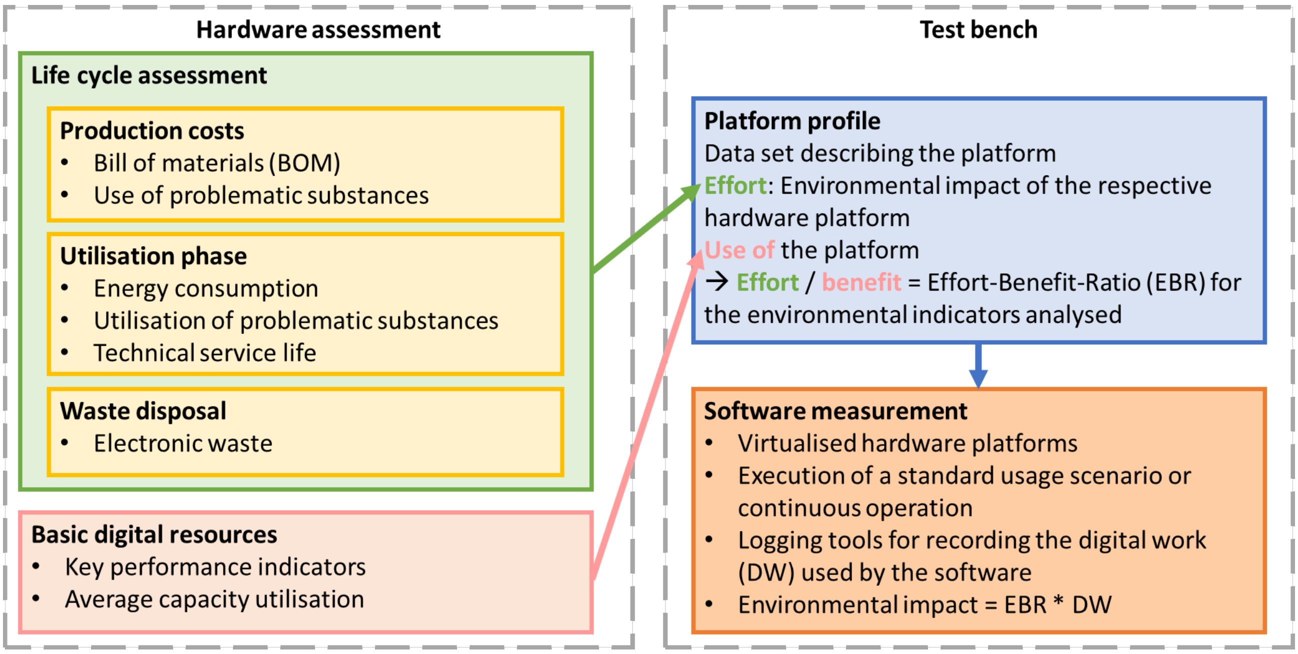
In order to carry out a life cycle assessment of software and digital services, data must be collected from the hardware platforms involved as well as data about the execution of the software on the respective platforms.

The following chapter outlines the minimum data that needs to be collected. This list is not exhaustive, but provides an initial overview of the measurements and assessments that need to be carried out by the project participants in the eco:digit project. As an alternative to a rough calculation using the input parameters listed below, you can of course also use your own life cycle assessments or *product environmental footprints* as a data basis.

Once the platforms have been measured, the effort indicators described above can be calculated and the figures can be abstracted as a *Platform profile*. Each platform is then included in the calculation within the digital test bench as a parameterised black box, which can be used to calculate the environmental impact of the software without further knowledge of the technical details of the platform.

Figure 4 shows the data collection schematically. The individual data collection steps are explained in more detail in the following sections.

Figure 4: Scheme of data collection



Source: Öko-Institut

Hardware level

Information on components and materials

In order to calculate the environmental manufacturing impacts of a product, a bill of materials (BOM), which describes the components and materials that make up a product, is first created in the life cycle assessment. For information technology products, existing life cycle assessments show that the main environmental impacts can be attributed to a reduced number of electronic components and materials.

The following list of input parameters is therefore sufficient for estimating the environmental impacts of manufacturing. The data on cables, flame retardants, plasticisers, and substances of very high concern ("SVHC") are required for the presentation of the pollutant content of the devices and the state of knowledge on the occurrence of SVHC (see section Problematic substances).

Table 10: Information on components and materials

Designation	Measured variable	Unit	Explanation
Complete device			
Device name	Free text	[text]	Data sheet!
Predominant function	Free text	[text]	[not specified, co, me, st, tr]
Technical service life	Free text	[Year]	Own determination
Housing			
Weight of entire device without PSUs	Weight	[kg]	Measure value!
Steel	Weight	[kg]	Measure value!
Aluminium	Weight	[kg]	Measure value!
Copper	Weight	[kg]	Measure value!
Plastics	Weight	[kg]	Measure value!
Fan			
Number of fans	Quantity	[-]	Data sheet! (optional)
Weight of all fans	Weight	[kg]	Measure value!
Cables			
Weight of all cables incl. plug and insulation	Weight	[kg]	Data sheet! (optional)
Printed circuit boards			
Area of the assembled printed circuit boards	Surface area	[cm²]	All circuit boards incl. mainboard, power board, graphics cards, etc. without network and SSD card
CPU			
Number of CPUs	Quantity	[-]	Data sheet!
Cores per CPU	Quantity	[-]	Data sheet!
Die size per CPU	Surface area	[cm²]	Data sheet! (optional)
TDP (thermal design power) per CPU	Electrical power	[Watt]	Data sheet!
Weight per CPU heatsink	Weight	[kg]	Measure value! (optional)
GPU card(s)			
Total: Number of GPUs	Quantity	[-]	Data sheet!
Die size per GPU	Surface area	[cm²]	Data sheet! (or https://www.techpowerup.com/gpu-specs/)
RAM			
Number of RAM modules	Quantity	[-]	Data sheet!
Storage space per RAM	Quantity	[GByte]	Data sheet!
Die size per RAM	Surface area	[cm²]	Data sheet! (optional)
SSD			
Quantity	Quantity	[-]	Data sheet!
Storage space per SSD	Quantity	[TByte]	Data sheet!
Die-Size per SSD	Surface area	[cm²]	Data sheet! (optional)
HDD			
Quantity	Quantity	[-]	Data sheet!

Designation	Measured variable	Unit	Explanation
Storage space per HDD	Quantity	[TByte]	Value for performance indicator
PSU			
Number per device	Quantity	[-]	Data sheet!
Weight per PSU	Weight	[kg]	Data sheet!
Network cards			
Number of ports	Quantity	[-]	Data sheet!
Problematic substances			
Cables containing halogen (e.g. PVC)	Weight	[kg]	Measure value!
Flame retardants (name, CAS no.)	Weight	[kg]	Information from the manufacturer
Plasticiser (Name, CAS-No.)	Weight	[kg]	Information from the manufacturer
Level of knowledge on SVHC in the whole appliance	SVHC score	[1...5]	Information from the manufacturer, link to ECHA-DB

Source: Öko-Institut

To calculate the environmental impact of servers and storage systems, the KPI4DCE and GCC calculation tool (Gröger and Liu 2021) can also be used.

Energy consumption

To calculate the energy consumption in the utilisation phase (and subsequently the environmental impact of using the software), the hardware components must be measured. As a minimum, an attempt should be made to determine the fixed basic contribution (P_{idle}) and the load-dependent contribution (P_{max} - P_{idle}) separately for each hardware component. If this is successful, a function for the power consumption of the respective hardware component should be determined as a function of the load (P= f(Load)).

Another important input parameter for calculating the average digital work performed (DW) is the average utilisation ($load_{average}$) of the respective component.

Table 11: Measurement of the energy consumption of the hardware components

Designation	Measured value	Unit
CPU (sum of the CPUs)		
P_{idle} and P_{max}	Performance	[W]
alternatively: P = f(Load)	Performance	[W]
$\mathbf{Load}_{average}$	Utilisation	[%]
$\mathbf{P}_{average}$ (calculated if necessary)	Performance	[W]
GPU (sum of GPUs)		
P_{idle} and P_{max}	Performance	[W]
alternatively: P = f(Load)	Performance	[W]
$\mathbf{Load}_{average}$	Utilisation	[%]
$\mathbf{P}_{average}$ (calculated if necessary)	Performance	[W]
RAM (sum of RAMs)		
P_{idle} and P_{max}	Performance	[W]
alternatively: P = f(Load)	Performance	[W]
$\mathbf{Load}_{average}$	Utilisation	[%]

$P_{average}$ (calculated if necessary)	Performance	[W]
Permanent memory (total)		
P_{idle} and P_{max}	Performance	[W]
alternatively: P = f(Load)	Performance	[W]
Load$_{average}$	Utilisation	[%]
$P_{average}$ (calculated if necessary)	Performance	[W]
Network card (sum of all ports)		
P_{idle} and P_{max}	Performance	[W]
alternatively: P = f(Load)	Performance	[W]
Load$_{average}$	Utilisation	[%]
$P_{average}$ (calculated if necessary)	Performance	[W]
Overall system (calculation overhead)		
P_{idle}	Performance	[W]
P_{max}	Performance	[W]
$P_{average}$	Performance	[W]

Source: Öko-Institut

If a platform only provides a single basic digital resource, as is the case with network specific hardware (routers, switches, amplifiers), it is sufficient to measure the overall system and determine the utilisation of the relevant basic digital resource.

If it is not possible to determine all power consumption by taking own measurements, information from data sheets (e.g., Thermal Design Power - TDP for CPUs), general information on components (e.g., https://www.buildcomputers.net/power-consumption-of-pc-components.html) or tools provided by hardware manufacturers for designing the power supply (e.g., *HPE Power Adviser* https://poweradvisorext.it.hpe.com) can also help.

Key performance indicators

To calculate the performance of the computer platform and the basic digital resources (DBR, see Table 1), the values shown in Table 12 are required. The calculation of the digital work performed (DW) also includes the average utilisation of the respective components, which are shown in Table 11.

Table 12: Key performance indicators

Designation	Measured value	Unit
CPU (per CPU)		
Clock frequency	Frequency	[GHz]
Bus width	Quantity	[Bit]
Performance indicator if applicable (e.g., SSJOPS)	Quantity	[...]
GPU (per GPU)		
Clock frequency	Frequency	[GHz]
Number of transistors	Quantity	[10^6]
Shader and raytracing computing units *	Quantity	[TFLOPS]
Tensor arithmetic units *	Quantity	[AI TOPS]

RAM		
Total storage space	Quantity	[GByte]
Permanent storage (SSD/HDD)		
Total storage space	Quantity	[TByte]
Network card (per port)		
Maximum bandwidth	Quantity	[Mbit/s]

* The suitability of these GPU key figures still needs to be checked during the course of the project
Source: Öko-Institut GPU performance, see: https://www.nvidia.com/de-de/geforce/graphics-cards/compare/

Problematic substances

The use and presence of problematic substances in the digital supply chain is addressed in the eco:digit project by four indicators:

1. The use of hazardous substances in the production of hardware components. Data from the life cycle assessment of hardware components is used for this purpose.
2. The content of harmful substances in the hardware components.
   This requires information on the presence of problematic substances in the devices.

   These include:

   - Heavy metal content in the appliance.
   - Type and concentration of halogenated flame retardants in the plastic parts.
   - Quantity of halogen-free or halogen-containing cables and
   - Type and concentration of plasticisers in the plastic parts.

   If no device-specific information is available, literature values on average concentrations in electronic devices are used for an initial estimate.
3. Use of problematic substances in the utilisation of hardware components.

   The consumption of refrigerants and insulating gases in data centres is balanced here. Information is required on the annual losses of these chemicals in the participating data centres.
4. State of knowledge on substances of very high concern (SVHC).

   Manufacturers of hardware components must notify the European Chemicals Agency if their components contain substances of very high concern (SVHC) in quantities of 0.1% (mass per cent) or more. In addition, this information must be communicated to private purchasers of the devices on request. This information is important to promote the substitution of SVHCs and reduce the introduction of these substances into waste streams. For this reason, the eco:digit assessment method also records whether this information is available or not as the "SVHC score" indicator. Private individuals or companies can request this information directly from the suppliers of their hardware components. This information must be provided within 45 days (see REACH Article 33, https://echa.europa.eu/de/regulations/reach/candidate-list-substances-in-articles/communication-in-the-supply-chain).

Platform profile

The results of the data collection and calculation of the effort indicators of the respective platform must be stored in a standardised data format so that the measured values can be transferred to a virtualised simulation environment. Platform profiles are created for this purpose, which consist of at least the following information:

Table 13: Platform profile with defined average usage

```
{
	"platform_profile": "average",
	"platform_ID": "name or identifier",
	"svhc_score": score,
	"usage": {
		"load_average": [av_co, av_me, av_st, av_tr],
		"lifetime_average": years
	},
	"embedded": {
		"EBR_CED": ["co", "me", "st", "tr"],
		"EBR_GWP": ["co", "me", "st", "tr"],
		"EBR_ADP": ["co", "me", "st", "tr"],
		"EBR_Water": ["co", "me", "st", "tr"],
		"EBR_WEEE": ["co", "me", "st", "tr"],
		"EBR_TOX": ["co", "me", "st", "tr"]
	},
	"power_demand": {
		"EBR_P": ["co", "me", "st", "tr"]
	}
}
```

Source: Öko-Institut

Here, `"co"`, `"me"`, `"st"` and `"tr"` are representative of the respective effort benefit ratios that are assigned to the basic digital resource. For the Effort benefit ratio for manufacturing (`"embedded"`), these are the environmental impact categories (EI) per average digital work (DW) (see Utilisation phase). For the Effort benefit ratios for utilisation phase (`"power_demand"`), the electrical power (P_{el}) is calculated per average digital basic resource (DBR) utilised.

Instead of a rigid platform profile, in which the technical service life of the hardware and the average utilisation are defined with `"average_load"`, a dynamic platform profile can also be created, in which the manufacturing emissions (`"embedded"`) are documented as a total value (EI) and the power consumption (`"power_demand"`) is specified as a function of the utilisation (P = f(Load)). Based on the transferred `"usage"` parameters, the effort indicators (EBR) can then be determined by the calculation model on a case-specific basis. This dynamic platform profile can be used to identify optimisation potential in the utilisation and service life of the hardware platform.

Table 14: Platform profile with dynamic service life and utilisation

```
{
	"platform_profile": "dynamic",
	"platform_ID": "name or identifier",
	"svhc_score": score,
	"usage": {
		"load_dynamic": [co, me, st, tr],
		"lifetime_dynamic": years
	},
	"embedded": {
		"EI_CED": ["co", "me", "st", "tr"],
		"EI_GWP": ["co", "me", "st", "tr"],
```

```
            "EI_ADP": ["co", "me", "st", "tr"],
            "EI_Water": ["co", "me", "st", "tr"],
            "EI_WEEE": ["co", "me", "st", "tr"],
            "EI_TOX": ["co", "me", "st", "tr"]
      },
      "power_demand": {
            "P_function": ["co", "me", "st", "tr"]
      }
}
```

Source: Öko-Institut

In order to model a simulation environment, further key figures for the respective platform will probably need to be collected and transferred to the platform profiles. These can be, for example, the technical data of the platform and performance indicators.

Measurement of the software to be analysed

Use of basic digital resources

On the consumption side, the utilisation of basic digital resources by the software is to be measured (cf. Software utilises basic digital resources).

Suitable logging tools must be used within the test bench to record the following parameters:

Table 15: Measurement of the digital work used by a software product

- Service units: Number of utilisation units in the measurement period [no.]
- DW_{co} : CPU or GPU work calculated from full load seconds [Gbit/s*s]
- DW_{me} : RAM memory work [GByte seconds]
- DW_{st} : Permanent memory work [GByte seconds]
- DW_{tr} : Data transmission work [Mbit/s*s]

Source: Öko-Institut, note: a different measurement parameter can be selected for CPU or GPU work if required

The "service units" as the number of utilisation units in the measurement period [number] must be defined on a context-specific basis.

Digital work (DW) can also be measured by first recording the difference in the average load of the respective components (calculated from the average load during the execution of the software minus the average load in the idle state without the software) and comparing this difference with the maximum basic digital resources (DBR) provided by the platform (see Table 1) and the execution time of the software (t_{soft}):

$$DW_{dbr} = \Delta Load_{average,dbr} \cdot DBR_{dbr} \cdot t_{soft} \text{ with } dbr = \{co, me, st, tr\}$$

A description of possible measurement methods can be found in Gröger et al. (2018). These measurement methods still need to be further developed in eco:digit and made applicable to all platforms.

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