Journal of Cleaner Production 231 (2019) 817–834

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Benefit-cost model for comparing data center performance from a biomimicry perspective

Sylvain Kubler [a, b, *], Éric Rondeau [a, b], Jean-Philippe Georges [a, b], Phoebe Lembi Mutua [a, b], Marta Chinnici [c]

[a] Universite de Lorraine, CRAN, UMR 7039, Campus Sciences, BP 70239, Vandœuvre-lès-Nancy, F-54506, France
[b] CNRS, CRAN, UMR 7039, France
[c] ENEA-ICT Division, C.R Casaccia Via Anguillarese 301, ROMA, 00123, Italy

A R T I C L E I N F O

Article history:
Received 7 January 2019
Received in revised form
14 May 2019
Accepted 16 May 2019
Available online 22 May 2019

Keywords:
Green computing
Green networking
Sustainability
Multiple criteria decision-making
Analytic hierarchy process (AHP)
Biomimicry

A B S T R A C T

Data centers are estimated to have the fastest growing carbon footprint from across the whole information and communication technology (ICT) sector. Evaluating the performance of data centers in terms of energy efficiency and sustainability is becoming an increasingly important matter for organizations and governments (e.g., for regulation or reputation purposes). It nonetheless remains difficult to achieve such evaluation, as data centers imply to take into consideration a wide range of dimensions and stakeholders. Even though a wide range of sustainability performance indicators exist in the literature, there is still a lack of frameworks to help data center stakeholders (spanning from data center owners, governmental regulators to engineers/field operators) to evaluate and understand how a data center performs in terms of sustainable development/behavior. Our research work proposes such a framework, whose originality lies in the combination of state-of-the-art sustainability metrics with the biomimicry commandments of eco-mature system, which enables holistic sustainability assessment of data centres. From a theoretical perspective, the proposed model is designed based on a benefit-cost analysis using the Analytic Hierarchy Process (AHP) technique. This approach allows data center stakeholders for specifying their own preferences and/or expertise in the comparison process, whose practicability is demonstrated in this paper considering three data center candidates, which are respectively located in France, Germany and Sweden.

1. Introduction

The rapid growth of data centers is driven by the increasing need for fast and efficient data processing and storage services (Dandres et al., 2017; Belkhir and Elmeligi, 2018). In a context where data centers are becoming the power plants of the information age, one of the greatest challenges is the exponential rise in energy consumption, as they must operate 24 /24 hours and 7 /7 days (Kurkjian and Glass, 2007). At the time of writing, the ICT sector contributes to 2% of the global carbon emissions with data centers accountable for 14% of the total ICT footprint (Mills). It therefore becomes crucial that the next generation of data centers integrates solutions that can lower the total cost of ownership, while decreasing the complexity of management (Dinesh Reddy et al., 2017).

Towards this goal, data center owners and operators should put in place measures to evaluate the performance of their facilities/services (Fiandrino et al., 2017; Ni and Bai, 2017). However, while businesses are forced to continuously evaluate their economic health, they often omit to analyze how sustainable they are. This has been revealed by the survey presented at the Datacenter Dynamics conferences (Alger, 2009), which reports that only 30% of the respondents analyzed the efficiency of their data center in terms of sustainability. However, research remains to be done to encompass the complexities of sustainability and enable holistic assessment of the sustainability of data centres (Whitehead et al., 2014, 2015). This is important because most of existing green building rating initiatives/tools focus mostly on environmental

* Corresponding author. Universite de Lorraine, CRAN, UMR 7039, Campus Sciences, BP 70239, Vandœuvre-lès-Nancy, F-54506, France.

E-mail addresses: s.kubler@univ-lorraine.fr (S. Kubler), eric.rondeau@univ-lorraine.fr (É. Rondeau), jean-philippe.georges@univ-lorraine.fr (J.-P. Georges), phoebe-lembi.mutua5@etu.univ-lorraine.fr (P.L. Mutua), marta.chinnici@enea.it (M. Chinnici).

https://doi.org/10.1016/j.jclepro.2019.05.183
0959-6526/

impact assessment (Pannier et al., 2018; Li et al., 2017; Geng et al., 2017; Peng, 2016), such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Methodology), CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), Green Globes, Green-Star, Green Mark, *etc.* (Le et al., 2018), while sustainability is a much wider concept. Just looking at the recent survey on *"Metrics for Sustainable Data Centers"* (Dinesh Reddy et al., 2017), more than one hundred sustainability metrics are reported, spanning from energy efficiency to cooling, networking, security and financial. One may then wonder how different categories of stakeholders, with different areas and levels of expertise, can make sense of all these metrics at once? This motivation question, which is also stressed by other studies (Garimella et al., 2013; Arianyan et al., 2015; Tseng et al., 2018), is at the origin of this research work. Fig. 1 provides a graphical representation of this motivation question.

In this paper, we attempt to address the gap in research in designing a holistic data center performance comparison model that has the capacity to fully capture the interlinked nature of a system, where improvements in one area and to one impact, can adversely affect a totally different area and totally different impacts. To achieve this, a benefit-cost model is adopted. Our approach differs from traditional CBA (Cost-Benefit Analyses) that usually focus on economical assessment, while ours is primarily designed to deal with sustainability metrics.

Section 2 provides further evidence that current research fails to shift away from environmental impact assessment towards sustainability, and thus that further research is required to encompass the complex multi-criteria nature of sustainability assessment in data centers. Section 3 presents the proposed benefit-cost model that follows a similar approach to the one proposed in (Anagnostopoulos and Petalas, 2011), namely a two-hierarchy approach using the Analytic Hierarchy Process (AHP): a first hierarchy identifying the benefits in terms of sustainability development/behavior of the data center candidates, and a second hierarchy identifying their costs. A key originality of our approach lies in the combination of state-of-the-art sustainability metrics with biomimicry commandments, which contributes to realize the holistic nature of the proposed benefit-cost model. The practicability of this model is demonstrated in section 4 considering three data center candidates; the conclusion follows.

Note that all abbreviations used in this paper are summarized in the form of tables in AppendixA and AppendixB.

2. Performance comparison in data center and cloud computing environments

Although some distinguish between data centers and cloud computing (e.g., considering the "on-premise" vs. "off-premise" forms of storing and processing data), existing models for comparing data center or cloud computing candidate solutions are often based on similar sets of criteria such as price, reputation, reliability, availability, *etc.* To deal with this real world problems with multiple, conflicting, and incommensurate criteria and/or objectives, multi-criteria decision analyses (MCDA) are carried out using MCDM techniques such as AHP, ELECTRE, PROMETHEE, TOPSIS. In Section 2.1, we briefly explain how MCDA stands with respect to the life cycle assessment (LCA) methodology. Section 2.2 then reviews the literature to analyze papers that deal with MCDM problems in data centers and cloud computing applications, as well as the extent to which they succeed (or fail) to cover the sustainability dimension. Based on this analysis, a more in-depth overview of state-of-the-art sustainability metrics is provided in Section 2.3, followed by Section 2.4 in which we introduce and discuss the biomimicry and Lifes' principles.

2.1. How MCDA is aiding life cycle assessment (LCA) in results interpretation

One may wonder how MCDA stands with respect to LCA analyses? To better understand the link between MCDA-LCA, we refer the reader to the paper published by Zanghelini et al. entitled *"How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation"* (Zanghelini et al., 2018), in which the authors explain very clearly the relation between these two methodologies. First, let us note that they are both decision-making aiding tools (impact indicators and criteria cover the same notion respectively from the LCA and MCDA viewpoint (Le Téno and Mareschal, 1998). The difference is that LCA quantifies its impact indicators (Hoogmartens et al., 2014), whereas MCDA often needs to be fed by criteria (interpretation-oriented only). While the former is directed to products and services and is based on the compilation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle (for Standardization, 2006), the latter is based on different protocols for eliciting inputs, structures, algorithms and processes to interpret and use formal results in actual advising or decision-making contexts.

Thus, generally, the combination of MCDA and LCA can occur in a two-ways path: LCA can be applied to add an environmental indicator to the MCDA process, and MCDA can be used to interpret LCA outcomes. There are many reasons for combining these tools, but according to (Hermann et al., 2007) the main one lies in their complementary characteristics: LCA is objective, reproducible and standardized, whereas MCDA evaluation methods take into account subjective elements (such as the opinions of stakeholders and decision makers) in the evaluation of the different criteria. In this

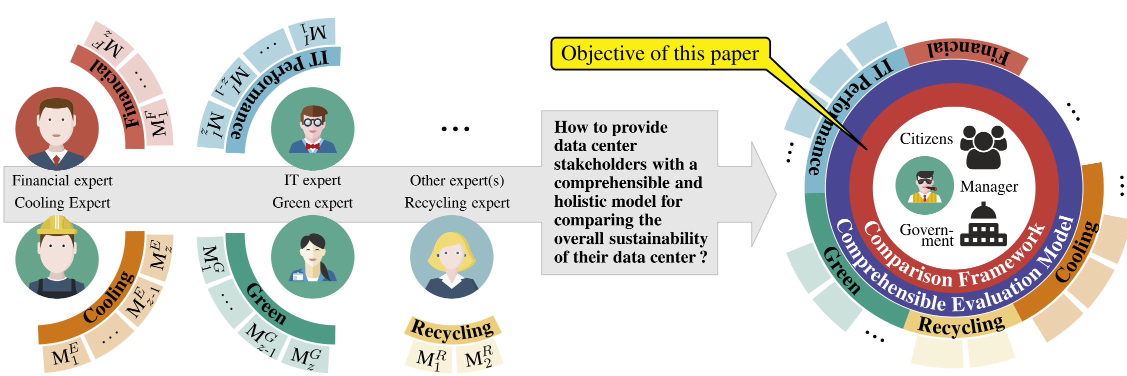


Fig. 1. A need of comprehensible schemes/models to help non-expert to evaluate and compare data center performance.

paper, the list of performance indicators used as part of our Benefit-Cost model are not based on a given LCA standards but on the survey on “Metrics for Sustainable Data Centers” carried out by Reddy et al. (Dinesh Reddy et al., 2017), which allows us to be very specific and exhaustive to the data center domain. However, our model could be either re-used as part of a more generic LCA model covering the economical and social dimensions, too, or refined with other performance indicators defined in one or more LCA standards.

2.2. Data center & cloud computing-related multi-criteria decision analysis

Evaluating and comparing the performance of data centers or cloud computing candidate solutions is one such problem due to both the large variety of performance metrics and the need to take human expertise into consideration in the decision process (Abdel-Basset et al., 2018; Garg et al., 2013; Daim et al., 2013). A number of research papers have applied MCDM techniques (Mardani et al., 2015; Kubler et al., 2016) (e.g., AHP, DEA, Delphi, ELECTRE, PROMETHEE, TOPSIS, VIKOR) to solve such problems, as summarized in Table 1. It can be observed that most of the papers employ such techniques, and particularly AHP (Saaty, 1980), to help users/decision makers in solving the problem of selection of the best cloud service provider or the best site to build a data center. The reported papers are more thoroughly discussed in the following, along with the lack of comprehensible and holistic models for comparing the overall sustainability of data centers.

To solve the problem of site selection for data centers, Daim et al. (2013) propose an AHP-based model that takes into account geographical, financial, political and social factors. Covas et al. (2013) claim, at the time of writing (i.e., back to 2013), that the existing research did not pay sufficient attention to include the location criterion for the development of sustainable data centers, and therefore come up with a new model. Later, Ounifi et al. (2015) present a model that covers the sustainability dimension by considering energy sources, electricity as well as the average temperature in the region. Their model uses ELECTRE with the goal to minimize the overall costs of data centers.

Looking at the cloud service selection problem, Kwon and Seo (2013) present a decision-making model using Fuzzy AHP in order to guide companies in selecting a suitable cloud service provider. The proposed model essentially focuses on performance, reputation and pricing metrics. Alabool et al. (Alabool and Mahmood, 2013) present an approach based on VIKOR for trust-based service selection in public cloud computing. In total, 15 criteria are covered, spanning from business, governance, certification, SLA, security and sustainability. Hybrid frameworks (i.e., combining distinct MCDM techniques) have been proposed, as in (Su et al., 2012; Lee and Seo, 2016; Liu et al., 2016a), in which criteria related to financial dynamics (ROI, maintenance costs …), management practices (risk sharing, reogranization/ …) and performance (service availability, accuracy, security …) are taken into consideration. For cloud service selection, Boutkhoum et al. (Boutkhoum et al., Tiknioujne) combine Fuzzy AHP and PROMETHEE, but with a special focus on ranking the most suitable cloud computing alternative to accommodate Big Data from an *e*-governance, security and business continuity perspective. Xu et al. (2015) propose a nonparametric DEA method to evaluate cloud services based on values related to price/hour, virtual core, compute units, memory and disk. Silas et al. (2012) present a methodology for selecting the best middleware services in cloud computing

Table 1
Research work in which MCDM techniques have been applied for data center performance evaluation and comparison purposes.

Ref.	Year	(Fuzzy) AHP	DEA	Delphi	ELECTRE	PROMOTHEE	TOPSIS	VIKOR	Others	Problem tackled	Sustainability-related criteria
Abdel-Basset et al. (2018)	2018	✓	✓							Cloud service selection	–
Jatoth et al. (2018)	2018	✓					✓			Cloud service selection	–
Jatoth et al. (2017)	2017	✓	✓							Cloud service selection	–
Liu et al. (2016a)	2016	✓		✓			✓		✓	Cloud service selection	–
Lee and Seo (2016)	2016	✓		✓						Cloud service selection	–
(Boutkhoum et al., Tiknioujne)	2016	✓				✓				Cloud service selection	–
Xu et al. (2015)	2015		✓							Cloud service selection	–
Ounifi et al. (2015)	2015								✓	Site selection	PUE
Liu et al. (2014)	2014	✓					✓			Cloud service selection	–
Kwon and Seo (2013)	2013	✓								Cloud service selection	–
Daim et al. (2013)	2013	✓								Site selection	Power availability, Water availability, Laws related to Urban Planning
Covas et al. (2013)	2013	✓								Site selection	Renewable Energy sources, Free cooling, Local environmental impact, Local pollution
Alabool and Mahmood (2013)	2013							✓		Cloud service selection	Sustainability
Su et al. (2012)	2012	✓						✓	✓	Cloud service selection	–
Karim et al. (2013)	2013	✓								Cloud service selection	–
Garg et al. (2013)	2013	✓								Cloud service selection	DCiE, PUE, DPPE
Silas et al. (2012)	2012				✓					Cloud service selection	–

environments by employing the ELECTRE technique; criteria such as flexibility, time, service cost, scalability, trust and capability are included. Karim et al. (2013) present a model aiming at ranking the candidate cloud services for end-users by, first, mapping the users' Quality of Service (QoS) requirements of cloud services to the right QoS specifications of Software-as-a-a-Service, and, second, by mapping them to the best Infrastructure-as-a-Service (i.e., the one that offers the optimal QoS guarantees). In a similar way, Garg et al. (40) and Jatoth et al. (2017) propose distinct frameworks that help customers to evaluate cloud offerings and to rank them based on their ability to meet the user's QoS requirements. These two frameworks take into account criteria such as interoperability, reliability, cost, accuracy, elasticity, suitability and other performance metrics such as service response time and throughput. In line with the idea to meet QoS requirements, Liu et al. (2014) propose an ontology-based service matching in order to maximize accuracy of cloud service discovery, while giving enough flexibility to cloud customers to discover their best suited services. Recently, Abdel-Basset et al. (2018) presented an original approach in the sense that the authors do not only focus on evaluating the quality of cloud services, but also on improving the service quality by creating a competition between cloud providers. This competition is based on their level of security, performance, accessibility, scalability and adaptability.

Overall, the above literature review reveals that even though the sustainability dimension is covered in a few studies (*cf.,* last column of Table 1), it is too often omitted, or, when considered, the sustainability metrics remain limited. For example, only DCiE (Data Center Infrastructure Efficience), DPPE (Data Center Performance per Energy) and PUE are considered in (Garg et al., 2013), while only the latter is considered in (Ounifi et al., 2015). Other studies, such as (Alabool and Mahmood, 2013), state that the sustainability is covered but without providing any detail about what sustainability is referring to. Another aspect evidenced by this review is that most of the proposed models have focused on cloud service and site selection so far, but none has ever proposed a comprehensible and holistic model that helps non-expert users in comparing the overall sustainability of data centers. In this paper, we seek to contribute to proposing such a model, as will be presented in the next section.

2.3. Sustainability metrics

Over the decades, a wide range of sustainability metrics for data centers and cloud computing solutions have been introduced (Grishina et al., 2018, 2019; Lykou et al., 2018; Riekstin et al., 2017; Whitehead et al., 2014; Beitelmal and Fabris, 2014). At the time of writing, and to the best of our knowledge, the most extensive study of sustainability metrics is given by Reddy et al. (Dinesh Reddy et al., 2017), who gathered and reported state-of-the-art metrics spanning from energy efficiency, cooling, green, air management, network, security, storage to financial. Since these metrics are going to be used as part of our comparison model, we summarized them in Table A.7.

The first limitation with the reported metrics is that they are often domain-specific and this specificity is not necessarily understandable by all stakeholders of a data center who have to globally (together) manage and optimize its performance. This issue is reinforced by the multiplication of metrics for greening data centers. In (Dinesh Reddy et al., 2017), the authors enumerate more than one hundred metrics, which makes it difficult for human beings, not to say impossible, to handle and consider all of them to make decisions. The second limitation is about reducing the complexity of the performance evaluation analysis. The same authors gather the metrics under nine categories, as will be discussed in Section 3, which can be seen as a first simplification of the model. However, such a categorization do not help different types of stakeholders to assess the overall sustainability of data centers because some contradictions between the categories and metrics may occur. In other words, the positive optimization of one metric may negatively impact the optimization of another metric (e.g., the "carbon emission" category can be mitigated in increasing the nuclear energy source, which is in total contrast with the "green energy source" category). The objective of our study is to provide a comprehensible and holistic comparison model that overcome the above limitations. The approach advocated here is to use biomimicry.

2.4. Biomimicry & lifes' principles

The biomimicry, which means "imitation of life", is defined by Oxford dictionary as: *"The design and production of materials, structures, and systems that are modelled on biological entities and processes"*. The majority of application domains inspired by the nature are materials and locomotion (Lurie-Luke, 2014) and consists in mainly copying physiology, morphology, and anatomy of vegetal and animal world for optimizing or making more efficient the structure of materials. In computer sciences, many heuristics for optimizing data processing/transport/storage solutions are commonly used and are based on natural behavioral observations, such as ant colony, bat, natural evolution (genetic algorithm), machine learning (e.g., neural networks). However, optimizing an artefact in copying biologic entity does not guarantee that the optimized artefact will have less negative impact on the nature (e.g., if the genetic algorithm fitness function seeks to maximize the pollution, the solution will not be environmentally friendly even if the optimisation algorithm copies a natural evolution process). Another idea initially suggested by J. Benyus (1997) is that the life on earth has evolved a set of strategies that have sustained over 3.8 billion years and these strategies could be interesting to apply when designing an artefact. The simple expectation is the following: if the artefact is developed along with life strategies, the artefact is likely to be environment-friendly. Originally, J. Benyus identified a set of ten strategies, named the "*Ten Commandments of Mature Ecosystem*", as reported in Table 2. De Pauw (De Pauw) explained that biomimicry guild[1] proposed successively new versions of life's principles in 2007, 2010 and 2013 respectively. The same author evidenced that case studies using the Life's principles for designing environmentally-friendly artefacts are scarce (Oguntona and Aigbavboa, 2017). studied the perception of life's principles in construction industry from a survey collecting responses from different construction professionals (Civil Engineers, architects, *etc.*). The primary objective was not to apply Life's principles for architecting a building but only to rank the importance of those principles in the construction sector (De Pauw et al., 2014). used different nature-inspired design strategies from two case studies developed by students, whose goal was to compare approaches based on the life's principles, cradle to cradle and eco-design. The main difference observed is that the students following the biomimicry and cradle-to-cradle methods investigated more solutions than the ones using eco-design. In the same vein as our study, Drouant et al. (2014) proposed to define green networking metrics based on the ten lessons of mature ecosystem.

Finally, the "Biomimicry for Social Innovation" initiative[2] help leaders bring nature's adaptive genius into their organizations and enterprises, and rely for this on 23 life's principles. Overall, the multiplication of life's principles are necessary to better guide

[1] https://biomimicry.org/, last access: May 2019.

[2] https://bio-sis.net/life-principles/, last access: May 2019.

Table 2
The ten biomimicry commandments (lessons) introduced by Benyus (1997)

Commandment (lesson)		Examples of interpretation in the context of data centers
C_1	Use waste as a resource	Considering data center (IT) equipment wastes as resources for recycling company. Reusing data center heat for heating building, swimming pools, *etc.* close to data centers.
C_2	Diversify and cooperate to fully use the habitat	Cooperating with local companies (ecopark); for example, reusing data center heating for heating building.
C_3	Gather and use energy efficiently	Mitigating data center energy consumption. Using Energy produced locally.
C_4	Optimize rather than maximize	Offering IT quality of service in respect to customer requirements.
C_5	Use materials sparingly	Increasing (IT) equipment lifetime. Mitigating (IT) equipment use (e.g., virtualization).
C_6	Don't foul their nests	Reducing harmful emissions in the environment (carbon in air …). Avoiding electronic wastes.
C_7	Don't draw down resources	Increasing green energy use. Mitigating (IT) equipment use to avoid earth resource depletion.
C_8	Remain in balance with biosphere	In our research, the idea of lessons 6 and 8 are similar and are merged accordingly.
C_9	Run on information	In our research, the idea of lessons 2 and 9 are similar and are merged accordingly.
C_{10}	Shop locally	Using local energy for avoiding energy transportation lost. Using air and water for cooling. Manufacturing data centers with local companies.

engineers in the selection of appropriate solutions and recommendations specific to the domain of design. For example, among the 23 life's principle, "Do chemistry in water" is a useful principle in material design, but not in software engineering. However, the multiplication of principles produce noise and complexity when they are applied for measuring an artefact in a holistic way. In our work, we decided to only use the initial Ten Commandments, which are more philosophical requirements disconnected to engineering process such as "Do chemistry in water" or "Fit form to function" principles. The commandments are easy to understand and do not require expertise in biology. Consequently, the artefact environmental assessment using the commandments is independent to the engineering area, especially when designing complex systems requiring multiple experts. The commandments can play the role of a universal language for considering environment. Table 2 presents the Ten Commandments and provides some examples of interpretation in the context of data centers. However, two commandments C_8 and C_9 are left aside in our study because: (i) C_8 conveys a similar message as C_6, namely that we are living in a closed system and it is crucial to maintain the stability of environment in avoiding to "foul our nests" (both commandments are therefore merged into a same commandment); (ii) C_9 conveys a similar message as C_2: "Run on information" (C_9) refers to feedback mechanisms for considering ecosystems (competition/collaboration between companies, new legislations, new marketing demands) with the objective to "diversify and cooperate to fully use the habitat" (C_2). Both commandments are thus also combined into a unique commandment. Even though other commandments have close meaning, they include specific information that enriches the knowledge of the artefact environmental impact, as will be discussed in the next section.

3. A comprehensible and holistic comparison model for sustainable data centers

Determining a model that allows us for comparing data centers alternatives requires to integrate a wide range of domain-specific metrics (more than one hundred for data centers (Dinesh Reddy et al., 2017)), and this from both a beneficial and detrimental viewpoint (as improvements in one area and to one impact, can adversely affect a totally different area and totally different impacts (Whitehead et al., 2015)). This paper aims at proposing a benefit-cost model that makes use of the biomimicry commandments for evaluation together with metric categories in order to simplify the evaluation/comparison process (reducing all metrics into eight biomimicry indicators). The proposed model can easily be configured by stakeholders (i.e., prioritizing or not one or more commandments) since commandments do not require expertise in biology. This complies with the original idea promoted by J. Benyus (1997) in her Chapter entitled *"Where will we go from here?"*.

The methodology underlying our comparison model is a two-step approach, as depicted in Fig. 2:

1. *Metric categorization & Translation:* with the aim to translate datacenter metrics into biomimicry lessons/commandments, the sustainability metrics reported in Table A.7 are categorized in terms of benefit and cost implications from a biomimicry perspective. This step is detailed in section 3.1;
2. *Benefit-Cost analysis:* the metrics, associated categories, and biomimicry commandments are then combined/structured in the form of a benefit-cost analysis using the AHP method. This step is described in section 3.2.

3.1. Metric categorization & translation

As a first step, the sustainability metrics listed in Table A.7 are categorized in terms of benefit and cost implications from a biomimicry standpoint (Pomponi and Moncaster, 2017; Homrich et al., 2018). Concretely, we ask ourselves whether a metric relates to the energy, carbon, recycling or other categories? and whether the metric maximization or minimization results in a benefit or cost from a sustainability viewpoint? In this study, the metric categorization is based on the categories identified in (Dinesh Reddy et al., 2017), namely:

- *Energy:* evaluates the energy efficiency of the system's overall useful work done in comparison to the energy consumed;
- *Materials:* evaluates IT equipment efficiency;
- *Cooling:* evaluates the cooling system efficiency;
- *Green:* evaluates the amount of energy of the data center that comes from clean sources;
- *Carbon:* partly evaluates carbon emissions (only associated with Co2/Wh);
- *Recycling:* evaluates waste resource utilization efficiency of energy and materials in data centers;
- *IT Performance:* evaluates the extent to which the system efficiently executes the IT tasks, which can be related to the (i) Network, (ii) Storage, or (iii) Security;
- *Water:* this is an important resource for consideration when designing, identifying ideal location for a data center. Energy and Water are the main metrics to be controlled in a data center (Ristic et al., 2015);
- *Financial:* increased resource utilization can contribute to high energy costs and maintenance of IT equipment. Organizations should therefore assess its performance for saving money.

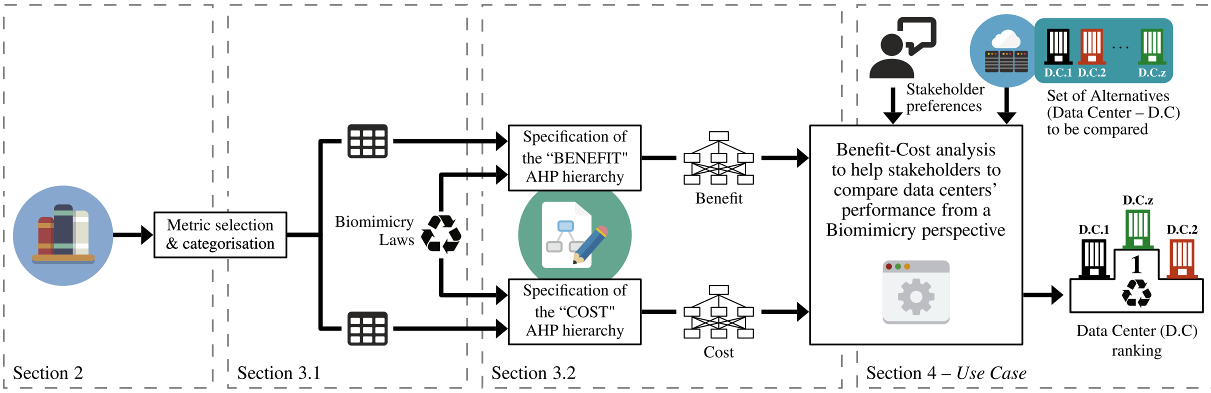


Fig. 2. Methodology towards the AHP-based comparison model to compare data centers in terms of sustainable development/behavior.

Table 3 highlights, for each category and sub-categories, what metrics must be minimized or maximized in order to "Benefit" the efficiency of data centers, while highlighting – *through the "Cost" categorization* – whether this can lead to negative efficiency impacts. Indeed, many contradictions may come up when studying ecological systems, for example: (i) the electricity produced by nuclear power plants must be limited when considering the GEC (Green Energy) metric, but at the same time should be increased with regard to CUE (Carbon), or (ii) the water usage must be mitigated when only analysing WUE (Water), but should be increased when looking at GEC (Green). In the following, we seek to specify the extent to which a given category may positively or negatively impact (benefit-cost) on each of the commandments.

To this end, we propose to first model the impact that one biomimicry commandment may have on the others, as given in Fig. 3(a). Let us take the modelling related to the "Energy" category, as given in Fig. 3(b). It can be stated that metrics under this category have an impact on C_3, C_4, $C_{6,8}$ and C_7. Indeed, C_3 and C_4 are about energy efficiency/optimization; $C_{6,8}$ is related to the pollution that is intrinsically linked to the energy consumption (emitted Co2); and C_7 is about earth resource utilization for non-renewable energy consumption minimization. The other commandments (i.e., C_1, $C_{2,9}$, C_9 and C_{10}) are not taken into account because their impact is either null, negligible, or too uncertain for providing a correspondence. In order to quantify the extent to which the maximization (or minimization) of a given metric category results in a benefit or cost in terms of sustainability efficiency, a three-scale rating has been used $\{3, 5, 9\}$, respectively meaning that a category has a **moderate**, **strong** or **absolute** beneficial or costly impact. Given the example of Fig. 3(b), the "Energy" category is deemed to have an **absolute** impact on C_3 and C_4 (all about energy efficiency/optimization); **strong** impact on $C_{6,8}$ due to some level of uncertainty about the type of energy used (e.g., level of pollution produced by coil being much higher compared with solar panels); and a **moderate** impact on C_7 due to uncertainty about the level of resources used (dependent on how energy is produced).

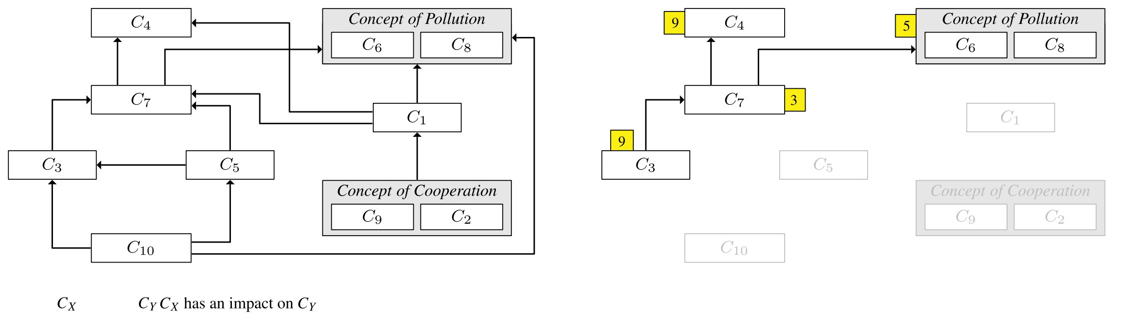
In a similar way, the above analysis was carried out for each category and the associated weight vectors generated (*cf.*, columns denoted by C_1 to C_{10} in Table 3). These vectors serve as inputs of the benefit/cost analysis presented in the next section.

3.2. Benefit/cost analysis

The objective of the proposed comparison model is to help assessing and identifying the overall most sustainable data center among a set of candidates, whose results must be expressed in non-

Table 3
Metric categorization from a "Benefit" and "Cost" perspective.

	Category	Optimization	Metrics	Impact on biomimicry commandments							
				C_1	$C_{2,9}$	C_3	C_4	C_5	$C_{6,8}$	C_7	C_{10}
Benefit	Energy	Minimize	DCa, DCLD, DC-FVER, EWR, PUE, pPUE, SI-POM, SPUE, TUE	–	–	9	9	–	5	3	–
		Maximize	APC, CADE, CPE, DCeP, DCiE, DCPD, DCPE, DPPE, DWPE, EES, H-POM, ITEE, ITEU, OSWE, PDE, PEs, PUEsc, PpW, SWaP								
	Materials	Maximize	DCcE, DH-UI, DH-UR, ScE	–	–	9	9	9	9	9	–
	Cooling	Minimize	DCCSE, DCSSF	–	–	9	9	3	5	3	–
		Maximize	CoP, EER, HSE, AEUF								
	Carbon	Minimize	CUE, TCE	–	–	9	9	3	9	5	**3**
		Maximize	Co2s								
	Green	Minimize	GUF	–	–	5	9	3	9	5	**9**
		Maximize	GEC								
	Recycling	Minimize	ERE, EDE, MRR	9	5	5	9	5	5	9	3
		Maximize	ERF								
	Water	Minimize	WUE, WUEs	–	–	–	9	–	–	–	–
	IT Perf.	Minimize	CNEE, ECR-VL, INPUE	–	–	9	9	5	3	5	–
		Maximize	BJC, NetT, RSmax, TEER, Unet, Capacity, LSP, MemU, OSE, Su, Thght, Ustor								
	Financial	Minimize	OpEx	–	–	9	9	9	3	5	–
Cost	Water	Minimize	WUE, WUEs	–	–	5	–	3	–	9	9
	IT Perf.	Minimize	ACPR, DTE, Lat, RC, RCD, T	–	–	9	–	9	5	9	–
		Maximize	ATR, CC, CER, DeD, DeP, HTTPt, IAS, IPFH, IPt, ITH, RT								
	Financial	Minimize	REL	–	–	9	9	9	3	5	–



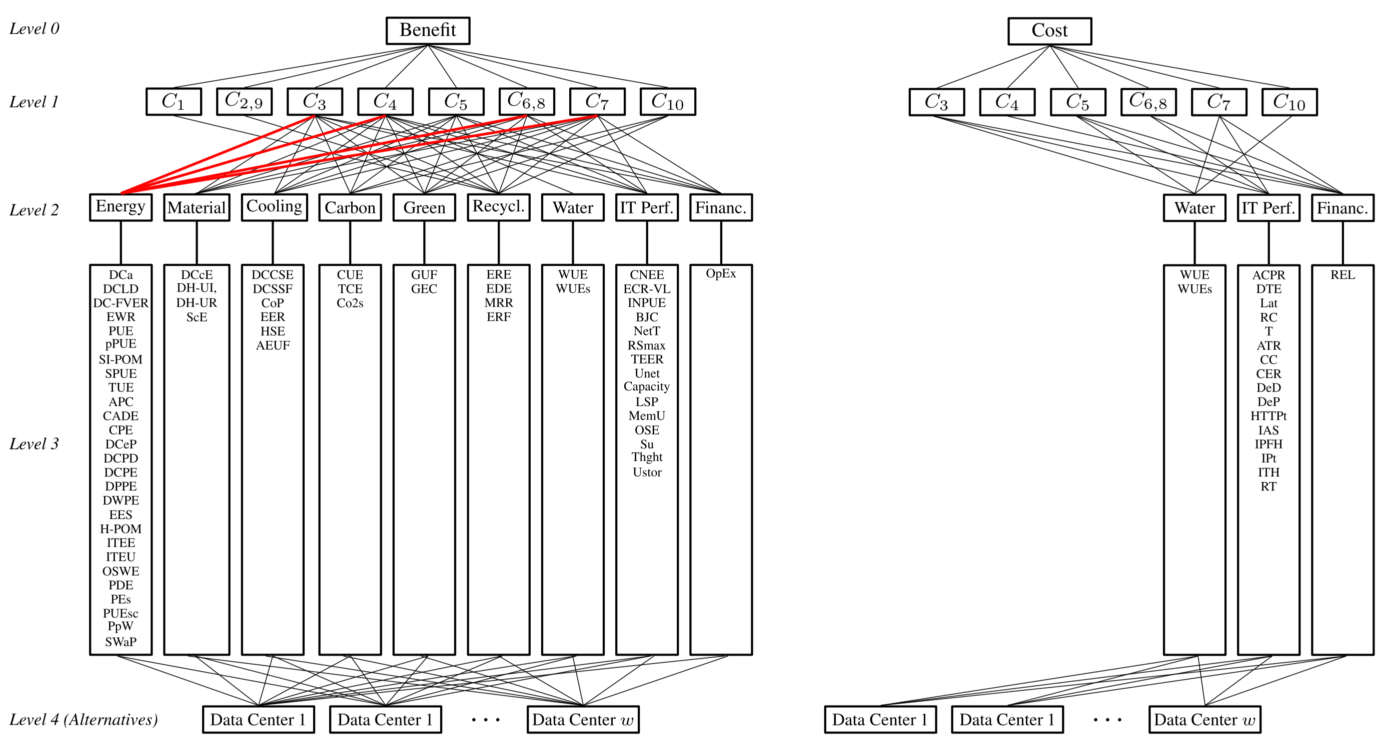
(a) Relationships between the ten biomimicry commandments (b) Extent to which "Energy" category impacts on commandments

Fig. 3. Relationships between biomimicry commandments & Extent to which a given metric category may impact on those commandments.

technical terms. To serve this purpose, a two-hierarchy approach is adopted, as proposed in (Anagnostopoulos and Petalas, 2011). Concretely, two distinct criteria hierarchies are specified, one quantifying the benefits in terms of sustainable data center behavior, and a second quantifying the cost implications. These two hierarchies (i.e., Benefit and Cost) are respectively given in Fig. 4(a)–(b), whose design follows the logic described below. Note that all variables used in this paper are summarized in Table B.8 (as an Appendix):

1. *Level 4 (Alternatives):* the set of data center candidates, denoted as $\mathscr{A}$, are individually evaluated with regard to the metrics reported in Table 3;
2. *Level 3 & 2:* those metrics are clustered according to the category they belong to, as defined in Table 3 (e.g., Energy, Material, *etc.*). This is denoted by $\mathscr{M}_{P_i}$, where P_i refers to the category to which a given set of metrics belongs to;
3. *Level 1:* those categories have been, in turn, clustered depending on what biomimicry commandment(s) their impact on. For example, the Energy category has beneficial implications on C_3, C_4, $C_{6,8}$, C_7 (no cost implication), which results in the bold/red linkage highlighted in Fig. 4(a);
4. *Level 0*: aggregated scores of all data center candidates are computed for both the Benefit and Cost hierarchies. These two scores, respectively denoted by $S^B_{A_l}$ and $S^C_{A_l}$, are divided to get the final Benefit/Cost score, which serves as basis to rank data center candidates in terms of sustainable development/behavior.

As a next step, pairwise comparisons between all elements of a given level of the AHP hierarchy must be carried out by one or more stakeholders of our approach/tool. Table 4 provides a brief insight into what stakeholders could be concerned by such a pairwise comparison process. Since the proposed model is intended to provide a holistic view of how sustainable a data center is, non-



(a) BENEFIT-related AHP (b) COST-related AHP

Fig. 4. AHP-based data center performance comparison from BENEFIT and COST perspectives.

Table 4
Stakeholders and respective involvement in the comparison process.

AHP	Data Center Stakeholders	Focus & Interest
Level 1	Data center owners; Executives; Sponsors; Regulators; Public	They take a big-picture approach to data center sustainabilty effectiveness
Level 2	Biomimicry experts	It corresponds to the expertise needed to model the extent to which the categories of metrics impact on the biomimicry commandments. This paper provides a first expertise in Section 3.1 and Table 3, although this does not prevent other biomimicry experts from modifying it.
Level 3	Designers, Engineers; Field operators; Maintainers	They must develop mechanical and electrical designs that drive energy efficiency and sustainability, while ensuring that solutions fit within the framework of a live, operational facility
Level 4	N/A	Pairwise comparisons are performed based on measurable/supervised system parameters (i.e., based on automated mechanisms)

technical stakeholders (e.g., executives, regulators) are more likely to communicate preferences at level 1 (e.g., to place particular emphasis on C_5 to know which data center performs the best in “using materials sparingly”), while stakeholders at level 3 are more likely to communicate preferences about domain-specific metrics (e.g., importance of PUE over other energy metrics). Level 2 corresponds to the expertise needed to match the biomimicry commandments with the sustainability metric categories, which corresponds to expertise. Although a first expertise is provided in Table 3, this does not prevent another biomimicry expert from modifying, if needed, the proposed expertise. Sections 3.2.1 to 3.2.5 detail the theoretical basis of the pairwise comparison process performed at levels 1, 2, 3 and 4 respectively, along with the aggregation process to obtain the final ranking of the data center alternatives.

3.2.1. Pairwise comparisons at level 1

Let $(C)_{z\times z}$ be the pairwise comparison matrix at level 1, as formalized in Eq (1), where c_{ij} $(i,j\in\mathscr{C})$ is supposed to reflect how many more times commandment i is preferred – *or deemed more important by the data center stakeholder* – over commandment j. In our study, the stakeholder's evaluation is carried out based on the Saaty's scale: $\{1,3,5,7,9\}$, where $c_{ij}=1$ means that C_i and C_j are of equal importance and $c_{ij}=9$ means that C_i is strongly preferred over C_j.

$$(C)_{z\times z} = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_z \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \dots & C_z \end{array} \\ \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1z} \\ c_{21} & c_{22} & \dots & c_{2z} \\ \vdots & \vdots & \vdots & \vdots \\ c_{z1} & c_{z2} & \dots & c_{zz} \end{bmatrix} \end{array} \tag{1}$$

The priority vector, denoted by $E_{(C)_{z\times z}}$ must then be computed. To this end, the geometric mean method proposed by Crawford and Williams (1985) is applied, as formalized in Eq. (2) in this study. Even though not detailed, it should be noted that the consistency ratio (CR) of any pairwise comparison matrix must be measured, whose inconsistency is regarded as acceptable if CR $\leq 10\%$ (Saaty, 1980).

$$E_{C_i} = \frac{\left(\prod_{j=1}^{z} c_{ij}\right)^{\frac{1}{z}}}{\sum_{i=1}^{z}\left(\prod_{j=1}^{z} c_{ij}\right)^{\frac{1}{z}}} \tag{2}$$

$$E_{(C)_{z\times z}} = \left[E_{(C)_{z\times z},1}, E_{(C)_{z\times z},2}, \dots, E_{(C)_{z\times z},z}\right]^T \tag{3}$$

3.2.2. Pairwise comparisons at level 2

Pairwise comparisons at level 2 of the Benefit and Cost hierarchies must be carried out as well. As explained in Table 4, pairwise comparison matrices between the metric categories with regard to the set of commandments are created based on the weights specified in Table 3. For example, the pairwise comparison matrix regarding C_{10}, which is denoted by $(P_{C_{10}})_{3\times 3}$, is generated as in Eq. (4) [3] (*cf.*, weights highlighted in bold/red correspond to the ones specified in Table 3). The resulting priority vectors are denoted by $E_{(P_{C_m})_{y\times y}}$.

$$\left(P_{C_{10}}\right)_{3\times 3} = \begin{array}{c} \\ \text{Carbon} \\ \text{Green} \\ \text{Recycling} \end{array} \begin{array}{c} \begin{array}{ccc} \text{Carbon} & \text{Green} & \text{Recycling} \end{array} \\ \begin{bmatrix} 1 & \mathbf{\frac{3}{9}} & \frac{3}{3} \\ \frac{1}{c_{12}} & 1 & \frac{9}{3} \\ \frac{1}{c_{13}} & \frac{1}{c_{23}} & 1 \end{bmatrix} \end{array} \tag{4}$$

It should be noted that we do not expect that data center stakeholders perform pairwise comparison at this level, even though it does not prevent an expert from modifying the impact analysis proposed in Section 3.1 and Table 3.

3.2.3. Pairwise comparisons at level 3

Pairwise comparisons at level 3 (i.e., between metrics of a given category P_k) must be performed by stakeholders (cf., Table 4). For example, regarding the Recycling category, one may want to put more emphasis on the “MRR” metric at the expense of “ERF” because the stakeholder deems the recycling of material as more important than the reuse of data center heat extraction/dissipation to warm up buildings. Pairwise comparison matrices are denoted by $(M_{P_k})_{x\times x}$ and the associated priority vector denoted by $E_{(M_{P_k})_{x\times x}}$.

3.2.4. Pairwise comparisons at level 4

Finally, pairwise comparisons at level 4 are carried out between the set of alternatives (i.e., data center candidates), which is denoted by $\mathscr{A}$. One difference with the previous pairwise comparisons is that, while before they were reflecting either the stakeholder preferences/expertise, they are now performed based upon measurable/supervised system parameters. In other words, all data center candidates are evaluated with respect to all metrics based on automated mechanisms. Pairwise comparison matrices are denoted by $(A^{M_{P_k,j}})_{w\times w}$, as in Eq. (5), j referring to the j^{th} metric of category P_k, and l to the l^{th} data center candidate. The resulting priority vectors are denoted by $E_{(A_l^{M_{P_k,j}})_{w\times w}}$.

[3] Note: All consistency rations (CR) of the pairwise comparison matrices of level 2 are <0.1.

$$\left(A1_{MPk,j}\right)w \times w = \begin{array}{c c} & \begin{array}{ccc} A_1 & \cdots & Aw \end{array} \\ \begin{array}{c} A_1 \\ \vdots \\ A_w \end{array} & \begin{bmatrix} 1 & \cdots & \frac{A1_{MPk,j}}{Aw_{MPk,j}} \\ \vdots & \vdots & \ddots \\ \frac{A1_{M_{P_k,j}}}{AwMPk,j} & \cdots & 1 \end{bmatrix} \end{array} \tag{5}$$

3.2.5. Alternative ranking

All the priority vectors previously computed must now be aggregated in order to obtain the final score of each alternative with respect to the Benefit and the Cost objectives (scores being respectively denoted by $S^B_{A_l}$ and $S^C_{A_l}$). To this end, the weighted sum method is applied, as given in Eq. (6), where $f(i)$ and $f(m)$ refer to the mapping functions that depend on the size of vectors $E_{(P_{C_m})_{y\times y}}$ and $E_{(M_{P_k})_{x\times x}}$ respectively.

$$S^{\{B;C\}}_{A_l} = \sum_{j=1}^{f(i)} \Big[\sum_{i=1}^{f(m)} \Big[\sum_{m=1}^{z} \left(E_{\left(A_i^{M_{P_k},j}\right)_{w\times w}, j} \right) \cdot \left(E_{(M_{P_k})_{x\times x}, i} \right) \cdot \left(E_{(P_{C_m})_{y\times y}, m} \right) \cdot \left(E_{(C)_{z\times z}, m} \right) \Big] \Big] \tag{6}$$

The Benefit/Cost score, denoted by S_{A_l} in Eq. (7), is carried out by dividing the two scores, which is used as basis for ranking all data center candidates in terms of sustainable development/behavior.

$$S_{A_l} = \frac{S^B_{A_l}}{S^C_{A_l}} \tag{7}$$

4. Case study

The geographic distribution of data centers across the globe goes along with different environmental and economic considerations (e.g., cost of the electricity or the cooling effort needed in a given country/region), which has a direct impact on the overall sustainability of data centers. In order to run experiments with data centers operating under different climate and energy production conditions, we selected three data centers respectively located in Nice (France), Karlsruhe (Germany) and Uppsala (Sweden), as depicted in Fig. 5. Table 5 reports the coefficients needed to produce energy in these three countries (data source: International Energy Authority website.[4]

Section 4.1 details the methodology that has been applied to collect the datasets related to each data center, as well as the computational steps performed with regard to the Benefit/Cost analysis. Section 4.2 analyzes the results/ranking obtained when comparing the three data center candidates using our approach.

4.1. Data center settings, stakeholder preference & computational steps

Section 4.1.1 details how datasets related to the data center candidates have been collected. Section 4.1.2 presents both the stakeholder preferences specified in the pairwise comparison process and the computational steps performed based on our approach.

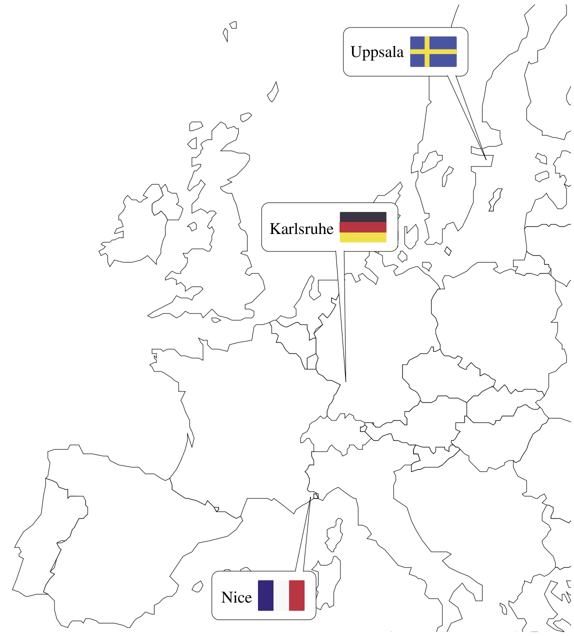


Fig. 5. Data center candidates compared in the case study.

4.1.1. Data center-related datasets

It is not an easy task for academics to be able to access/collect data center-related datasets. The reason for this is two-fold: (i) due to a lack of transparency and impossibility of accessing backend systems of data center organizations; (ii) some of the state-of-the-art metrics are not necessarily implemented/monitored by data center organizations. While the first difficulty can be partially overcome/influenced by government regulatory bodies (Guo et al., 2018; van den Berg et al., 2018; De Napoli et al., 2016), the second one requires further sensor network deployments in data centers to be able to compute all the state-of-the-art metrics integrated to our model (*cf.*, Table 3) (Li et al., 2018; Liu et al., 2016b; Hong et al., 2013; Rodriguez et al., 2011). Nonetheless, as the primary objective of our research is not to provide an in-depth comparison study of existing data centers, but rather to present the theoretical foundation of our approach, we made use of an online calculator — *Data Center Tradeoff Tools of Schneider Electric*[5] — to generate the datasets related to the data center candidates. However, this tool only allows us to generate a limited number of metrics compared with the one integrated to our model (*cf.*, Fig. 4). The subset of metrics for which data could be generated is detailed in Table 6.

The Schneider Electric calculator requires to set up some operating conditions of the data center, as given in the software screenshot in Fig. 6 (*cf.*, *Power & Environmental Characteristics*). The following conditions were specified for experiment purposes:

- Data Center IT Capacity: 1000 kW;
- Data Center IT Load: 70%;
- IT Operating Environment: User defined temperature;
- IT Inlet Temperature: 32°;
- Power & Lighting: No power of lighting losses.

In addition of this scenario, a second one was specified consisting in virtualizing part of the physical infrastructure. This requires to modify the alternative level of the Benefit and Cost

[4] https://www.iea.org, last access: May 2019.

[5] https://www.schneider-electric.com/en/work/solutions/for-business/data-centers-and-networks/trade-off-tools/, last access: May 2019.

Table 5
Country-related data from IEA.[4].

	country	Hydro	Wind	Biomass	Solar CSP	Geothermal	Solar PV	Nuclear	Natural Gaz	Oil	Coal
Energy	Fr	11	4	2	2	0	/	73	6	0	2
(%)	Ge	3	12	9	6	0	/	13	13	1	43
	Sw	41	10	7	0	0	/	40	1	0	1
Carbon (kg/kWh) (10^{-3})		4	12	18	22	45	46	16	469	84	1001

Table 6
Values of metrics related to the three use case scenarios: TC, CW, V.

	Formula	Traditional Cooling (TC)			Virtualization (V)		
		Fr	Ge	Sw	Pre-V	Post-V	Post-V-R
PUE (Ratio)	$\frac{\text{Total Facility Power}}{\text{IT Equipment Power}}$	**1.560**	**1.550**	**1.540**	2.278	1.720	2.117
CUE (Co2/Wh)	$\frac{\text{Total Carbon Emissions}}{\text{Total IT Equipment Energy}}$	0.096	0.785	0.039	0.140	0.106	0.130
GEC (%)	$\frac{\text{Green Energy used in the Data center}}{\text{Total Data Center Source Energy}}$	0.190	0.300	0.580	0.190	0.190	0.190
WUE (L/kWh)	$\frac{\text{Annual Water Usage}}{\text{IT Equipment Energy}}$	0.000	0.000	0.000	0.137	0.169	0.169
WUEs (L/kWh)	$\frac{\text{Annual Site Water Use} + \text{Annual Srce Water Use}}{\text{IT Equipment Energy}}$	10.083	3.897	29.356	10.083	10.181	10.083
DCiE (%)	$\frac{1}{\text{PUE}}$	0.640	0.650	0.650	0.440	0.580	0.470
OPEX ($)	Energy Cost × Consumed Energy	1151K	1807K	1086K	1197K	733K	902K
SPUE (Ratio)	$\frac{\text{Total Facility Power}}{\text{Server Power}}$	N/A	N/A	N/A	4.556	4.473	5.518
REL (Faults/h)rowhead	$\frac{\text{number of failures or outages}}{\text{Total surviving hours}}$	N/A	N/A	N/A	0.001	0.001	0.0005

hierarchies, for which alternatives are no longer the data center candidates but the set of virtualization configuration candidates in a data center. Three configuration candidates are compared: *(i) Pre-Virtualization (Pre-V):* amount of energy used in the data center and by the IT equipments before virtualization; *(ii) Post-Virtualization (Post-50%):* a total of 1000 physical servers are considered for set up, 50% of which being virtualized without redundancy; and *(iii) Post-Virtualization (Post-50%-R):* same except that physical servers are redundant. Given these scenarios, all metric values regarding the three data center and virtualization candidates were generated, as given in Table 6. The following section details an example of how a the weights are generated and aggregated in our approach.

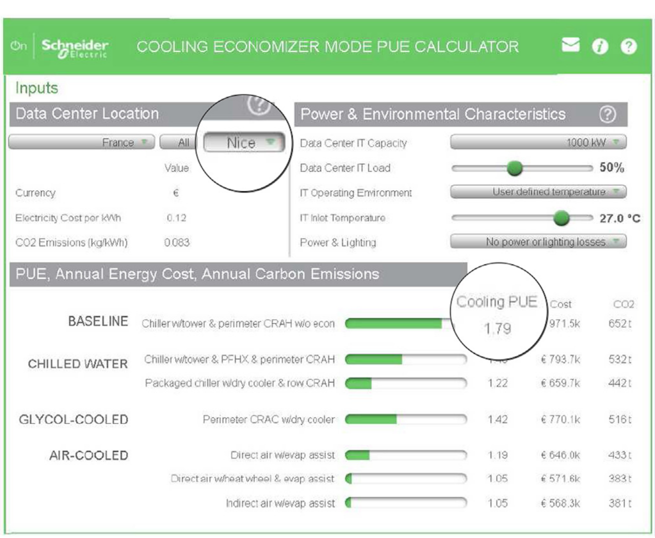


Fig. 6. Screenshot of Schneider Electric online calculator.

4.1.2. Stakeholder preference & computational steps

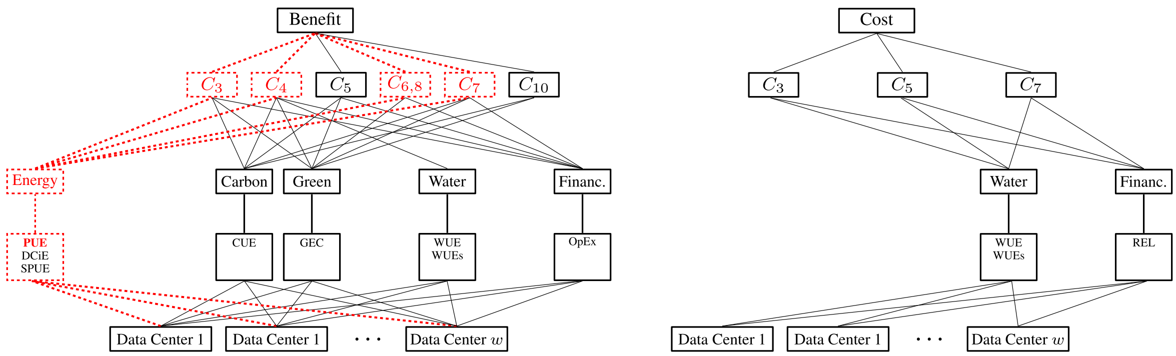
In this scenario, we assume that stakeholders at levels 1 and 3 do not want to prioritize one commandment/metric criterion over others. It is important to understand that this preference set is only meant to illustrate the functioning of our approach and could be easily adapted, if needed, depending on the stakeholders' needs/interests. Given the set of metrics considered in our scenario (*cf.*, Table 6), along with the benefit/cost analysis detailed in section 3.2, the resulting Benefit and Cost hierarchies are depicted in Fig. 7(a)–(b) respectively. In order to ease the understanding of how weights are generated/computed and aggregated in our approach, we propose to detail in the following the computational steps regarding the PUE metric from the Benefit hierarchy (*cf.*, red/dashed lines in Fig. 7(a)).

1. *Level 1 (L1):* As it is assumed that all commandments are considered of the same importance by the stakeholder, this results in the pairwise comparison matrix and priority vector given in Eq. (8);

$$C = \begin{array}{c} \\ C_3 \\ C_4 \\ C_5 \\ C_{6,8} \\ C_7 \\ C_{10} \end{array} \begin{array}{c} \begin{array}{cccccc} C_3 & C_4 & C_5 & C_{6,8} & C_7 & C_{10} \end{array} \\ \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \end{array}$$

$$E_C = \begin{array}{c} \begin{array}{cccccc} C_3 & C_4 & C_5 & C_{6,8} & C_7 & C_{10} \end{array} \\ [1\,/\,61\,/\,61\,/\,61\,/\,61\,/\,6] \end{array} \quad (8)$$

2. *Level 2 (L2):* Eq. (9) details the pairwise comparison matrix related to commandment C_3, along with the resulting priority



(a) BENEFIT hierarchy (b) COST hierarchy

Fig. 7. AHP-based data center performance comparison from BENEFIT and COST perspectives.

vector (please refer to section 3.2.2 to obtain more details on how the pairwise comparison matrix is created). Eq. (10)–(12) only provide the priority vectors resulting from the pairwise comparison matrix related to commandments $C_3, C_4, C_{6,8}$ and C_7 (the ones needed to compute the red/dashed part highlighted in Fig. 7(a)).

$$P_{C_3} = \begin{array}{c c} & \begin{array}{cccc} \text{Ener} & \text{Carb} & \text{Gree} & \text{Fina} \end{array} \\ \begin{array}{c} \text{Ener} \\ \text{Carb} \\ \text{Gree} \\ \text{Fina} \end{array} & \begin{bmatrix} 1 & \frac{9}{9} & \frac{9}{5} & \frac{9}{9} \\ \frac{9}{9} & 1 & \frac{9}{5} & \frac{9}{9} \\ \frac{5}{9} & \frac{5}{9} & 1 & \frac{5}{9} \\ \frac{9}{9} & \frac{9}{9} & \frac{9}{5} & 1 \end{bmatrix} \end{array}$$

$$E_{P_{C_3}} = \begin{array}{c} \begin{array}{cccc} \text{Ener} & \text{Carb} & \text{Gree} & \text{Fina} \end{array} \\ \begin{bmatrix} 0.281 & 0.281 & 0.157 & 0.281 \end{bmatrix} \end{array} \tag{9}$$

$$E_{P_{C_4}} = \begin{array}{c} \begin{array}{ccccc} \text{Ener} & \text{Carb} & \text{Gree} & \text{Wate} & \text{Fina} \end{array} \\ \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix} \end{array} \tag{10}$$

$$E_{P_{C_{6,8}}} = \begin{array}{c} \begin{array}{ccc} \text{Ener} & \text{Gree} & \text{Fina} \end{array} \\ \begin{bmatrix} 0.295 & 0.529 & 0.176 \end{bmatrix} \end{array} \tag{11}$$

$$E_{P_{C_7}} = \begin{array}{c} \begin{array}{cccc} \text{Ener} & \text{Carb} & \text{Gree} & \text{Fina} \end{array} \\ \begin{bmatrix} 0.166 & 0.278 & 0.278 & 0.278 \end{bmatrix} \end{array} \tag{12}$$

3. *Level 3 (L3):* As we assume that metrics in this category are considered of the same importance by the stakeholder, this leads to the comparison matrix and priority vector given in Eq. (13);

$$M_{\text{Ener}} = \begin{array}{c c} & \begin{array}{ccc} \text{PUE} & \text{DCiE} & \text{SPUE} \end{array} \\ \begin{array}{c} \text{PUE} \\ \text{DCiE} \\ \text{SPUE} \end{array} & \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \end{array}$$

$$E_{M_{\text{Ener}}} = \begin{array}{c} \begin{array}{ccc} \text{PUE} & \text{DCiE} & \text{SPUE} \end{array} \\ \begin{bmatrix} 1/3 & 1/3 & 1/3 \end{bmatrix} \end{array} \tag{13}$$

4. *Level 4 (L4):* The three data center candidates are then evaluated with respect to each metric of the Energy, Carbon, Green, Water and Financial categories. Eq. (14) details only the pairwise comparison matrix and the resulting priority vector related to the PUE metric. Each pairwise comparison is built based on the values reported in Table 6 (*cf.*, red/bold row in the table).

$$\left(A^{\text{PUE}}\right) = \begin{array}{c c} & \begin{array}{ccc} \text{Fr} & \text{Ge} & \text{Sw} \end{array} \\ \begin{array}{c} \text{Fr} \\ \text{Ge} \\ \text{Sw} \end{array} & \begin{bmatrix} 1 & \frac{1.560}{1.550} & \frac{1.560}{1.540} \\ \frac{1.550}{1.560} & 1 & \frac{1.550}{1.540} \\ \frac{1.540}{1.560} & \frac{1.540}{1.550} & 1 \end{bmatrix} \end{array}$$

$$E_{M_{\text{Ener}}} = \begin{array}{c} \begin{array}{ccc} \text{Fr} & \text{Ge} & \text{Sw} \end{array} \\ \begin{bmatrix} 0.336 & 0.333 & 0.331 \end{bmatrix} \end{array} \tag{14}$$

5. *Weight aggregation:* All the priority vectors previously computed must then be aggregated – *based on* Eq. (7) – in order to obtain the "benefit" score of each data center candidate with regard to each metric, of each category. In our example, we detail the aggregation score with regard to the PUE metric, which is denoted by $S_{A_i}^{B(\text{PUE})}$ in the following. This computational stage is detailed in Eq. (15) for the data center located in France (score of 0.0176). Data centers located in Germany and Sweden obtain a lower beneficial score with regard to PUE, as given in Eqs. (16) and (17) ($S_{Sw}^{B(\text{PUE})} < S_{Ge}^{B(\text{PUE})} < S_{Fr}^{B(\text{PUE})}$). All benefit and cost scores, with regard to all metrics, are computed and aggregated in a similar way, and further divided (*cf.*, Eq. (7)) to rank the data center candidates in terms of sustainable behavior.

$$\begin{aligned} S_{Fr}^{B(\text{PUE})} &= \sum_{i=\{C_{3,4,6,8,7}\}} \left(E_{A^{\text{PUE}}}[\text{Fr}] \cdot E_{M_{\text{Ener}}}[\text{PUE}] \cdot E_{P_{C_3}}[\text{PUE}] \cdot E_C[C_3] \right) \\ &= (0.336 \cdot 1/3 \cdot 0.281 \cdot 1/6) + (0.336 \cdot 1/3 \cdot 0.2 \cdot 1/6) + (0.336 \cdot 1/3 \cdot 0.295 \cdot 1/6) + (0.336 \cdot 1/3 \cdot 0.166 \cdot 1/6) \\ &= 0.0176 \end{aligned} \tag{15}$$

$$S_{Ge}^{B(\text{PUE})} = 0.0174 \tag{16}$$

$$S_{Sw}^{B(\text{PUE})} = 0.0173 \tag{17}$$

4.2. Benefit/cost analysis

Given the experimental settings, the Benefit/Cost analyses for the two scenarios were carried out using MATLAB, which are respectively presented in sections 4.2.1 and 4.2.2, while section 4.2.3 discusses the limitation of our experiments and the "take away" message of our research.

4.2.1. Comparison of data center candidates

Fig. 8(a)–(b) provide insight into the overall scores obtained by the three data center candidates in terms of Benefit ($S_{A_l}^B$) and Cost ($S_{A_l}^C$) implications, while Fig. 8(c) gives insight into the final Benefit/Cost analysis (S_{A_l}). Looking independently at the benefit and cost analyses, it can be observed that data center 3 (Uppsala) is the most beneficial and data center 2 the less beneficial (*cf.*, Fig. 8(a)), while the situation is exactly the opposite regarding the cost analysis. This logically leads to increasing the gap when carrying out the Benefit/Cost analysis in Fig. 8(c): data center 3 (Uppsala) being ranked first in terms of sustainable behavior/development, followed by data centers 1 (Nice) and 2 (Karlsruhe) respectively. A comment about these results is that a data center with a same specification has different environmental impacts depending on its location, which is mainly due to the type of climate, of energy used, and the cost of energy. One may imagine that such a ranking model could be used by data center owners in the decision making process for deciding where to build new data centers, which has a direct impact on the economy of a country/region depending on the adopted political decisions.

To more thoroughly analyze the results and to better understand how a data center behaves regarding one or more of the biomimicry commandements (i.e., level 1 of the AHP hierarchies) and/or one or more of the metric categories (i.e., level 2), let us look at Fig. 9(a)–(b). While the latter provides a technical representation that is more adapted to data center experts (all axes referring to the Datacenter metric categories), the former is more adapted to non-expert users. For example, the representation from:

- Fig. 9(a) could be integrated into a more global analysis such as an ecopark (gathering other industries) or as support for political decision-making in Conference of the Parties (COP)-like events during which ICT performance are analyzed and debated. In this respect, the holistic nature of our approach could be used. For example, if politicians would like to focus the debate on pollution mitigation, they would just need to privilege C_6 over the other commandments in order to get the corresponding data center ranking.
- Fig. 9(b) could be used by experts to take appropriate actions in order to meet the political decisions above-discussed. For example, an interesting finding from Fig. 9(b) is that Sweden is actually less performant than the other data centers regarding the Water category, but it is less costly when evaluating the Cost implication (*cf.*, Fig. 8(b)). The reason for this is that water implies to emit less carbon and to use less non-renewable energy.

Another comment about Fig. 9(a)–(b) is that the perception of the performance is different. For example, for Sweden, Fig. 9(a) shows balanced and good results, which is not the case in Fig. 9(b) regarding the Water category. This means that, when decisions are selected by experts (Fig. 9(b)), it is important to analyze Fig. 9(a) at the same time, as it provides a holistic view of the impacts on ecosystems. Overall, these two views could help data center operators to tune data center parameters by considering all interrelations of complex ecological systems.

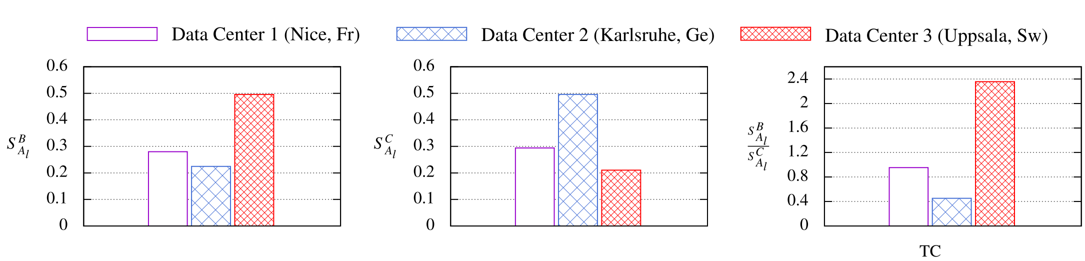
4.2.2. Comparison of virtualization configuration candidates

In a similar manner as before, Fig. 10(a)–(b) provide insight into the overall scores obtained by the three virtualization configuration candidates in terms of Benefit and Cost implications, and Fig. 10(c) into the final Benefit/Cost analysis. The Benefit and Cost analyses confirm the fact that virtualizing physical servers contributes to improving the overall sustainability of the data center, and, interestingly, the redundancy of servers does not affect/degrade – *or very lightly* – the sustainability score in this experiment. Even though we do not need to be an expert to understand this result, one may imagine to use this approach for marketing purposes with customers or politics.

4.2.3. Discussion of experiment results & findings

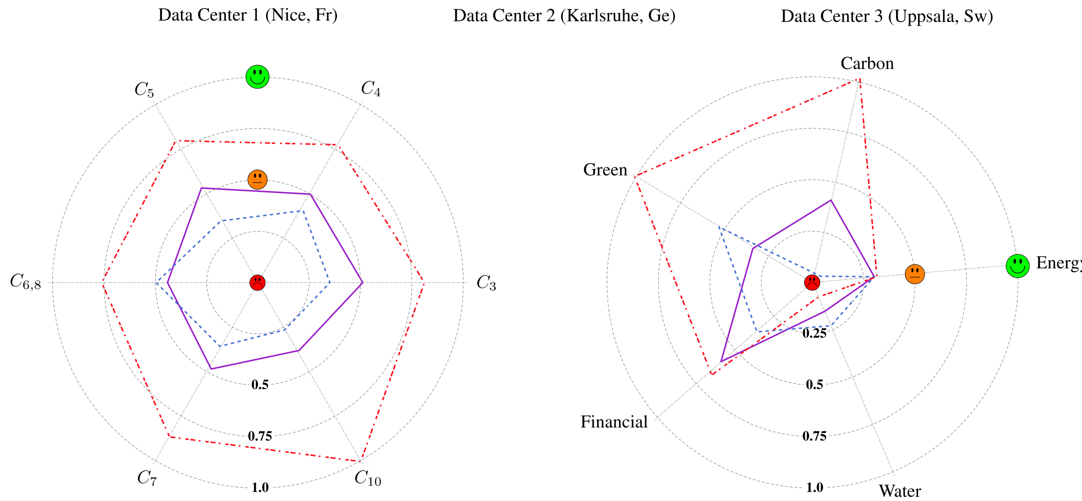
Before concluding this paper, it is important to remind ourselves that the above experiments are only meant to illustrate the practicality and holistic nature of the proposed approach, as was discussed in section 4.2.1. This is important to be noted because the key message to be conveyed in this paper is that we do not aim to carry out an in-depth comparison study of existing data centers over the globe, but rather to present the theoretical foundation of an innovative approach that could help data center stakeholders to compare the overall sustainability of data centers in a holistic and non-technical manner. This message is important as our experiments are limited in the following respect:

- we could not collect real datasets from existing data centers;



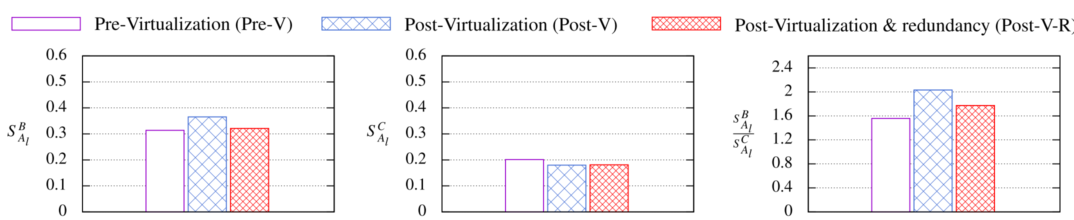
(a) Benefit analysis (b) Cost analysis (c) Benefit/Cost analysis

Fig. 8. Benefit/Cost analysis of the three data center candidates: Nice *vs.* Karlsruhe *vs.* Upssala



(a) Data center sustainability w.r.t the biomimicry commandments (b) Data center sustainability w.r.t the metric categories

Fig. 9. Holistic view of the data center sustainability with regard to both the biomimicry commandments and the metric categories.



(a) Benefit analysis (b) Cost analysis (c) Benefit/Cost analysis

Fig. 10. Benefit/Cost analysis of the three Virtualization configuration candidates: Pre-V *vs.* Post-V *vs.* Post-V-R.

- the online calculator enabled us to work only with a limited number of metrics compared with the exhaustive list considered in the theoretical model of our approach (*cf.*, section 3).

Such limitations have direct impact on the relevance of our comments/findings when discussing the data center performance results. This should therefore be taken with caution, or at least understood by the reader.

5. Conclusions, implications, limitations and future research

5.1. Conclusions

The importance of data centers for society has changed, as public life, economy and society depend to a large extend on the proper functioning of data centers. From different parts of society, the sustainability of data centers is questioned, thus raising questions about the “data center equation” of “people, planet, profit”. While it is common place to think that making data centers sustainable comes down to implementing technical measures, it actually goes well beyond the walls of the data center, touching upon economic and political questions. As a consequence, it is imperative to develop and propose holistic models that help data center stakeholders, spanning from data center owners, governmental regulators to engineers/field operators, to evaluate and understand how a data center performs in terms of sustainable development and behavior. While a large number of sustainability metrics exist in the literature, there is still a lack of frameworks that make it possible to reduce the complexity of the performance evaluation analysis.

In order to fill this gap in literature, this paper presents an innovative approach based on a benefit-cost analysis using the Analytic Hierarchy Process (AHP). The originality lies in the combination of state-of-the-art sustainability metrics with the biomimicry commandments of eco-mature system defined by J. Benyus (1997), and the possibility for data center stakeholders to analyze and compare performance of data centers in a more or less holistic manner (depending on their needs, focus, expertise). For example, one data center stakeholder may want to prioritize the biomimicry commandment C_6 when debating on pollution aspects (data centers would, indeed, be ranked with emphasis on the extent to which the pollute locally), while another one could be provided with a more in-depth analysis of how a data center performs with respect to the energy, water, green or still financial dimensions. The practicability of our model is demonstrated considering three data center candidates, which are respectively located in France, Germany and Sweden. However, it is important to note that the key contribution and message to be conveyed in this paper is about the theoretical foundation of the proposed approach, rather than on comparing existing data centers over the world.

5.2. Implications

This research presents three main theoretical implications.

First, it has implications in the field of LCA (as was previously discussed in section 2.1), and particularly of CBA (Cost-Benefit Analysis) (Hoogmartens et al., 2014). Even though our approach differs from traditional CBA analyses (which mostly focus on economical assessment), many studies have considered AHP in order to cope with the CBA's weakness in reflecting stakeholders' knowledge in the evaluation process of projects (Lee et al., 2009; Tudela et al., 2006). Although the assessment of CBA versus AHP capabilities remains an open research question (Foo et al., 2012; Arroyo et al., 2012), our Benefit-Cost model is, to the best of our knowledge, the first one that explores the possibility of combining state-of-the-art sustainability metrics with the biomimicry principles in order to enable holistic assessment of the sustainability performance of data centres. One key interest and novelty of such a combination lies in the fact that the biomimicry commandments provide a universal language/representation that makes it possible the integration of any future/new metrics without having to change the underlying model (except complementing the expertise specified in Table 3).

Second, the proposed approach also contributes to move towards increasing professional and public awareness of how data centers behave in terms of sustainability, both from a biomimicry viewpoint and/or when looking at specific metric categories (e.g., from an energy, financial, green or still water viewpoint). This could be helpful for organizations and regulatory institutions to establish strategic plans to both improve current data center practices to meet the United Nations Sustainable Development Goals[6] (SDGs) and contribute to the welfare of the society. In this respect, and from a theoretical implication perspective, our approach could serve as a basis to further address the Arrow's impossibility theorem (Arrow, 2012), as it has been proved that the combination of the AHP and geometric mean methods (approach adopted in this paper) contributes to find a social welfare function that satisfies the four conditions: (i) Pareto optimality, (ii) Independence from irrelevant alternatives, (iii) unrestricted domain, and (iv) Non-dictatorship (Saaty and Vargas, 2012; Waldron and Waldron, 2013).

Third, our approach supports, to a certain extent, an efficient solution to tackle environmental externalities. Indeed, different overconsumption (e.g. in terms of energy) will result in an increase of the costs (i.e., negative externality) in our model; for instance, satisfying commandment C_3 (mitigating energy consumption and local energy production) would be a true leverage for a private cooperation to minimize that effect (the cost will be here the incentive). The same may apply for commandment C_1 (use waste as ressource). In addition, society will intervene in the markets and apply new taxes (for instance related to Co2) and may even define temporary closures for instance in case of (carbon in) air pollution, leading to a loss of income and usage effectiveness. Commandment C_6 will aim at repelling this risk.

5.3. Limitations

In this research work, AHP is used as underlying technique for combining, in a holistic way, the biomimicry commandments and state-of-the-art sustainability metrics. However, several limitations of this approach should be noted, which are respectively discussed through sections 5.3.1, 5.3.2 and 5.3.3.

5.3.1. Dealing with uncertainties

The path towards sustainable development is not a straightforward process, as explained by Zanghelini et al. (2018) who point out three complex factors in the ideal environmental decision-making: *(i) uncertainty & vagueness:* difficulty lies in the quantity of data, the multiple unit types, judgmental values to be applied and the uncertainty of background and foreground data; *(ii) subjectivity:* because personal judgment vary on which topics are most important; and the *(iii) multi-stakeholders involvement:* because it must be considered in ideal decision-making. Given these factors, Petrillo et al. (2016) explain that providing a real and substantial application of sustainability through the measurement and comparability of results, in a way that satisfies the principles of sustainability of all the stakeholders is one of the biggest challenge (knowing that uncertainties vary depending on who we ask). There is still research to be done in this area.

Although AHP is among the most popular techniques for dealing with MCDA, it does not allow us to tackle uncertainty and vagueness in the expert judgments/preferences, while it could be arguable to ask for precise pairwise comparison values because these coefficients are arguably imprecisely known by experts (Cooke, 1991). To overcome this, AHP could further be combined with Fuzzy Logic, also known as FAHP (Fuzzy AHP) (Kubler et al., 2016), even though some scholars, such as Dubois (2011), argue that fuzzy sets have often been incorporated into existing methods (e.g., into AHP, PROMETHEE, ELECTRE) without clear benefits. The main reason behind such a criticism lies in the difficulty of successfully satisfying the transitivity and reciprocal axioms (Dubois, 2011; Kubler et al., 2018). Other approaches than FAHP could also be explored to handle uncertainty and vagueness, such as the Statistical Value Chain (SVC) (Herrmann et al., 2013), which is designed to help evaluating the process of decision support from a statistical viewpoint.

5.3.2. Misuse of the analysis?

One may raise the question: *"would it be possible to misuse the analysis by manipulating either data or analysis procedure?"* A straightforward answer would be "yes", but any multi-attribute decision-making (MADM) technique that takes into consideration (as inputs) human judgments/preferences, as is the case with AHP, can lead to risks of misusing/manipulating the input judgments in order to obtain the desired alternative ranking (different sets of preferences resulting in different ranking results). However, this is more a problem of integrity than a limitation of AHP. Although making transparent the pairwise comparison judgments/preferences would help to not mislead anyone, this problem is out of scope of this study.

5.3.3. Lack of real-life datasets

Even though the primary message of this research is not to present an in-depth comparison analysis of existing data centers over the globe, but rather present the theoretical foundation of our approach, a next step would be to carry out such comparison analysis considering real-life datasets from data centers. As was discussed in section 4.1.1, this poses a two-fold challenge: (i) to be able to access backend systems of data center organizations; and (ii) to support and/or incentivize organizations to implement/monitor new sustainability metrics in their facilities.

5.4. Future research

Beyond addressing the limitations raised in the previous section, we believe that the theoretical model proposed in this paper is fully applicable to other green ICT sectors including core network infrastructures, internet providers, ICT in enterprise, or still to smart applications such as smart cities, smart transport, Industry 4.0, *etc.* One perspective of this research is thus to keep refining the modelling in translating other metrics in term of eco-mature system lessons. To this end, and as previously discussed in section 2.1, we believe that our model could be either re-used as part of a more generic LCA model covering the economical and social dimensions, too, or be refined with other performance indicators defined in LCA standards.

6 https://www.un.org/sustainabledevelopment, last access: May 2019.

Acknowledgment

The research reported here was supported and funded by the PERCCOM Erasmus Mundus Program of the European Union (PERCCOM- FPA 2013-0231). The authors would like to express their gratitude to all the partner institutions, sponsors, and researchers involved in the PERCCOM program (Klimova et al., 2016).

Appendix A. Sustainable data center metrics

Table A.7
Metrics for Sustainable data centers reported in (Dinesh Reddy et al., 2017)

Metric	Definition
ACPR	Average Comparisons Per Rule
AEUF	Air Economizer Utilization Factor
APC	Adaptability Power Curve
ATR	Application Transaction Rate
BJC	Bits per Joule Capacity
CADE	Corporate Average Data Center Efficiency
Capacity	Capacity
CC	Concurrent Connections
CER	Connection Establishment Rate
CNEE	Communication Network Energy Efficiency
Co2s	Co2 Savings
CoP	Coefficient of Performance Ensemble
CPE	Compute Power Efficiency
CUE	Carbon Usage Effectiveness
DCA	DCAdapt
DCcE	Data Center Compute Efficiency
DCCSE	Data Center Cooling System Efficiency
DCeP	Data Center Energy Productivity
DC-FVER	Data Center Fixed to Variable Energy Ratio
DCiE	Data Center Infrastructure Efficiency
DCLD	Data Center Lighting Density
DCPD	Data Center Power Density
DCPE	Data Center Performance Efficiency
DCSSF	Data Center Cooling System Sizing Factor
DeD	Defense Depth
DeP	Detection Performance
DH-UE	Deployed Hardware Utilization Efficiency
DH-UR	Deployed Hardware Utilization Ratio
DPPE	Data Center Performance Per Energy
DTE	Data Transmission Exposure
DWPE	Data Center Workload Power Efficiency
ECR-VL	Energy Consumption Rating Variable Load
EDE	Electronics Disposal Efficiency
EER	Energy Efficiency Ratio
EES	Energy ExpenseS
ERE	Energy Reuse Effectiveness
ERF	Energy Reuse Factor
EWR	Energy Wasted Ratio
GEC	Green Energy Coefficient
GUF	Grid Utilization Factor
H-POM	IT Hardware Power Overhead Multiplier
HSE	HVAC System Effectiveness
HTTP	HTTP Transfer Rate
IAS	Interface Accessibility Surface
IPFH	IP Fragmentation Handling
IPt	IP throughput
ITEE	IT Equipment Energy
ITEU	IT Equipment Utilization
ITH	Illegal Traffic Handling
Lat	Lat
LSP	Low-cost Storage Percentage
MemU	Memory Usage
MRR	Material Recycling Ratio
NetT	Network Traffic per Kilowatt-Hour
NPUE	Network Power Usage Effectiveness
OSE	Overall Storage Efficiency
OSWE	Operating System Workload Efficiency
OpEx	Operational Expenditure

(continued on next page)

Table A.7 (*continued*)

Metric	Definition
PDE	Power Density Efficiency
PEs	Primary Energy Savings
pPUE	partial Power Usage Effectiveness
PpW	Performance per Watt
PUE	Power Usage Effectiveness
PUEs	Power Usage Effectiveness Scalability
RC	Reachability Count
RCD	Rogue Change Days
REL	Reliability
RSmax	Maximum Relative Size
RT	Response Time
ScE	Server Compute Efficiency
SI-POM	Site Infrastructure Power Overhead Multiplier
SPUE	Server Power Usage Efficiency
SU	Slot Utilization
SWaP	Space, Watts and Performance
T	Vulnerability Exposure
TCE	Technology Carbon Efficiency
TEER	Telecommunications Energy Efficiency Ratio
Thght	Throughput
TUE	Total-Power Usage Effectiveness
Unet	Network Utilization
Ustor	Storage Usage
WUE	Water Usage Effectiveness (on-site)
WUEs	Water Usage Effectiveness (on-site and off-site)

Appendix B. Abbreviation & Important concepts

Table B.8 summarizes all abbreviations used throughout the paper, except the list of sustainable data center metrics which is given as a separate table in AppendixA.

Table B.8
List of acronyms and variables used throughout the paper

	Acronym	Full form
Abbreviation	AHP - FAHP	Analytic Hierarchy Process - Fuzzy Analytic Hierarchy Process
	CBA	Cost-Benefit Analysis
	COP	Conference of the Parties
	CR	Consistency Ratio
	Solar CSP-PV	Concentrated Solar Power - Solar Photovoltaic
	DEA	Data Envelopment Analysis
	ELECTRE	ÉLimination Et Choix Traduisant la RÉalit
	ICT/IT	Information (and Communication) Technologies
	LCA	Life Cycle Assessment
	MADM	Multi-Attribute Decision Making
	MCDA	Multi-Criteria Decision Analysis
	MCDM	Multi-Criteria Decision Making
	PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
	QoS	Quality of Service
	Pre-V	Pre-Virtualization
	Post-V(-R)	Post-Virtualization (Post-V); Post-Virtualization with Redundancy (Post-V-R)
	SDGs	Sustainable Development Goals
	SLA	Service Level Agreement
	SVC	Statistical Value Chain
	TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
	VIKOR	VlseKriterijumska Optimizacija I Kompromisno Resenje (means: multicriteria optimization and compromise solution)
Mathematical Variables	$\mathscr{C}$	Set of biomimicry commandments. Elements of $\mathscr{C}$ are denoted by $\{C_1,..,C_i,..,C_z\}$ and the associated pairwise comparison matrix is denoted by $(C)_{z\times z}$, as given in Eq. (1).
	$\mathscr{P}$, $\mathscr{P}_{C_m}$	$\mathscr{P}$ refers to the set of categories given in Table 3 (i.e., Energy, Materials, Cooling, *etc.*). Elements of $\mathscr{P}$ are denoted by $\{P_1,..,P_k,..,P_u\}$. $\mathscr{P}_{C_m}$ refers to a subset of $\mathscr{P}$ indicating what categories impact on, and thus are linked with, a given commandment C_m. For example, $\mathscr{P}_{C_{10}}=$ {Cooling, Carbon, Green, Recycling} for the Benefit hierarchy, and $\mathscr{P}_{C_{10}}=$ {Water} for the Cost hierarchy (cf., Table 3). Elements of $\mathscr{P}_{C_m}$ are denoted by $\{P_{C_m,1},..,P_{C_m,i},..,P_{C_m,y}\}$ and the associated pairwise comparison matrix is denoted by $(P_{C_m})_{y\times y}$.
	$\mathscr{M}_{P_k}$	Set of metrics that belongs to category P_k (*cf.*, Table 3). Elements of $\mathscr{M}_{P_k}$ being denoted by $\{M_{P_k,1},..,M_{P_k,i},..,M_{P_k,x}\}$ and the associated pairwise comparison matrix is denoted by $(M_{P_k})_{x\times x}$.
	$\mathscr{A}$	Set of alternative (data center) candidates. Elements of $\mathscr{A}$ being denoted by $\{A_1,...,A_l,..A_w\}$. All candidates must be evaluated with respect to all metrics and categories. The corresponding pairwise comparison matrix is denoted by $(A^{M_{P_k,j}})_{w\times w}$, with j the j^{th} metric of category P_k and l the l^{th} data center candidate.

Table B.8 (*continued*)

Acronym	Full form
E_p	Priority/Eigen vector (EV) of a pairwise comparison matrix p. Elements of E_p are denoted by $\{E_{p,1},..,E_{p,i},..,E_{p,v}\}$. In our study, p corresponds to one of the above-specified pairwise comparison matrices, namely $(C)_{z\times z}$, $(P_{C_m})_{y\times y}$, *etc.*, whose corresponding eigenvectors are denoted by $E_{(C)_{z\times z}}$, $E_{(P_{C_m})_{y\times y}}$, *etc.*
$S^{\{B;C\}}_{A_l}$	Aggregated scores of a given alternative (data center) A_l with regard to the Benefit hierarchy (score denoted by $S^B_{A_l}$) and the Cost hierarchy (score denoted by $S^C_{A_l}$). The formula to compute these two scores is given in Eq. (6).
S_{A_l}	Overall score of a given alternative (data center) A_l, which is the division of the Benefit and Cost aggregated scores (*cf.*, Eq. (7)). This overall score is used to achieve the final ranking of the compared data center candidates.

References

Abdel-Basset, M., Mohamed, M., Chang, V., 2018. NMCDA: a framework for evaluating cloud computing services. Future Gener. Comput. Syst. 86, 12–29.
Alabool, H.M., Mahmood, A.K., 2013. Trust-based service selection in public cloud computing using fuzzy modified VIKOR method. Aust. J. Basic Appl. Sci. 7 (9), 211–220.
Alger, D., 2009. Grow a Greener Data Center. Pearson Education.
Anagnostopoulos, K.P., Petalas, C., 2011. A fuzzy multicriteria benefit–cost approach for irrigation projects evaluation. Agric. Water Manag. 98 (9), 1409–1416.
Arianyan, E., Taheri, H., Sharifian, S., 2015. Novel energy and SLA efficient resource management heuristics for consolidation of virtual machines in cloud data centers. Comput. Electr. Eng. 47, 222–240.
Arrow, K.J., 2012. Social Choice and Individual Values, vol. 12. Yale university press.
Arroyo, P., Tommelein, I., Ballard, G., 2012. Comparing multi-criteria decision-making methods to select sustainable alternatives in the AEC industry. In: 2nd International Conference for Sustainable Design, Engineering and Construction, Fort Worth, TX, pp. 869–876.
Beitelmal, A.H., Fabris, D., 2014. Servers and data centers energy performance metrics. Energy Build. 80, 562–569.
Belkhir, L., Elmeligi, A., 2018. Assessing ICT global emissions footprint: trends to 2040 & recommendations. J. Clean. Prod. 177, 448–463.
Benyus, J.M., 1997. Biomimicry: Innovation Inspired by Nature. Morrow, New York.
O. Boutkhoum, M. Hanine, T. Agouti, A. Tikniouine, Selection problem of cloud solution for big data accessing: fuzzy AHP-PROMETHEE as a proposed methodology., J. Digit. Inf. Manag. 14 (6).
Cooke, R., 1991. Experts in Uncertainty: Opinion and Subjective Probability in Science. Oxford University Press, USA.
Covas, M.T., Silva, C.A., Dias, L.C., 2013. Multicriteria decision analysis for sustainable data centers location. Int. Trans. Oper. Res. 20 (3), 269–299.
Crawford, G., Williams, C., 1985. A note on the analysis of subjective judgment matrices. J. Math. Psychol. 29 (4), 387–405.
Daim, T.U., Bhatla, A., Mansour, M., 2013. Site selection for a data centre – a multi-criteria decision-making model. Int. J. Sustain. Eng. 6 (1), 10–22.
Dandres, T., Moghaddam, R.F., Nguyen, K.K., Lemieux, Y., Samson, R., Cheriet, M., 2017. Consideration of marginal electricity in real-time minimization of distributed data centre emissions. J. Clean. Prod. 143, 116–124.
De Napoli, C., Forestiero, A., Laganà, D., Lupi, G., Mastroianni, C., Spataro, L., 2016. Business scenarios for geographically distributed data centers. Tech. Rep. 1–36. RT-ICARCS-16-03.
I. De Pauw, Nature-Inspired Design: Strategies for Sustainable Product Development .
De Pauw, I., Karana, E., Kandachar, P., Poppelaars, F., 2014. Comparing Biomimicry and Cradle to Cradle with Ecodesign: a case study of student design projects. J. Clean. Prod. 78, 174–183.
Dinesh Reddy, V., Setz, B., Rao, G.V., Gangadharan, G.R., Aiello, M., 2017. Metrics for sustainable data centers. IEEE Trans. Sustain. Comput. 2 (3), 290–303.
Drouant, N., Rondeau, E., Georges, J.-P., Lepage, F., 2014. Designing green network architectures using the ten commandments for a mature ecosystem. Comput. Commun. 42, 38–46.
Dubois, D., 2011. The role of fuzzy sets in decision sciences: old techniques and new directions. Fuzzy Sets Syst. 184 (1), 3–28.
Fiandrino, C., Kliazovich, D., Bouvry, P., Zomaya, A.Y., 2017. Performance and energy efficiency metrics for communication systems of cloud computing data centers. IEEE Trans. Cloud Comput. 5 (4), 738–750.
Foo, D.C.Y., El-Halwagi, M.M., Tan, R.R., 2012. Recent Advances in Sustainable Process Design and Optimization: with CD-ROM, vol. 3. World Scientific.
for Standardization, I.O., 2006. Environmental Management: Life Cycle Assessment; Principles and Framework. ISO, 2006.
Garg, S.K., Versteeg, S., Buyya, R., 2013. A framework for ranking of cloud computing services. Future Gener. Comput. Syst. 29 (4), 1012–1023.
Garimella, S.V., Persoons, T., Weibel, J., Yeh, L.-T., 2013. Technological drivers in data centers and telecom systems: multiscale thermal, electrical, and energy management. Appl. Energy 107, 66–80.
Geng, S., Wang, Y., Zuo, J., Zhou, Z., Du, H., Mao, G., 2017. Building life cycle assessment research: a review by bibliometric analysis. Renew. Sustain. Energy Rev. 76, 176–184.
Grishina, A., Chinnici, M., De Chiara, D., Guarnieri, G., Kor, A.-L., Rondeau, E., Georges, J.-P., 2018. DC energy data measurement and analysis for productivity and waste energy assessment. In: 21st IEEE International Conference on Computational Science and Engineering.
Grishina, A., Chinnici, M., De Chiara, D., Rondeau, E., Kor, A., 2019. Energy-oriented analysis of HPC cluster queues: emerging metrics for sustainable data center. In: Lecture Notes in Electrical Engineering. Springer, 1876-1100 (in press).
Guo, Y., Xia, X., Zhang, S., Zhang, D., 2018. Environmental regulation, government R&D funding and green technology innovation: evidence from China provincial data. Sustainability 10 (4), 940.
Hermann, B.G., Kroeze, C., Jawjit, W., 2007. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. J. Clean. Prod. 15 (18), 1787–1796.
Herrmann, I.T., Henningsen, G., Wood, C.D., Blake, J.I., Mortensen, J.B., Spliid, H., 2013. The statistical value chain-a benchmarking checklist for decision makers to evaluate decision support seen from a statistical point-of-view. Int. J. Decis. Sci. 4 (2), 71–83.
Homrich, A.S., Galvao, G., Abadia, L.G., Carvalho, M.M., 2018. The circular economy umbrella: trends and gaps on integrating pathways. J. Clean. Prod. 175, 525–543.
Hong, K., Yang, S., Ma, Z., Gu, L., 2013. A synergy of the wireless sensor network and the data center system. In: IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems, pp. 263–271.
Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M., 2014. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ. Impact Assess. Rev. 48, 27–33.
Jatoth, C., Gangadharan, G.R., Fiore, U., 2017. Evaluating the efficiency of cloud services using modified data envelopment analysis and modified super-efficiency data envelopment analysis. Soft Comput. 21 (23), 7221–7234.
Jatoth, C., Gangadharan, G.R., Fiore, U., Buyya, R., 2018. SELCLOUD: a hybrid multi-criteria decision-making model for selection of cloud services. Soft Comput. 1–15.
Karim, R., Ding, C., Miri, A., 2013. An end-to-end QoS mapping approach for cloud service selection. In: IEEE Ninth World Congress on Services, pp. 341–348.
Klimova, A., Rondeau, E., Andersson, K., Porras, J., Rybin, A., Zaslavsky, A., 2016. An international Master's program in green ICT as a contribution to sustainable development. J. Clean. Prod. 135, 223–239.
Kubler, S., Robert, J., Derigent, W., Voisin, A., Le Traon, Y., 2016. A state-of the-art survey & testbed of Fuzzy AHP (FAHP) applications. Expert Syst. Appl. 65, 398–422.
Kubler, S., Derigent, W., Voisin, A., Robert, J., Le Traon, Y., Viedma, E.H., 2018. Measuring inconsistency and deriving priorities from fuzzy pairwise comparison matrices using the knowledge-based consistency index. Knowl. Based Syst. 162, 147–160.
Kurkjian, C., Glass, J., 2007. Meeting the needs of 24/7 data centers. ASHRAE J. 49 (2), 24.
Kwon, H.-K., Seo, K.-K., 2013. A decision-making model to choose a cloud service using fuzzy AHP. Adv. Sci. Technol. Lett. 35, 93–96.
Le, K.N., Tran, C.N.N., Tam, V.W.Y., 2018. Life-cycle greenhouse-gas emissions assessment: an Australian commercial building perspective. J. Clean. Prod. 199, 236–247.
Le Téno, J.F., Mareschal, B., 1998. An interval version of PROMETHEE for the comparison of building products' design with ill-defined data on environmental quality. Eur. J. Oper. Res. 109 (2), 522–529.
Lee, S., Seo, K.-K., 2016. A hybrid multi-criteria decision-making model for a cloud service selection problem using BSC, fuzzy Delphi method and fuzzy AHP. Wireless Pers. Commun. 86 (1), 57–75.
Lee, J., Kang, S., Kim, C.-K., 2009. Software architecture evaluation methods based on cost benefit analysis and quantitative decision making. Empir. Softw Eng. 14 (4), 453–475.
Li, Y., Chen, X., Wang, X., Xu, Y., Chen, P.-H., 2017. A review of studies on green building assessment methods by comparative analysis. Energy Build. 146, 152–159.
Li, C., Li, J., Jafarizadeh, M., Badawy, G., Zheng, R., 2018. To monitor or not: lessons from deploying wireless sensor networks in data centers. In: Proceedings of the 7th International Workshop on Real-World Embedded Wireless Systems and Networks, pp. 43–48.

Liu, L., Yao, X., Qin, L., Zhang, M., 2014. Ontology-based service matching in cloud computing. In: IEEE International Conference on Fuzzy Systems.
Liu, S., Chan, F.T.S., Ran, W., 2016a. Decision making for the selection of cloud vendor: an improved approach under group decision-making with integrated weights and objective/subjective attributes. Expert Syst. Appl. 55, 37–47.
Liu, Q., Ma, Y., Alhussein, M., Zhang, Y., Peng, L., 2016b. Green data center with IoT sensing and cloud-assisted smart temperature control system. Comput. Network. 101, 104–112.
Lurie-Luke, E., 2014. Product and technology innovation: what can biomimicry inspire? Biotechnol. Adv. 32 (8), 1494–1505.
Lykou, G., Mentzelioti, D., Gritzalis, D., 2018. A new methodology toward effectively assessing data center sustainability. Comput. Secur. 76, 327–340.
Mardani, A., Jusoh, A., Zavadskas, E.K., 2015. Fuzzy multiple criteria decision-making techniques and applications – two decades review from 1994 to 2014. Expert Syst. Appl. 42 (8), 4126–4148.
M. P. Mills, The cloud begins with coal-an overview of the electricity used by the global digital ecosystem, IEEE Trans. Cloud Comput. .
Ni, J., Bai, X., 2017. A review of air conditioning energy performance in data centers. Renew. Sustain. Energy Rev. 67, 625–640.
Oguntona, O.A., Aigbavboa, C.O., 2017. Biomimicry principles as evaluation criteria of sustainability in the construction industry. Energy Procedia 142, 2491–2497.
Ounifi, H.A., Ouhimmou, M., Paquet, M., Momtecinos, J., 2015. Data centre localization for Internet services. In: 11ème Congrès International de Génie Informatique.
Pannier, M.-L., Schalbart, P., Peuportier, B., 2018. Comprehensive assessment of sensitivity analysis methods for the identification of influential factors in building life cycle assessment. J. Clean. Prod. 199, 466–480.
Peng, C., 2016. Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. J. Clean. Prod. 112, 453–465.
Petrillo, A., De Felice, F., Jannelli, E., Autorino, C., 2016. Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system. Renew. Energy 95, 337–355.
Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: a research framework. J. Clean. Prod. 143, 710–718.
Riekstin, A.C., Rodrigues, B.B., Nguyen, K.K., de Brito Carvalho, T.C.M., Meirosu, C., Stiller, B., Cheriet, M., 2017. A survey on metrics and measurement tools for sustainable distributed cloud networks. IEEE Commun. Surv. Tutorials 20 (2), 1244–1270.
Ristic, B., Madani, K., Makuch, Z., 2015. The water footprint of data centers. Sustainability 7 (8), 11260–11284.
Rodriguez, M.G., Uriarte, L.E.O., Jia, Y., Yoshii, K., Ross, R., Beckman, P.H., 2011. Wireless sensor network for data-center environmental monitoring. In: 5th International Conference on Sensing Technology, pp. 533–537.
Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.
Saaty, T.L., Vargas, L.G., 2012. The possibility of group choice: pairwise comparisons and merging functions. Soc. Choice Welfare 38 (3), 481–496.
Silas, S., Rajsingh, E.B., Ezra, K., 2012. Efficient service selection middleware using ELECTRE methodology for cloud environments. Inf. Technol. J. 11 (7), 868–875.
Su, C.-H., Tzeng, G.-H., Tseng, H.-L., 2012. Improving cloud computing service in fuzzy environment—combining fuzzy DANP and fuzzy VIKOR with a new hybrid FMCDM model. In: International Conference on Fuzzy Theory and It's Applications, pp. 30–35.
Tseng, F.-H., Wang, X., Chou, L.-D., Chao, H.-C., Leung, V.C.M., 2018. Dynamic resource prediction and allocation for cloud data center using the multi-objective genetic algorithm. IEEE Syst. J. 12 (2), 1688–1699.
Tudela, A., Akiki, N., Cisternas, R., 2006. Comparing the output of cost benefit and multi-criteria analysis: an application to urban transport investments. Transport. Res. Pol. Pract. 40 (5), 414–423.
van den Berg, B., Sadowski, B.M., Pals, L., 2018. Towards sustainable data centres: novel internal network technologies leading to sustainable cost and energy consumption in data centres in The Netherlands. In: Trento: International Telecommunications Society. ITS.
Waldron, M.B., Waldron, K.J., 2013. Mechanical Design: Theory and Methodology. Springer Science & Business Media.
Whitehead, B., Andrews, D., Shah, A., Maidment, G., 2014. Assessing the environmental impact of data centres part 1: background, energy use and metrics. Build. Environ. 82, 151–159.
Whitehead, B., Andrews, D., Shah, A., Maidment, G., 2015. Assessing the environmental impact of data centres part 2: building environmental assessment methods and life cycle assessment. Build. Environ. 93, 395–405.
Xu, C., Ma, Y., Wang, X., 2015. A non-parametric data envelopment analysis approach for cloud services evaluation. In: International Conference on Service-Oriented Computing, pp. 250–255.
Zanghelini, G.M., Cherubini, E., Soares, S.R., 2018. How multi-criteria decision analysis (mcda) is aiding life cycle assessment (LCA) in results interpretation. J. Clean. Prod. 172, 609–622.