Carbon- and Precedence-Aware Scheduling for Data Processing Clusters

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Abstract

As large-scale data processing workloads continue to grow, their carbon footprint raises concerns. Prior research on carbon-aware schedulers has focused on shifting computation to align with the availability of low-carbon energy, but these approaches assume that each task can be executed independently. In contrast, data processing jobs have precedence constraints that complicate decisions, since delaying an upstream "bottleneck" task to a low-carbon period also blocks downstream tasks, impacting makespan. In this paper, we show that carbon-aware scheduling for data processing benefits from knowledge of both time-varying carbon and precedence constraints. Our main contribution is PCAPS, a carbon-aware scheduler that builds on state-of-the-art scoring or probability-based techniques – in doing so, it explicitly relates the structural importance of each task against the time-varying characteristics of carbon intensity. To illustrate gains due to fine-grained task-level scheduling, we also study CAP, a wrapper for any carbon-agnostic scheduler that generalizes the provisioning ideas of PCAPS. Both techniques allow a user-configurable priority between carbon and makespan, and we give basic analytic results to relate the trade-off between these objectives. Our prototype on a 100-node Kubernetes cluster shows that a moderate configuration of PCAPS reduces carbon footprint by up to 32.9% without significantly impacting total efficiency.

CCS Concepts: • **Software and its engineering** → **Scheduling**; • **Social and professional topics** → *Sustainability*.

Keywords: precedence constraints, data processing, carbon-aware scheduling

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1 Introduction

Concerns about the climate impact of machine learning (ML) and artificial intelligence (AI) models have primarily considered the footprint of training [11, 22] or, in some cases, inference [15]. However, as model sizes have ballooned, the *data processing* tasks that must be completed before training account for almost one-third of the cumulative computation for an AI model during its life cycle [23].

Therefore, efforts towards sustainable AI must consider and optimize the carbon footprint of data processing. Even beyond sustainability, companies such as Microsoft have implemented *internal carbon pricing* for short- and long-term decisions [7, 19] that assign financial responsibility for operational CO_2 emissions. In data centers, current schedulers do not consider the time-varying aspect of carbon intensity and the resulting compute-carbon impact – this must change to accommodate these additional concerns.

Data processing (e.g., Spark) workloads are composed of *precedence-constrained tasks* where e.g., the outputs of one operation are the inputs to another [24], forming a directed acyclic dependency graph (DAG). Optimal scheduling of precedence-constrained jobs is known to be NP-hard [14], so existing work is split between simple settings that are studied theoretically to obtain approximation guarantees [3, 4, 13, 16] and experimental settings where data-driven heuristics and evolutionary approaches have been developed [5, 10, 12, 18, 25]. A select few works have considered multi-objective variants of the problem that balance e.g., energy-efficiency or cost against performance [8, 17, 20]. *Carbon-efficiency*, however, often conflicts with energy-efficiency: the time-varying nature of the grid means that minimizing carbon may require energy-inefficient processing "bursts" during

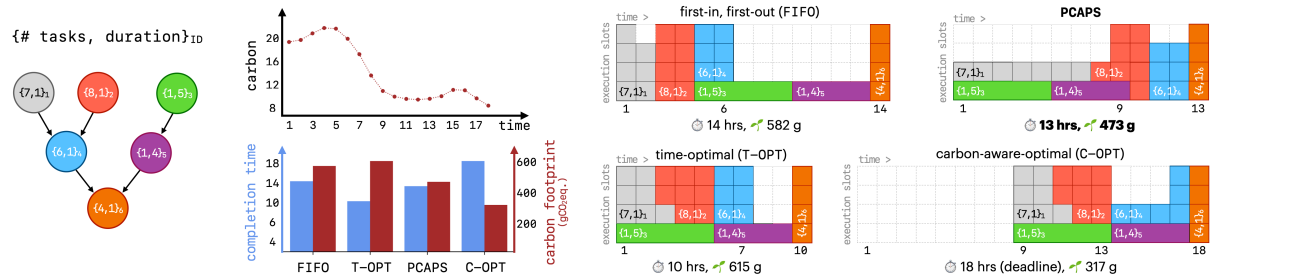

Figure 1. Four schedules for a motivating DAG and 18-hour carbon intensity trace (on the left hand side). Compared to a carbon-agnostic first-in first-out (FIFO) scheduler, the time-optimal schedule (T-OPT) prioritizes green and purple stages early to reduce makespan. A carbon-aware-optimal schedule (C-OPT) with a *deadline* to finish the DAG within 18 hours reduces carbon emissions by 51.2%, at the expense of increasing makespan by 28.5% compared to FIFO. By prioritizing green and purple stages during high-carbon periods, PCAPS reduces carbon by 23.1% and still reduces makespan by 7% compared to FIFO.

low-carbon periods. To address the multi-objective setting of carbon-aware scheduling for precedence-constrained tasks, we propose a middle-ground approach: namely, we seek an interpretable framework that comes with provable trade-off guarantees between carbon emissions and performance while catering to realistic scenarios. Our main contributions are as follows:

1. PCAPS (**P**recedence- and **C**arbon-**A**ware **P**rovisioning and **S**cheduling), a carbon-aware scheduler that defines a notion of relative importance for each task to make fine-grained scheduling decisions and achieve a favorable trade-off between carbon savings and performance.
2. CAP (Carbon-Aware Provisioning), a simplification of PCAPS that reconfigures the resources available to data processing jobs without replacing an existing scheduler, making it easier to implement (*see full paper*).
3. We evaluate PCAPS and CAP in experiments using a Spark simulator and prototypes for Spark on Kubernetes. [1]

2 Carbon-Aware DAG Scheduling Problem

Each job is represented as a directed acyclic graph (DAG) $\mathcal{J} = \{\mathcal{V}, \mathcal{E}\}$, where each node in $\mathcal{V}$ is a task, and each edge in $\mathcal{E}$ encodes precedence constraints between tasks – e.g., for tasks $j, j' \in \mathcal{V}$, an edge $j \to j'$ indicates that j' cannot start until after j has completed. We index continuous time by $t \geq 0$. The goal of a typical scheduler is *performance* in terms of makespan or average job completion time. We additionally consider the goal of *carbon emissions* – given a time-varying carbon signal described by a function $c(t) : t \geq 0$, the objective is to minimize a combination of typical metrics (i.e., makespan) and the overall carbon footprint (on a global, cluster basis). In an online setting, future carbon values are unknown to the scheduler. We follow prior work [2] and assume there are constants L and U such that $L \leq c(t) \leq U : t \geq 0$. In practice, these values capture e.g., short-term forecasts of grid carbon conditions. Due to the additional objective of carbon, an scheduler must consider the time-varying carbon intensity while scheduling the nodes of a job DAG(s) to balance the goal of reducing carbon footprint against traditional metrics of performance – see Fig. 1 for an illustration of this trade-off for four different schedules.

3 Design & Evaluation

We briefly detail the design of our PCAPS scheduler and report our main experiment results – see our full paper for details.

The key idea of PCAPS is a notion of *relative importance* inferred from a set of probabilities or scores assigned to tasks that are ready to execute. Many state-of-the-art DAG schedulers (e.g,. Decima [18], Graphene [9]) operate by scoring (resp. assigning probabilities to) all tasks. In doing so, these techniques encode important information about DAG structure – a high score or probability is likely to indicate e.g., a bottleneck task. PCAPS builds on top of this existing intuition – for a given task v with score/probability p_v, we define the relative importance $r_v \coloneqq p_v / \max_{u \in \mathcal{A}} p_u \in [0, 1]$, where $\mathcal{A}$ denotes the set of tasks that are ready to execute.

For carbon-awareness, PCAPS is designed to ramp up during low-carbon periods and ramp down during high-carbon periods, while ensuring that certain bottleneck tasks are still scheduled during high-carbon periods to avoid adversely increasing makespan. To do so, PCAPS takes cues from the related theoretical literature on carbon-aware scheduling [2]

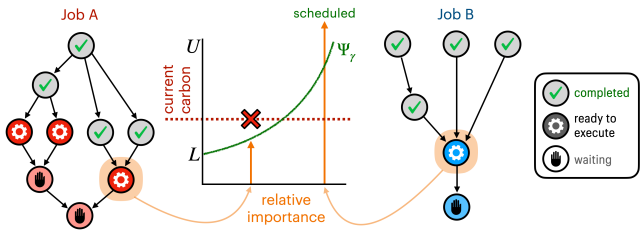

Figure 2. Illustrating PCAPS's carbon-awareness filter. Jobs A and B are DAGs found in TPC-H queries and Alibaba traces [1, 21]. Highlighted nodes detail two possible outcomes. In job A, the highlighted node has low relative importance, so it is deferred. In contrast, job B's highlighted node is a *bottleneck* task with high relative importance: even when the current carbon intensity is high, such tasks are scheduled to avoid increasing makespan.

[1] Full paper and code: github.com/umass-solar/carbon-aware-dag.

and defines a threshold function Ψ_γ that considers the current carbon and the relative importance of a task. $\gamma \in [0, 1]$ is a user-specified parameter that controls the "strictness" of the function: $\gamma = 0$ recovers carbon-agnostic actions, while $\gamma = 1$ is maximally carbon-aware. Given a task's relative importance r, we define $\Psi_\gamma(r) \coloneqq (\gamma L + (1-\gamma)U) + [U - (\gamma L + (1-\gamma)U)] \frac{\exp(\gamma r)-1}{\exp(\gamma)-1}$. PCAPS uses the Ψ_γ function in a carbon-awareness filter that decides which tasks can be scheduled – see Fig. 2 for an intuition of this. In the full paper, we give analytic bounds to characterize the trade-off between carbon savings and makespan for PCAPS.

We implement PCAPS and CAP as a prototype for Spark on Kubernetes, and conduct additional large-scale experiments in a realistic Spark simulator. We use workloads from TPC-H benchmarks [21] and Alibaba production DAG traces [1], alongside historical carbon traces for six grid regions from Electricity Maps [6]. In addition to the default scheduling behavior of Spark on Kubernetes, we implement the Decima scheduler [18] as a carbon-agnostic baseline. Decima uses reinforcement learning to assign a probability to each task – in our PCAPS implementation, we use Decima's probabilities for the computation of relative importance. Table 1 reports carbon reduction, makespan, and job completion time metrics for all schedulers in our prototype experiments – see the full paper for individual experiments and results.

Table 1. Summary of prototype results averaged over all tested carbon traces. Each metric is normalized with respect to the Spark / Kubernetes default behavior. PCAPS and CAP are configured to be moderately carbon aware (i.e., $\gamma = 0.5$).

Metric normalized w.r.t. Default	**Default**	**Decima** [18]	**CAP**	**PCAPS**
Carbon Reduction (%)	0%	1.2%	24.7%	**32.9%**
Avg. Makespan	1.0	0.857	1.126	**1.013**
Avg. JCT	1.0	0.852	1.996	**1.381**

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