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# Benefit-Cost model for comparing data center performance from a Biomimicry perspective

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## Abstract

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.

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

## 1. Introduction

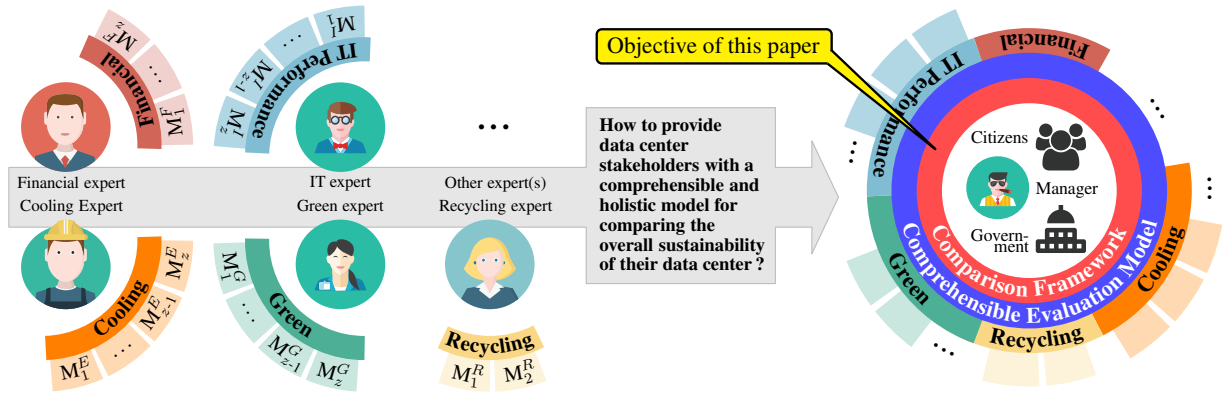
The rapid growth of data centers is driven by the increasing need for fast and efficient data processing and storage services [1, 2]. In a context where data centers are becoming the power plants of the information age, one of the greatest challenges is the exponential rise in energy consumption, as they must operate 24/24 hours and 7/7 days [3]. 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 [4]. 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 [5].

Towards this goal, data center owners and operators should put in place measures to evaluate the performance of their facilities/services [6, 7]. 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 [8], 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 [9, 10]. This is important because most of existing green building rating initiatives/tools focus mostly on environmental impact assessment [11, 12, 13, 14], 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. [15], while sustainability is a much wider concept. Just looking at the recent survey on “Metrics for Sustainable Data Centers” [5], more than one hundred sustainability metrics are reported, spanning from energy efficiency to cooling, networking, security and financial. One may then wonder how different cate-

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$M_X, k$ : Refers to a domain-specific metric,  $X$  referring to the application domain and  $k$  to the  $k^{\text{th}}$  metric that domain-related experts are acquainted with.

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

gories 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 [16, 17, 18], is at the origin of this research work. Figure 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 [19], 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 Appendix A and Appendix B.

## 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” [20], 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 [21].

The difference is that LCA quantifies its impact indicators [22], 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 [23], 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 [24] 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 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. [5], 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 [25, 40, 35]. A number of research papers have applied MCDM techniques [42, 43] (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 [44], 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. [35] propose an AHP-based model that takes into account geographical, financial, political and social factors. Covas et al. [36] 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. [32] 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 [34] 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. [37] 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 [38, 29, 28], in which criteria related to financial dynamics (ROI, maintenance costs...), management practices (risk sharing, reorganization/...) and performance (service availability, accuracy, security...) are taken into consideration. For cloud service selection, Boutkhom et al. [30] 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. [31] 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. [41] present a methodology for selecting the best middleware services in cloud computing environments by employing the ELECTRE technique; criteria such as flexibility, time, service cost, scalability, trust and capability are included. Karim et al. [39] 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-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. [27] 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. [33] propose an ontology-based service matching in order to maximize accuracy of cloud service discovery, while giving enough flexibility to cloud customers to dis-

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
[25]	2018	✓	✓							Cloud service selection	-
[26]	2018	✓					✓			Cloud service selection	-
[27]	2017	✓	✓							Cloud service selection	-
[28]	2016	✓		✓			✓		✓	Cloud service selection	-
[29]	2016	✓		✓						Cloud service selection	-
[30]	2016	✓				✓				Cloud service selection	-
[31]	2015		✓							Cloud service selection	-
[32]	2015								✓	Site selection	PUE
[33]	2014	✓					✓			Cloud service selection	-
[34]	2013	✓								Cloud service selection	-
[35]	2013	✓								Site selection	Power availability, Water availability, Laws related to Urban Planning
[36]	2013	✓								Site selection	Renewable Energy sources, Free cooling, Local environmental impact, Local pollution
[37]	2013							✓		Cloud service selection	Sustainability
[38]	2012	✓						✓	✓	Cloud service selection	-
[39]	2013	✓								Cloud service selection	-
[40]	2013	✓								Cloud service selection	DCiE, PUE, DPPE
[41]	2012				✓					Cloud service selection	-

cover their best suited services. Recently, Abdel-Basset et al. [25] 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 Efficiency), DPPE (Data Center Performance per Energy) and PUE are considered in [40], while only the latter is considered in [32]. Other studies, such as [37], 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 [46, 47, 48, 49, 9, 50]. At the time of writing, and to the best of our knowl-

edge, the most extensive study of sustainability metrics is given by Reddy et al. [5], 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 [5], 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

Table 2: The ten biomimicry commandments (lessons) introduced by Benyus [45]

Commandment (lesson)	Examples of interpretation in the context of data centers
C <sub>1</sub> 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, <i>etc.</i> close to data centers.
C <sub>2</sub> Diversify and cooperate to fully use the habitat	Cooperating with local companies (ecopark); for example, reusing data center heating for heating building.
C <sub>3</sub> Gather and use energy efficiently	Mitigating data center energy consumption. Using Energy produced locally.
C <sub>4</sub> Optimize rather than maximize	Offering IT quality of service in respect to customer requirements.
C <sub>5</sub> Use materials sparingly	Increasing (IT) equipment lifetime. Mitigating (IT) equipment use (e.g., virtualization).
C <sub>6</sub> Don't foul their nests	Reducing harmful emissions in the environment (carbon in air. . .). Avoiding electronic wastes.
C <sub>7</sub> Don't draw down resources	Increasing green energy use. Mitigating (IT) equipment use to avoid earth resource depletion.
C <sub>8</sub> Remain in balance with biosphere	In our research, the idea of lessons 6 and 8 are similar and are merged accordingly.
C <sub>9</sub> Run on information	In our research, the idea of lessons 2 and 9 are similar and are merged accordingly.
C <sub>10</sub> Shop locally	Using local energy for avoiding energy transportation lost. Using air and water for cooling. Manufacturing data centers with local companies.

294 model that overcome the above limitations. The ap- 333  
 295 proach advocated here is to use biomimicry. 334

296 *2.4. Biomimicry & Lifes' principles* 335

297 The biomimicry, which means "imitation of life", 336  
 298 is defined by Oxford dictionary as: "*The design and* 337  
 299 *production of materials, structures, and systems that* 338  
 300 *are modelled on biological entities and processes*". 339  
 301 The majority of application domains inspired by the 340  
 302 nature are materials and locomotion [51] and con- 341  
 303 sists in mainly copying physiology, morphology, and 342  
 304 anatomy of vegetal and animal world for optimiz- 343  
 305 ing or making more efficient the structure of materi- 344  
 306 als. In computer sciences, many heuristics for opti- 345  
 307 mizing data processing/transport/storage solutions are 346  
 308 commonly used and are based on natural behavioral 347  
 309 observations, such as ant colony, bat, natural evolu- 348  
 310 tion (genetic algorithm), machine learning (e.g., neu- 349  
 311 ral networks). However, optimizing an artefact in 350  
 312 copying biologic entity does not guarantee that the 351  
 313 optimized artefact will have less negative impact on 352  
 314 the nature (e.g., if the genetic algorithm fitness func- 353  
 315 tion seeks to maximize the pollution, the solution will 354  
 316 not be environmentally friendly even if the optimi- 355  
 317 sation algorithm copies a natural evolution process). 356  
 318 Another idea initially suggested by J. Benyus [45] is 357  
 319 that the life on earth has evolved a set of strategies 358  
 320 that have sustained over 3.8 billion years and these 359  
 321 strategies could be interesting to apply when design- 360  
 322 ing an artefact. The simple expectation is the fol- 361  
 323 lowing: if the artefact is developed along with life 362  
 324 strategies, the artefact is likely to be environmen- 363  
 325 t-friendly. Originally, J. Benyus identified a set of ten 364  
 326 strategies, named the "*Ten Commandments of Mature* 365  
 327 *Ecosystem*", as reported in Table 2. De Pauw [52] 366  
 328 explained that biomimicry guild<sup>1</sup> proposed succes- 367  
 329 sively new versions of life's principles in 2007, 2010 368  
 330 and 2013 respectively. The same author evidenced 369  
 331 that case studies using the Life's principles for de- 370  
 332 signing environmentally-friendly artefacts are scarce. 371

332 [53] studied the perception of life's principles in con-  
 333 struction industry from a survey collecting responses  
 334 from different construction professionals (Civil Engi-  
 335 neers, architects, *etc.*). The primary objective was not  
 336 to apply Life's principles for architecting a building  
 337 but only to rank the importance of those principles  
 338 in the construction sector. [54] used different nature-  
 339 inspired design strategies from two case studies de-  
 340 veloped by students, whose goal was to compare ap-  
 341 proaches based on the life's principles, cradle to cradle  
 342 and eco-design. The main difference observed is that  
 343 the students following the biomimicry and cradle-to-  
 344 cradle methods investigated more solutions than the  
 345 ones using eco-design. In the same vein as our study,  
 346 Drouant et al. [55] proposed to define green network-  
 347 ing metrics based on the ten lessons of mature ecosys-  
 348 tem. 349

350 Finally, the "Biomimicry for Social Innovation"  
 351 initiative<sup>2</sup> help leaders bring nature's adaptive genius  
 352 into their organizations and enterprises, and rely for  
 353 this on 23 life's principles. Overall, the multiplication  
 354 of life's principles are necessary to better guide engi-  
 355 neers in the selection of appropriate solutions and rec-  
 356 ommendations specific to the domain of design. For  
 357 example, among the 23 life's principle, "Do chem-  
 358 istry in water" is a useful principle in material de-  
 359 sign, but not in software engineering. However, the  
 360 multiplication of principles produce noise and com-  
 361 plexity when they are applied for measuring an arte-  
 362 fact in a holistic way. In our work, we decided to  
 363 only use the initial Ten Commandments, which are  
 364 more philosophical requirements disconnected to en-  
 365 gineering process such as "Do chemistry in water" or  
 366 "Fit form to function" principles. The commandments  
 367 are easy to understand and do not require expertise  
 368 in biology. Consequently, the artefact environmen-  
 369 tal assessment using the commandments is independ-  
 370 ent to the engineering area, especially when design-  
 371 ing complex systems requiring multiple experts. The  
 372 commandments can play the role of a universal lan-

<sup>1</sup><https://biomimicry.org/>, last access: May 2019

<sup>2</sup><https://bio-sis.net/life-principles/>, last access: May 2019

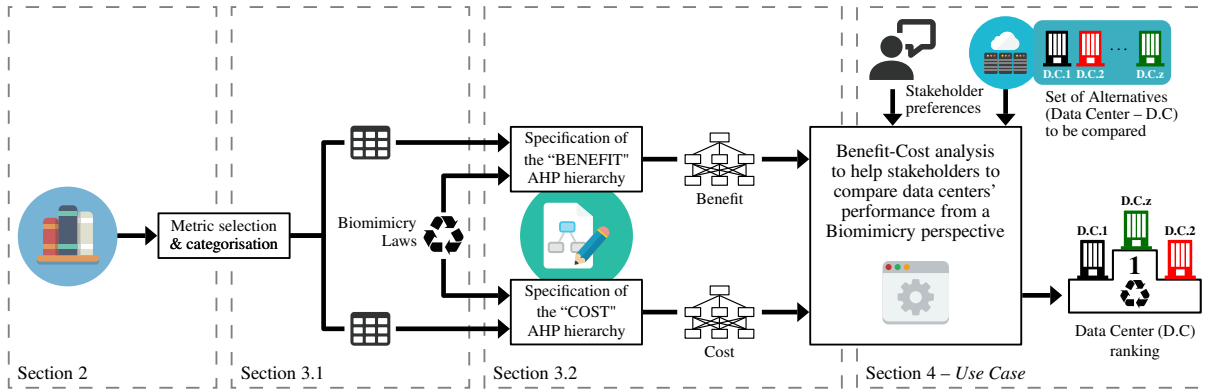


Figure 2: Methodology towards the AHP-based comparison model to compare data centers in terms of sustainable development/behavior

373 guage for considering environment. Table 2 presents 412  
 374 the Ten Commandments and provides some examples 413  
 375 of interpretation in the context of data centers. How- 414  
 376 ever, two commandments  $C_8$  and  $C_9$  are left aside 415  
 377 in our study because: (i)  $C_8$  conveys a similar mes- 416  
 378 sage as  $C_6$ , namely that we are living in a closed system 417  
 379 and it is crucial to maintain the stability of envi- 418  
 380 ronment in avoiding to “foul our nests” (both com- 419  
 381 mandments are therefore merged into a same com- 420  
 382 mandment); (ii)  $C_9$  conveys a similar message as  $C_2$ : 421  
 383 “Run on information” ( $C_9$ ) refers to feedback mech- 422  
 384 anisms for considering ecosystems (competition/col- 423  
 385 laboration between companies, new legislations, new 424  
 386 marketing demands) with the objective to “diversify 425  
 387 and cooperate to fully use the habitat” ( $C_2$ ). Both 426  
 388 commandments are thus also combined into a unique 427  
 389 commandment. Even though other commandments  
 390 have close meaning, they include specific information  
 391 that enriches the knowledge of the artefact environ-  
 392 mental impact, as will be discussed in the next sec-  
 393 tion.

### 394 3. A comprehensible and holistic comparison 395 model for sustainable data centers

396 Determining a model that allows us for comparing 397  
 398 data centers alternatives requires to integrate a wide 399  
 400 range of domain-specific metrics (more than one hun- 401  
 402 dred for data centers [5]), and this from both a bene- 403  
 403 ficial and detrimental viewpoint (as improvements in 404  
 404 one area and to one impact, can adversely affect a to- 405  
 405 tally different area and totally different impacts [10]). 406  
 406 This paper aims at proposing a benefit-cost model that 407  
 407 makes use of the biomimicry commandments for eval- 408  
 408 uation together with metric categories in order to sim- 409  
 409 plify the evaluation/comparison process (reducing all 410  
 410 metrics into eight biomimicry indicators). The pro- 411  
 411 posed model can easily be configured by stakeholders  
 (i.e., prioritizing or not one or more commandments)  
 since commandments do not require expertise in biol-  
 ogy. This complies with the original idea promoted by

J. Benyus [45] in her Chapter entitled “Where will we go from here?”.

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

- i) *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;
- ii) *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.

#### 428 3.1. Metric Categorization & Translation

429 As a first step, the sustainability metrics listed in 430  
 431 Table A.7 are categorized in terms of benefit and cost 432  
 433 implications from a biomimicry standpoint [56, 57]. 434  
 434 Concretely, we ask ourselves whether a metric relates 435  
 435 to the energy, carbon, recycling or other categories? 436  
 436 and whether the metric maximization or minimization 437  
 437 results in a benefit or cost from a sustainability view-  
 point? In this study, the metric categorization is based on the categories identified in [5], 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  $\text{Co}_2/\text{Wh}$ );

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	-	-	9	9	9	9	9	-
	Materials	Maximize	DCcE, DH-UI, DH-UR, ScE	-	-	9	9	9	9	9	-
		Minimize	DCCSE, DCSSF	-	-	9	9	3	5	3	-
	Cooling	Maximize	CoP, EER, HSE, AEUF	-	-	9	9	3	5	3	-
		Minimize	CUE, TCE	-	-	9	9	3	9	5	<b>3</b>
	Carbon	Maximize	Co2s	-	-	9	9	3	9	5	<b>3</b>
		Minimize	GUF	-	-	5	9	3	9	5	<b>9</b>
	Green	Maximize	GEC	-	-	5	9	3	9	5	<b>9</b>
		Minimize	ERE, EDE, MRR	-	-	5	9	3	9	5	<b>9</b>
	Recycling	Maximize	ERF	9	5	5	9	5	5	9	3
		Minimize	ERF	9	5	5	9	5	5	9	3
	Water	Minimize	WUE, WUEs	-	-	-	9	-	-	-	-
		Maximize	CNEE, ECR-VL, INPUE	-	-	-	9	-	-	-	-
IT Perf.	Minimize	BJC, NetT, RSmax, TEER, Unet, Capacity, LSP, MemU, OSE, Su, Thght, Ustor	-	-	9	9	5	3	5	-	
	Maximize	BJC, NetT, RSmax, TEER, Unet, Capacity, LSP, MemU, OSE, Su, Thght, Ustor	-	-	9	9	5	3	5	-	
Financial	Minimize	OpEx	-	-	9	9	9	3	5	-	
	Maximize	OpEx	-	-	9	9	9	3	5	-	
Cost	Water	Minimize	WUE, WUEs	-	-	5	-	3	-	9	9
		Maximize	ACPR, DTE, Lat, RC, RCD, T	-	-	9	-	9	5	9	-
	IT Perf.	Minimize	ATR, CC, CER, DeD, DeP, HTTPt, IAS, IPFH, IPt, ITH, RT	-	-	9	-	9	5	9	-
Maximize		ATR, CC, CER, DeD, DeP, HTTPt, IAS, IPFH, IPt, ITH, RT	-	-	9	-	9	5	9	-	
Financial	Minimize	REL	-	-	9	9	9	3	5	-	
	Maximize	REL	-	-	9	9	9	3	5	-	

- *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 [58];
- *Financial*: increased resource utilization can contribute to high energy costs and maintenance of IT equipment. Organizations should therefore assess its performance for saving money.

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.

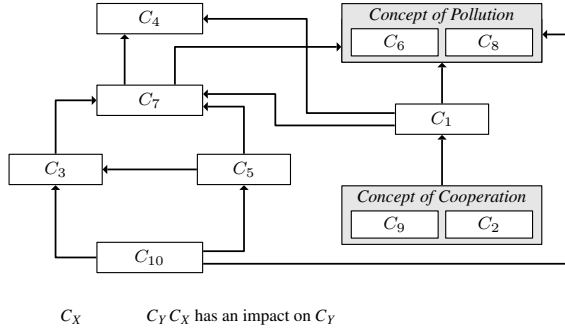
To this end, we propose to first model the impact that one biomimicry commandment may have on the others, as given in Figure 3(a). Let us take the modelling related to the “Energy” category, as given in Figure 3(b). It can be stated that metrics under this

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 Co<sub>2</sub>); 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 Figure 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).

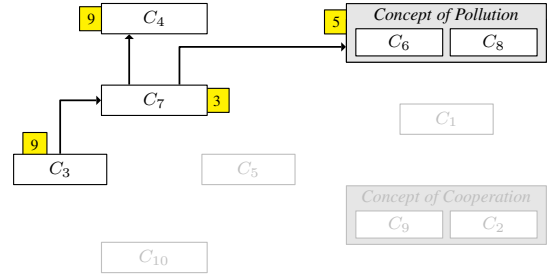
In a similar way, the above analysis was carried out for each category and the associated weight vectors generated (*cf.*, columns denoted by  $C_1$  to  $C_{10}$  in Table 3). These vectors serve as inputs of the benefit/cost analysis presented in the next section.

### 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-technical terms. To serve this purpose, a two-hierarchy approach is adopted, as proposed in [19]. Concretely, two distinct criteria hierarchies are specified, one quantify-



(a) Relationships between the ten biomimicry commandments



(b) Extent to which “Energy” category impacts on commandments

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

519 ing the benefits in terms of sustainable data center 558  
 520 behavior, and a second quantifying the cost implica- 559  
 521 tions. These two hierarchies (i.e., Benefit and Cost) 560  
 522 are respectively given in Figures 4(a) and 4(b), whose 561  
 523 design follows the logic described below. Note that 562  
 524 all variables used in this paper are summarized in Table 563  
 525 B.8 (as an Appendix):

- 526 1. *Level 4 (Alternatives)*: the set of data center candidates, denoted as  $\mathcal{A}$ , are individually evaluated with regard to the metrics reported in Table 3;
- 527 528
- 529 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  $M_{P_i}$ , where  $P_i$  refers to the category to which a given set of metrics belongs to;
- 530 531 532 533
- 534 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 Figure 4(a);
- 535 536 537 538 539
- 540 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  $S_{A_i}^B$  and  $S_{A_i}^C$ , are divided to get the final Benefit/Cost score, which serves as basis to rank data center candidates in terms of sustainable development/behavior.
- 541 542 543 544 545 546

547 As a next step, pairwise comparisons between all 573  
 548 elements of a given level of the AHP hierarchy must 574  
 549 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-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 575  
 576  
 577  
 578  
 579  
 580

558 in “using materials sparingly”), while stakeholders at 559  
 560 level 3 are more likely to communicate preferences 561  
 562 about domain-specific metrics (e.g., importance of 562  
 563 PUE over other energy metrics). Level 2 corresponds 564  
 565 to the expertise needed to match the biomimicry 565  
 566 commandments with the sustainability metric categories, 566  
 567 which corresponds to expertise. Although a first 567  
 568 expertise is provided in Table 3, this does not prevent 568  
 569 another biomimicry expert from modifying, if needed, 569  
 570 the proposed expertise. Sections 3.2.1 to 3.2.5 detail 570  
 571 the theoretical basis of the pairwise comparison process 571  
 572 performed at levels 1, 2, 3 and 4 respectively, along 572  
 573 with the aggregation process to obtain the final 573  
 574 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  $c_{ij}$  ( $i, j \in C$ ) 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  $C_j$ .

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

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 [59] 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  $CR \leq 10\%$  [44].

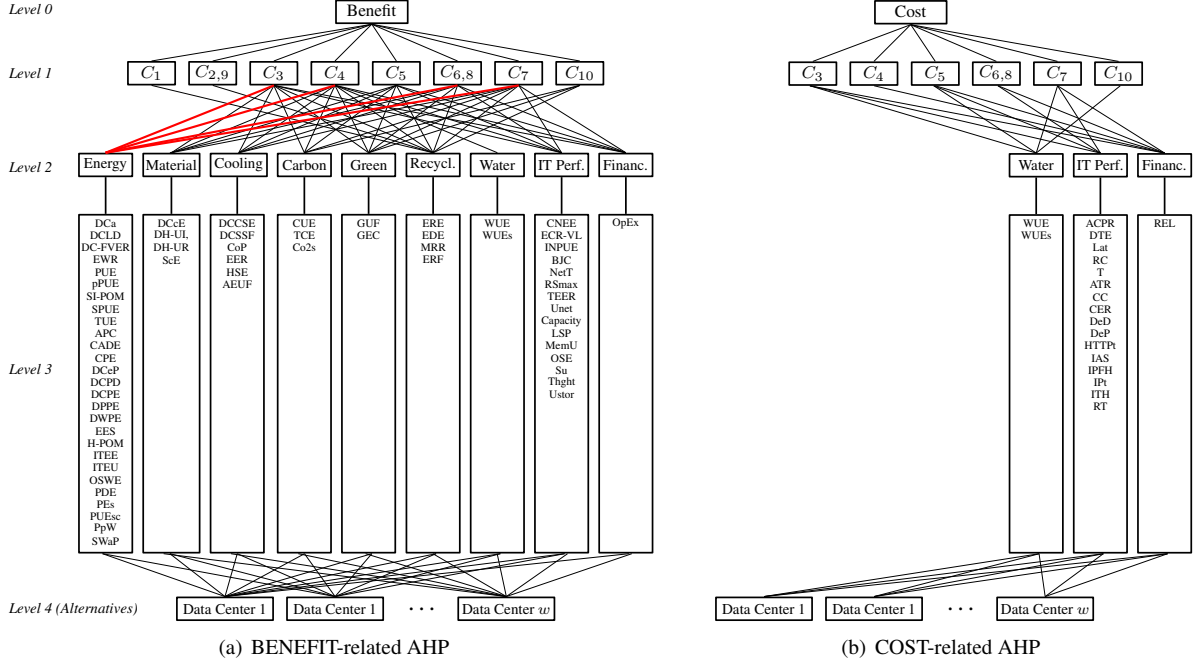


Figure 4: AHP-based data center performance comparison from BENEFIT and COST perspectives

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 sustainability 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)

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

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

### 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<sup>3</sup> (cf., weights highlighted in bold/red correspond to the ones specified in

<sup>3</sup>Note: All consistency ratios (CR) of the pairwise comparison matrices of level 2 are  $< 0.1$ .

Table 3). The resulting priority vectors are denoted by  $E_{(P_{C_m})_{y \times y}}$ .

$$(P_{C_{10}})_{3 \times 3} = \begin{matrix} & \begin{matrix} \text{Carbon} & \text{Green} & \text{Recycling} \end{matrix} \\ \begin{matrix} \text{Carbon} \\ \text{Green} \\ \text{Recycling} \end{matrix} & \begin{bmatrix} 1 & \mathbf{\frac{3}{9}} & \frac{3}{3} \\ \frac{1}{c_{12}} & 1 & \frac{3}{3} \\ \frac{1}{c_{13}} & \frac{1}{c_{23}} & 1 \end{bmatrix} \end{matrix} \quad (4)$$

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’’ be-

605 cause the stakeholder deems the recycling of material  
 606 as more important than the reuse of data center heat  
 607 extraction/dissipation to warm up buildings. Pairwise  
 608 comparison matrices are denoted by  $(M_{P_k})_{x \times x}$  and the  
 609 associated priority vector denoted by  $E_{(M_{P_k})_{x \times x}}$ .

### 610 3.2.4. Pairwise comparisons at Level 4

611 Finally, pairwise comparisons at level 4 are carried  
 612 out between the set of alternatives (i.e., data center  
 613 candidates), which is denoted by  $\mathcal{A}$ . One difference  
 614 with the previous pairwise comparisons is that, while  
 615 before they were reflecting either the stakeholder pref-  
 616 erences/expertise, they are now performed based upon  
 617 measurable/supervised system parameters. In other  
 618 words, all data center candidates are evaluated with  
 619 respect to all metrics based on automated mecha-  
 620 nisms. Pairwise comparison matrices are denoted by  
 621  $(A^{M_{P_k,j}})_{w \times w}$ , as in Eq. 5,  $j$  referring to the  $j^{\text{th}}$  metric of  
 622 category  $P_k$ , and  $l$  to the  $l^{\text{th}}$  data center candidate. The  
 623 resulting priority vectors are denoted by  $E_{(A^{M_{P_k,j}})_{w \times w}}$ .

$$624 \quad (A^{M_{P_k,j}})_{w \times w} =: \begin{matrix} & A_1 & \dots & A_w \\ \begin{matrix} A_1 \\ \vdots \\ A_w \end{matrix} & \begin{bmatrix} 1 & \dots & \frac{A_1^{M_{P_k,j}}}{A_w^{M_{P_k,j}}} \\ \vdots & \vdots & \ddots \\ \frac{A_w^{M_{P_k,j}}}{A_1^{M_{P_k,j}}} & \dots & 1 \end{bmatrix} \end{matrix} \quad (5)$$

### 624 3.2.5. Alternative ranking

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

$$633 \quad S_{A_l}^{\{B;C\}} = \sum_{j=1}^{f(i)} \left[ \sum_{i=1}^{f(m)} \left[ \sum_{m=1}^z \left( E_{(A^{M_{P_k,j}})_{w \times w}} \cdot (E_{(M_{P_k})_{x \times x}})^i \cdot \right. \right. \right. \\ \left. \left. \left. \left( E_{(P_{C_m})_{y \times y}} \right) \cdot (E_{(C)_{z \times z}})^m \right] \right] \right] \quad (6)$$

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

$$637 \quad S_{A_l} = \frac{S_{A_l}^B}{S_{A_l}^C} \quad (7)$$

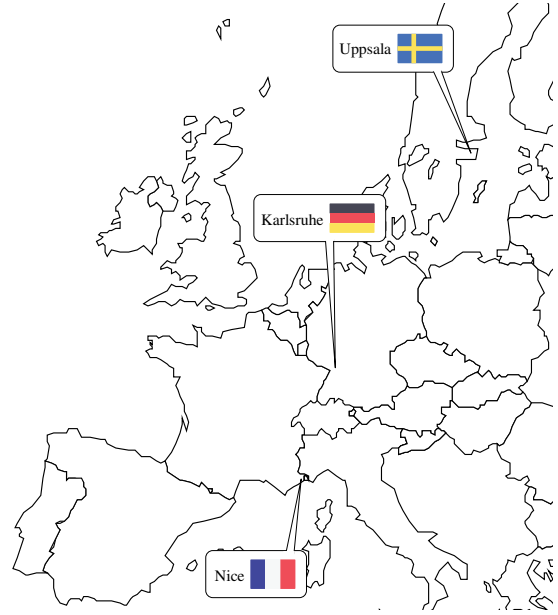


Figure 5: Data center candidates compared in the case study

## 637 4. Case study

638 The geographic distribution of data centers across  
 639 the globe goes along with different environmental and  
 640 economic considerations (e.g., cost of the electricity  
 641 or the cooling effort needed in a given country/region),  
 642 which has a direct impact on the overall sustainability  
 643 of data centers. In order to run experiments with data  
 644 centers operating under different climate and energy  
 645 production conditions, we selected three data centers  
 646 respectively located in Nice (France), Karlsruhe (Ger-  
 647 many) and Uppsala (Sweden), as depicted in Figure 5.  
 648 Table 5 reports the coefficients needed to produce en-  
 649 ergy in these three countries (data source: Interna-  
 650 tional Energy Authority website<sup>4</sup>).

651 Section 4.1 details the methodology that has been  
 652 applied to collect the datasets related to each data cen-  
 653 ter, as well as the computational steps performed with  
 654 regard to the Benefit/Cost analysis. Section 4.2 an-  
 655 alyzes the results/ranking obtained when comparing  
 656 the three data center candidates using our approach.

### 657 4.1. Data center settings, Stakeholder preference & 658 Computational steps

659 Section 4.1.1 details how datasets related to the data  
 660 center candidates have been collected. Section 4.1.2  
 661 presents both the stakeholder preferences specified in  
 662 the pairwise comparison process and the computa-  
 663 tional steps performed based on our approach.

<sup>4</sup><https://www.iea.org>, last access: May 2019.

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 $\times$ 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)	$\frac{\text{number of failures or outages}}{\text{Total surviving hours}}$	N/A	N/A	N/A	0.001	0.001	0.0005

Table 5: Country-related data from IEA<sup>4</sup>

country	Hydro	Wind	Biomass	Solar CSP	Geothermal	Solar PV	Nuclear	Natural Gaz	Oil	Coal
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
Energy (%)										
Carbon (kg/kWh) ( $10^{-3}$ )	4	12	18	22	45	46	16	469	84	1001

#### 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 [60, 61, 62], 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) [63, 64, 65, 66]. 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*<sup>5</sup> – 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., Figure 4). The subset of metrics for which data could be generated is detailed in Table 6.

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

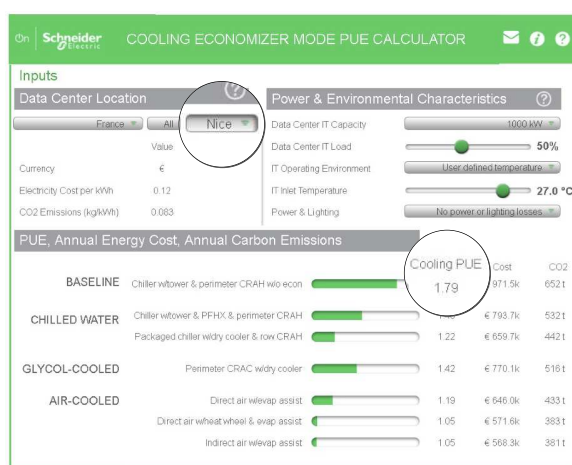


Figure 6: Screenshot of Schneider Electric online calculator

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

- Data Center IT Capacity: 1000kW;
- Data Center IT Load: 70%;
- IT Operating Environment: User defined temperature;
- IT Inlet Temperature: 32°;
- Power & Lighting: No power or 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 hierarchies, for which alternatives are no longer the data center candidates but the set of virtualization configuration candidates in a

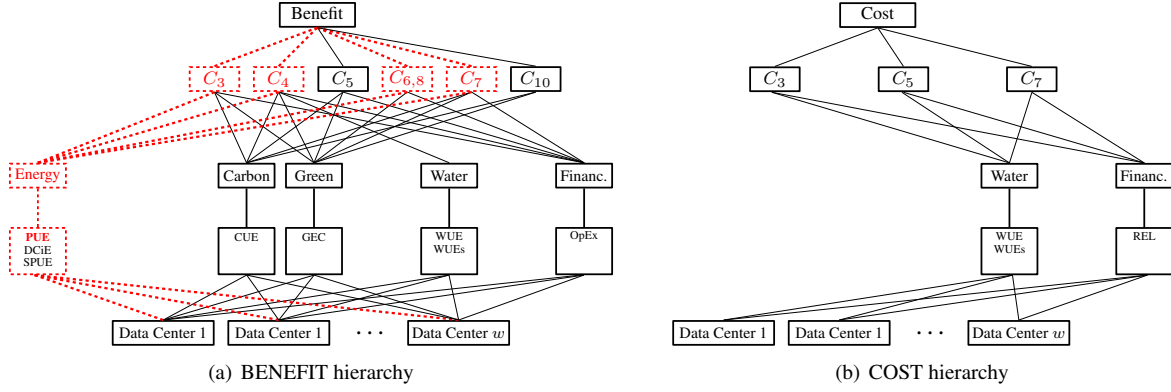


Figure 7: AHP-based data center performance comparison from BENEFIT and COST perspectives

706 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 the weights are generated and aggregated in our approach.

#### 719 4.1.2. Stakeholder preference & Computational steps

720 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 Figures 7(a) and 7(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 Figure 7(a)).

736 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;

$$\begin{aligned}
 & C_3 \quad C_4 \quad C_5 \quad C_{6,8} \quad C_7 \quad C_{10} \\
 C = & \begin{bmatrix} C_3 & 1 & 1 & 1 & 1 & 1 \\ C_4 & 1 & 1 & 1 & 1 & 1 \\ C_5 & 1 & 1 & 1 & 1 & 1 \\ C_{6,8} & 1 & 1 & 1 & 1 & 1 \\ C_7 & 1 & 1 & 1 & 1 & 1 \\ C_{10} & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \\
 E_C = & \begin{bmatrix} C_3 & C_4 & C_5 & C_{6,8} & C_7 & C_{10} \\ 1/6 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 \end{bmatrix} \quad (8)
 \end{aligned}$$

741 2. *Level 2 (L2)*: Eq. 9 details the pairwise comparison matrix related to commandment  $C_3$ , along with the resulting priority vector (please refer to section 3.2.2 to obtain more details on how the pairwise comparison matrix is created). Eq. 10 to 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 Figures 7(a)).

$$\begin{aligned}
 & \text{Ener} \quad \text{Carb} \quad \text{Gree} \quad \text{Fina} \\
 E_{PC_3} = & \begin{bmatrix} \text{Ener} & 1 & \frac{9}{9} & \frac{9}{5} & \frac{9}{9} \\ \text{Carb} & \frac{9}{9} & 1 & \frac{9}{5} & \frac{9}{9} \\ \text{Gree} & \frac{5}{9} & \frac{5}{9} & 1 & \frac{5}{9} \\ \text{Fina} & \frac{9}{9} & \frac{9}{9} & \frac{9}{5} & 1 \end{bmatrix} \\
 E_{PC_3} = & \begin{bmatrix} \text{Ener} & \text{Carb} & \text{Gree} & \text{Fina} \\ 0.281 & 0.281 & 0.157 & 0.281 \end{bmatrix} \quad (9)
 \end{aligned}$$

$$\begin{aligned}
 & \text{Ener} \quad \text{Carb} \quad \text{Gree} \quad \text{Wate} \quad \text{Fina} \\
 E_{PC_4} = & \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix} \quad (10)
 \end{aligned}$$

$$\begin{aligned}
 & \text{Ener} \quad \text{Gree} \quad \text{Fina} \\
 E_{PC_{6,8}} = & \begin{bmatrix} 0.295 & 0.529 & 0.176 \end{bmatrix} \quad (11)
 \end{aligned}$$

$$\begin{aligned}
 & \text{Ener} \quad \text{Carb} \quad \text{Gree} \quad \text{Fina} \\
 E_{PC_7} = & \begin{bmatrix} 0.166 & 0.278 & 0.278 & 0.278 \end{bmatrix} \quad (12)
 \end{aligned}$$

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;

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

$$E_{M_{\text{Ener}}} = \begin{bmatrix} \text{PUE} & \text{DCiE} & \text{SPUE} \\ 1/3 & 1/3 & 1/3 \end{bmatrix} \quad (13)$$

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).

$$A^{\text{PUE}} = \begin{matrix} & \text{Fr} & \text{Ge} & \text{Sw} \\ \text{Fr} & \begin{bmatrix} 1 & \frac{1.560}{1.550} & \frac{1.560}{1.540} \end{bmatrix} \\ \text{Ge} & \begin{bmatrix} \frac{1.550}{1.560} & 1 & \frac{1.550}{1.540} \end{bmatrix} \\ \text{Sw} & \begin{bmatrix} \frac{1.540}{1.560} & \frac{1.540}{1.550} & 1 \end{bmatrix} \end{matrix}$$

$$E_{A^{\text{PUE}}} = \begin{bmatrix} \text{Fr} & \text{Ge} & \text{Sw} \\ 0.336 & 0.333 & 0.331 \end{bmatrix} \quad (14)$$

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 Eq. 16 and 17 ( $S_{S_w}^{B(\text{PUE})} < S_{G_e}^{B(\text{PUE})} < S_{F_r}^{B(\text{PUE})}$ ). 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.

$$S_{F_r}^{B(\text{PUE})} = \sum_{i=\{C_{3,4,6,8,7}\}} (E_{A^{\text{PUE}}}[F_r] \cdot E_{M_{\text{Ener}}}[\text{PUE}] \cdot E_{P_{C_3}}[\text{PUE}] \cdot E_C[C_3])$$

$$= (0.336 \cdot 1/3 \cdot 0.281 \cdot 1/6) + (0.336 \cdot 1/3 \cdot 0.2 \cdot 1/6) + (0.336 \cdot 1/3 \cdot 0.295 \cdot 1/6) + (0.336 \cdot 1/3 \cdot 0.166 \cdot 1/6)$$

$$= 0.0176 \quad (15)$$

$$S_{G_e}^{B(\text{PUE})} = 0.0174 \quad (16)$$

$$S_{S_w}^{B(\text{PUE})} = 0.0173 \quad (17)$$

## 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

Figures 8(a) and 8(b) provide insight into the overall scores obtained by the three data center candidates in terms of Benefit ( $S_{A_i}^B$ ) and Cost ( $S_{A_i}^C$ ) implications, while Figure 8(c) gives insight into the final Benefit/Cost analysis ( $S_{A_i}$ ). 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.*, Figure 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 Figure 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 commandments (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 Figures 9(a) and 9(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:

- Figure 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.

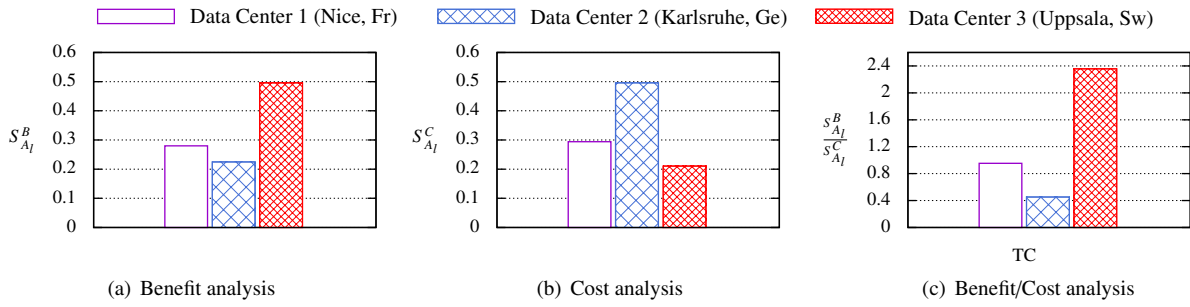


Figure 8: Benefit/Cost analysis of the three data center candidates: Nice vs. Karlsruhe vs. Uppsala

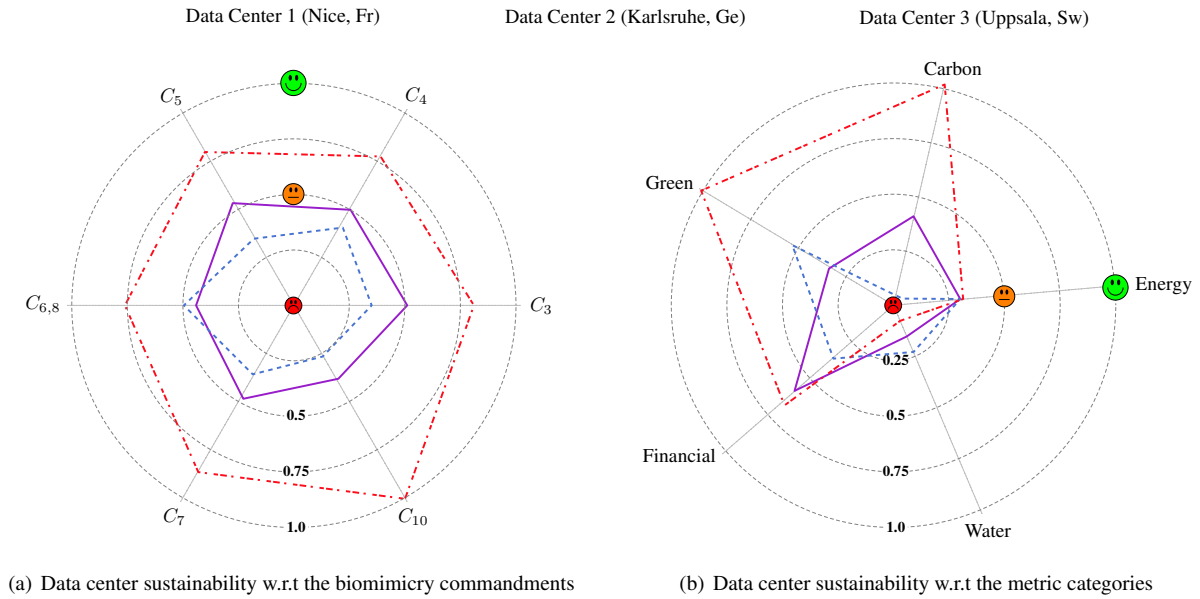


Figure 9: Holistic view of the data center sustainability with regard to both the biomimicry commandments and the metric categories

837 • Figure 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 Figure 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., Figure 8(b)). The reason for this is that water implies to emit less carbon and to use less non-renewable energy.

847 Another comment about Figures 9(a) and 9(b) is that the perception of the performance is different. For example, for Sweden, Figure 9(a) shows balanced and good results, which is not the case in Figure 9(b) regarding the Water category. This means that, when decisions are selected by experts (Figure 9(b)), it is important to analyze Figure 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

858 In a similar manner as before, Figures 10(a) and 10(b) provide insight into the overall scores obtained by the three virtualization configuration candidates in terms of Benefit and Cost implications, and Figure 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

874 Before concluding this paper, it is important to remind ourselves that the the above experiments are only meant to illustrate the practicality and holistic nature of the proposed approach, as was discussed in

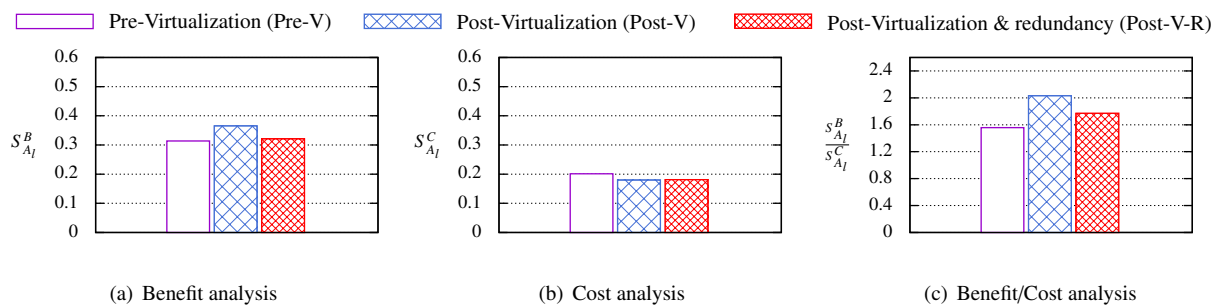


Figure 10: Benefit/Cost analysis of the three Virtualization configuration candidates: Pre-V vs. Post-V vs. Post-V-R

879 section 4.2.1. This is important to be noted because 918  
 880 the key message to be conveyed in this paper is that 919  
 881 we do not aim to carry out an in-depth comparison 920  
 882 study of existing data centers over the globe, but rather 921  
 883 to present the theoretical foundation of an innovative 922  
 884 approach that could help data center stakeholders to 923  
 885 compare the overall sustainability of data centers in 924  
 886 a holistic and non-technical manner. This message is 925  
 887 important as our experiments are limited in the fol- 926  
 888 lowing respect: 927

- 889 • we could not collect real datasets from existing 928  
 890 data centers; 929
- 891 • the online calculator enabled us to work only 930  
 892 with a limited number of metrics compared with 931  
 893 the exhaustive list considered in the theoretical 932  
 894 model of our approach (*cf.*, section 3). 933

895 Such limitations have direct impact on the relevance 934  
 896 of our comments/findings when discussing the data 935  
 897 center performance results. This should therefore 936  
 898 be taken with caution, or at least understood by the 937  
 899 reader. 938

## 900 5. Conclusions, implications, limitations and fu- 941 901 ture research 942

### 902 5.1. Conclusions 943

903 The importance of data centers for society has 944  
 904 changed, as public life, economy and society depend 945  
 905 to a large extent on the proper functioning of data 946  
 906 centers. From different parts of society, the sustainability 947  
 907 of data centers is questioned, thus raising questions 948  
 908 about the “data center equation” of “people, planet, 949  
 909 profit”. While it is common place to think that making 950  
 910 data centers sustainable comes down to implementing 951  
 911 technical measures, it actually goes well beyond the 952  
 912 walls of the data center, touching upon economic and 953  
 913 political questions. As a consequence, it is imperative 954  
 914 to develop and propose holistic models that help data 955  
 915 center stakeholders, spanning from data center own- 956  
 916 ers, governmental regulators to engineers/field oper- 957  
 917 ators, to evaluate and understand how a data center 958  
 918

919 performs in terms of sustainable development and be- 920  
 921 havior. While a large number of sustainability metrics 921  
 922 exist in the literature, there is still a lack of frame- 922  
 923 works that make it possible to reduce the complexity 923  
 924 of the performance evaluation analysis. 924

925 In order to fill this gap in literature, this pa- 925  
 926 per presents an innovative approach based on a 926  
 927 benefit-cost analysis using the Analytic Hierarchy 927  
 928 Process (AHP). The originality lies in the combina- 928  
 929 tion of state-of-the-art sustainability metrics with the 929  
 930 biomimicry commandments of eco-mature system de- 930  
 931 fined by J. Benyus [45], and the possibility for data 931  
 932 center stakeholders to analyze and compare perfor- 932  
 933 mance of data centers in a more or less holistic man- 933  
 934 ner (depending on their needs, focus, expertise). For 934  
 935 example, one data center stakeholder may want to pri- 935  
 936 oritize the biomimicry commandment  $C_6$  when debat- 936  
 937 ing on pollution aspects (data centers would, indeed, 937  
 938 be ranked with emphasis on the extent to which the 938  
 939 pollute locally), while another one could be provided 939  
 940 with a more in-depth analysis of how a data center per- 940  
 941 forms with respect to the energy, water, green or still 941  
 942 financial dimensions. The practicability of our model 942  
 943 is demonstrated considering three data center candi- 943  
 944 dates, which are respectively located in France, Ger- 944  
 945 many and Sweden. However, it is important to note 945  
 946 in this paper is about the theoretical foundation of the 946  
 947 proposed approach, rather than on comparing existing 947  
 948 data centers over the world. 948

### 949 5.2. Implications 950

949 This research presents three main theoretical impli- 950  
 950 cations. 951

951 First, it has implications in the the field of LCA 952  
 952 (as was previously discussed in section 2.1), and par- 953  
 953 ticularly of CBA (Cost-Benefit Analysis) [22]. Even 954  
 954 though our approach differs from traditional CBA 955  
 955 analyses (which mostly focus on economical assess- 956  
 956 ment), many studies have considered AHP in order to 957  
 957 cope with the CBA’s weakness in reflecting stakehold- 958  
 958 ers’ knowledge in the evaluation process of projects 959  
 959 [67, 68]. Although the assessment of CBA versus 959

AHP capabilities remains an open research question [69, 70], 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<sup>6</sup> (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 [71], 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 [72, 73].

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 resource). In addition, society will intervene in the markets and apply new taxes (for instance related to  $CO_2$ ) 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. [20] 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. [74] 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 [75]. To overcome this, AHP could further be combined with Fuzzy Logic, also known as FAHP (Fuzzy AHP) [43], even though some scholars, such as Dubois [76], 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 [76, 77]. Other approaches than FAHP could also be explored to handle uncertainty and vagueness, such as the Statistical Value Chain (SVC) [78], 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

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

1067 AHP. Although making transparent the pairwise com-  
 1068 parison judgments/preferences would help to not mis-  
 1069 lead anyone, this problem is out of scope of this study.

1070 **5.3.3. Lack of real-life datasets**

1071 Even though the primary message of this research  
 1072 is not to present an in-depth comparison analysis of  
 1073 existing data centers over the globe, but rather present  
 1074 the theoretical foundation of our approach, a next step  
 1075 would be to carry out such comparison analysis con-  
 1076 sidering real-life datasets from data centers. As was  
 1077 discussed in section 4.1.1, this poses a two-fold chal-  
 1078 lenge: (i) to be able to access backend systems of  
 1079 data center organizations; and (ii) to support and/or  
 1080 incentivize organizations to implement/monitor new  
 1081 sustainability metrics in their facilities.

1082 **5.4. Future research**

1083 Beyond addressing the limitations raised in the pre-  
 1084 vious section, we believe that the theoretical model  
 1085 proposed in this paper is fully applicable to other  
 1086 green ICT sectors including core network infrastruc-  
 1087 tures, internet providers, ICT in enterprise, or still to  
 1088 smart applications such as smart cities, smart trans-  
 1089 port, Industry 4.0, etc. One perspective of this re-  
 1090 search is thus to keep refining the modelling in trans-  
 1091 lating other metrics in term of eco-mature system  
 1092 lessons. To this end, and as previously discussed in  
 1093 section 2.1, we believe that our model could be either  
 1094 re-used as part of a more generic LCA model cover-  
 1095 ing the economical and social dimensions, too, or be  
 1096 refined with other performance indicators defined in  
 1097 LCA standards.

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 1104 searchers involved in the PERCCOM program [79].

1105 **Appendix A. Sustainable data center metrics**

Table A.7: Metrics for Sustainable data centers reported in [5]

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

Continued on next column

**Continued from previous column**

Metric	Definition
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
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

Continued on next column

Continued from previous column

Metric	Definition
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 Appendix A.

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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 Réalité
	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	ViseKriterijumska Optimizacija I Kompromisno Resenje (means: multicriteria optimization and compromise solution)	
Mathematical Variables	$C$	Set of biomimicry commandments. Elements of $C$ are denoted by $\{C_1, \dots, C_i, \dots, C_z\}$ and the associated pairwise comparison matrix is denoted by $(C)_{z \times z}$ , as given in Eq. 1.
	$\mathcal{P}, \mathcal{P}_{C_m}$	$\mathcal{P}$ refers to the set of categories given in Table 3 (i.e., Energy, Materials, Cooling, etc.). Elements of $\mathcal{P}$ are denoted by $\{P_1, \dots, P_k, \dots, P_u\}$ . $\mathcal{P}_{C_m}$ refers to a subset of $\mathcal{P}$ indicating what categories impact on, and thus are linked with, a given commandment $C_m$ . For example, $\mathcal{P}_{C_{10}} = \{\text{Cooling, Carbon, Green, Recycling}\}$ for the Benefit hierarchy, and $\mathcal{P}_{C_{10}} = \{\text{Water}\}$ for the Cost hierarchy (cf., Table 3). Elements of $\mathcal{P}_{C_m}$ are denoted by $\{P_{C_m,1}, \dots, P_{C_m,i}, \dots, P_{C_m,y}\}$ and the associated pairwise comparison matrix is denoted by $(P_{C_m})_{y \times y}$ .
	$M_{P_k}$	Set of metrics that belongs to category $P_k$ (cf., Table 3). Elements of $M_{P_k}$ being denoted by $\{M_{P_k,1}, \dots, M_{P_k,i}, \dots, M_{P_k,x}\}$ and the associated pairwise comparison matrix is denoted by $(M_{P_k})_{x \times x}$ .
	$\mathcal{A}$	Set of alternative (data center) candidates. Elements of $\mathcal{A}$ being denoted by $\{A_1, \dots, A_l, \dots, A_w\}$ . 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 $j^{\text{th}}$ metric of category $P_k$ and $l$ the $l^{\text{th}}$ data center candidate.
	$E_p$	Priority/Eigen vector (EV) of a pairwise comparison matrix $p$ . Elements of $E_p$ are denoted by $\{E_{p,1}, \dots, E_{p,i}, \dots, E_{p,v}\}$ . 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.
	$S_{A_l}^{(B;C)}$	Aggregated scores of a given alternative (data center) $A_l$ with regard to the Benefit hierarchy (score denoted by $S_{A_l}^B$ ) and the Cost hierarchy (score denoted by $S_{A_l}^C$ ). 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.

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