A parameterized test bed for carbon aware job scheduling

Ein parametrisierbares Testbed für kohlenstoffbewusste Jobplanung

Vincent Opitz

A parameterized test bed for carbon aware job scheduling

Ein parametrisierbares Testbed für kohlenstoffbewusste Jobplanung

Vincent Opitz

Arbeit zur Erlangung des Grades "Master of Science" der
Digital-Engineering-Fakultät der Universität Potsdam

A parameterized test bed for carbon aware job scheduling
(Ein parametrisierbares Testbed für kohlenstoffbewusste Jobplanung)
von Vincent Opitz

Arbeit zur Erlangung des Grades "Master of Science" der Digital-Engineering-Fakultät der Universität Potsdam

Betreuer:in: Prof. Dr. rer. nat. habil. Andreas Polze
                Universität Potsdam,
                Digital Engineering-Fakultät,
                Fachgebiet für Betriebssysteme und Middleware

Gutachter:in: Prof. Dr. Jack Alsohere
                University of San Serife
                Facultiy of Computer Doings

                Amelia van der Beenherelong
                ACME Cooperation

Datum der Einreichung: 29. September 2024

Zusammenfassung

ummarize thesis

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

Contents

Zusammenfassung

ummarize thesis

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

1 Introduction

- I could start with a fact stating that datacenters use X amount of energy which in turn emits carbon for its production
- We can reduce the amount of carbon emitted for the same amount of work by scheduling our work in smart way
- this is not a new idea; datacenters around the world are already using data provided by e.g. electricitymaps
- one thing that is not represented in literature however is the heterogenity of jobs, as well as the emphcheckpoint & resume capabilities of some jobs, particularly machine learning jobs which are projected to make UP X amount of energy in the coming years [QUOTATION NEEDED]
- I want to create a better model for jobs in datacenters
- I then want to use that new model to investigate wether we can exploit the heterogenity of jobs to further reduce carbon emissions
- One hypothesis is for example that, we can match high-power phases of jobs to the lowest carbon-intensive time frames, so we do not "waste" those rare times with low-power phases
- We can also investigate wether the previously proposed stop & resume techniques still work if the assumption that stopping and resuming a job has no overhead is broken.
- We hypothesis that a stop & resume strategy can stil lead to reduced carbon emissions but only on certain jobs.

2 Background

This chapter will be used to introduce some basic terminology as well as some basic arguments on why carbon-aware scheduling is useful.

The composition of the public grid The public grid is made up of many energy producers. This *energy mix* is composed of different sources: low-carbon technologies like solar, wind, or hydroelectricity and carbon-intensive sources like coal, gas, or oil.

Figure 2.1 shows one such energy example, for a specific location, in this case Germany. As it was summer, solar production made up large amount of power at that time. Germany is further interesting in the sense, that it is a country that has no nuclear power stations anymore.

Over the day, the demand and supply for power changes. Carbon-efficient sources will generally follow the weather: Solar production follows the amount of sun shining and thus follows a *diurnal* rhythm over the day. Wind and hydroelectricity will also depend on the weather. Nuclear energy is generally also considered carbon-efficient, but is generally not useful for carbon-efficient scheduling as the amount of energy produced from is generally stable throughout the day, meaning that there is little use in deferring work to a later time.

As near-time weather predictions have high accuracy, this enables X.

Thus, at each point in time the amount of CO_2 per unit of electric power can be determined by averaging the amount of power each source supplies to the grid and how much carbon it emits. Figure 2.2 is an example X-day timeframe of the carbon-curve.

Power grid Signals Carbon-aware scheduling commonly works two possible metrics or signals: the *average emissions* are the metric describing the amount of carbon per unit of energy, basically what has been used in the text so far. Another metric is the *marginal emissions*, answering the question of "if more energy is used at this point in time, how much carbon would that cost?". The answer to that question is usually that non-renewable power plants have to increase production as renewable sources cannot increase production to meet demand (as the sun and wind intensity are set by the weather). Going by the marginal metric, any kind of carbon aware scheduling would be pointless, as any work at any point in time would result in the same increase of carbon. Thankfully, there are secondary reasons that would render carbon-aware scheduling useful. One of them are is *curtailment*. This encompasses any methods that reduce the amount of produced renewable energy. As the power grid always needs to have a balance between demand and production, curtailment methods such as turning of wind turbines, selling power at a loss, or charging batteries may be used. Carbon aware scheduling via the average emissions signal, would lower the amount of curtailment needed, as demand for energy would increase at those times. Another argument can also be made that by increasing

> QUOTATION NEEDED, maybe use look in on of the related work papers

> QUOTATION NEEDED

> Find the quote

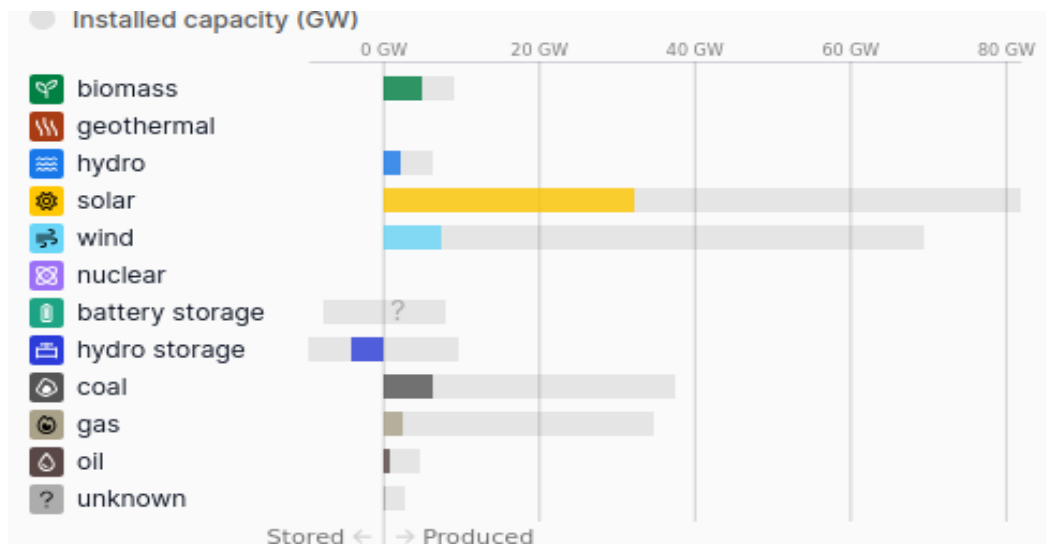**Figure 2.1:** An example snapshot of the energy mix in Germany, at DATE

Missing figure

The carbon curve for a few countries at the same time Germany, France, and Poland,
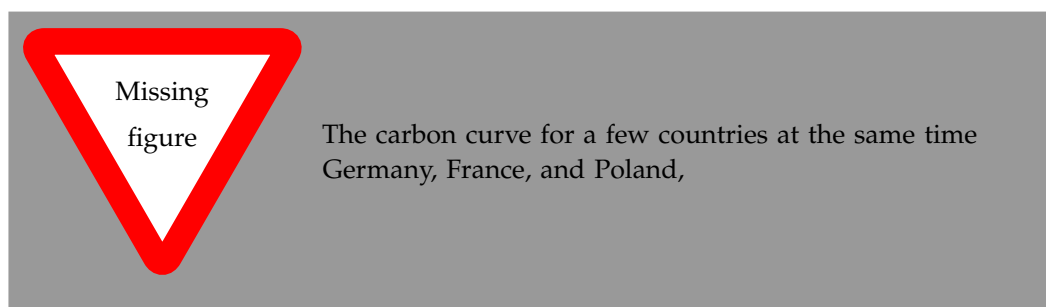
Figure 2.2: Carbon in per unit of energy in select countries

power demand during times when renewable production is high, energy producers would be "signalled" that there is demand for renewable energy. Lastly, as renewable energy is generally cheaper in production than non-renewable energy, scheduling work on low carbon-periods coincides with cheaper energy prices as well. While this would not reduce costs on most energy contracts, there are also some contracts that use dynamic pricing[1]

> Need a citation here!

Types of work in a datacenter   According to [1], there are 3 environments in which scheduling may take place. *Batch systems* describe environments in which there is no user interaction. A user may submit their job, and it would be executed according to the scheduler at some point in time. On the contrary, in *interactive* settings, a user would be interacting with the system "live", and would thus expect quick responses to their inputs. The last environment would be a *real time* system. There deadlines and predictability would dictate how a scheduler would operate.

> Does this need more examples?

For this work's topic, carbon-aware scheduling, only batch systems will be looked at as they allow more freedom to the times of scheduled jobs.

Which metrics are there POI-A, etc.

> I could also add more stuff about metrics and so on, but I am not using them yet in my implementation

Power intake of a computer   As there will be power measurements in 4.1.1, some basic understanding of energy and power used for computation will be provided:

- I could mostly borrow from the EBRH slides; there is some base power needed that is correlated to the hardware (dynamic and static energy)

- this also depends on frequency (which is why later we set our CPU frequency to some hard coded value [or do not do that in the case of my GPU lol])

- basically, use this paragraph to outline all things we take care of in my power measurements

---

[1]One example for dynamic pricing would be *Tibber*: `https://tibber.com/de`

3 Related Work

A systematic approach   I used the following system for finding related work to my topic; first, my supervisors and I would brainstorm for search engine keywords. The specific words are in the attachments, but can be grouped into two groups: one for all things carbon-aware and one for keywords about servers / computing / HPC and such.

Using these two groups, I could then create Google Scholar queries via the cross product between them. Using the double-quotation feature would further limit the results. For each query, I would then read the abstracts of roughly the first 5 results, depending on if their titles sounded subjectively fit.

These would then be entered into a spreadsheet: for each query, 5 paper titles. Additionally, I would also further explore papers through *connected papers*[2] or looking up individual authors on a subjective basis. The papers from the 2023 and 2024 HotCarbon Workshops[3] also proved to be related.

I then "rated" each paper into three categories:

- Green, meaning that they seem very connected and are good first entries into the topic

- Orange, which would indicate that are somehow connected to the paper and might be read at a later date

- Red, the paper is either irrelevant or had some other flaw. These would not be touched again in the course of my work

With this approach, X abstracts were read. Figure 3.1 shows that X abstracts were deemed "good" for the purpose of this work. The complete list of papers analyzed can be found in

I would like to highlight some papers:

---

[2] https://www.connectedpapers.com/
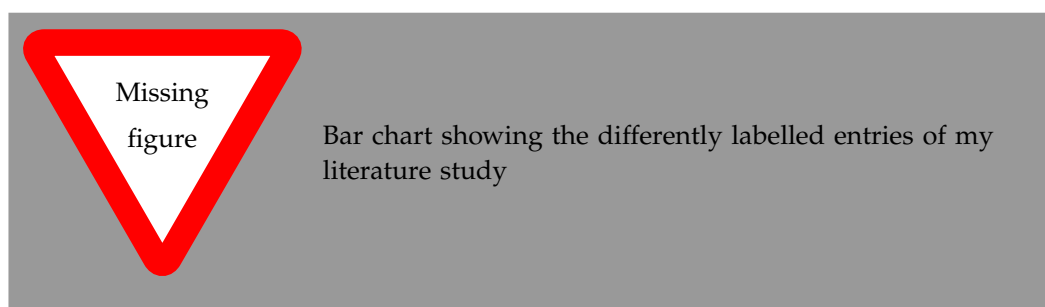[3] https://hotcarbon.org/

Figure 3.1: Results of the literature study

9

GreenSlot: Scheduling energy consumption in green datacenters[0]   According to the analyzed papers, this seems to be the first paper that deals with carbon aware scheduling by implementing it as a *Slurm* plugin (See section 4.2.1 for further information on Slurm and such plugins) In contrast to our scenario, where we try to optimize carbon emissions via the public electricity grid, GreenSlot is about datacenters having their own renewable energy production (solar panels on the roof). Using weather data, *GreenSlot* would then predict when solar energy production is high, scheduling jobs to those time frames.

The War of the Efficiencies: the Tension between Carbon and Energy Optimization   [0] outline the different ways of carbon aware computing. Among those are *temporal shifting*, the idea that jobs can be executed later when energy is more carbon efficient, is also the main idea for my work. They also use *spatial shifting*, moving jobs across the globe to areas where higher carbon efficiency is possible. *Resource scaling* uses dynamic amounts of hardware according to carbon emissions. In the end, *rate shifting* is the idea to also scale hardware frequencies. During carbon-efficient times, CPU speeds would be increased, leading to faster processing speeds and more energy usage.

All of these techniques are then tested under various parameters. My work will only make use of the temporal shifting, and abstract away the other methods of further saving carbon.

Let's wait awhile: how temporal workload shifting can reduce carbon emissions in the cloud This paper will be built upon in my work the most. [**wiesner_lets_2021**] uses a simulation approach, to simulate temporal shifting. Their workload model consists of known length jobs that can use *checkpoint & restore* to be executed at different time slices. They would further use different traces and test these traces under the assumption of different job-deadlines, meaning that each job would have to be completed by a certain timeframe, and also different regions of the world as described in the background part. Their main takeaways are that increased deadlines lead to reduced carbon emissions, but that this effect also has diminishing returns. They also deduced that regions such as California, with high amounts of solar power, have higher potential for carbon-savings in comparison to nuclear-heavy regions such as France.

Think about linking this to the earlier part

4 Methodology

Based on our related work, describe (using the goals outlined in the beginning) the approach I take: creating a better model to be used in carbon-aware scheduling using the model and evaluating it.

4.1 Improving the current Job model

We should probably argue why the current job model used in literature is not sufficient (WaitAWhile[**wiesner_lets_2021**] assumed constant power usage and no overhead from stopping and resuming)

4.1.1 Power Measurements on Machine Learning Jobs

Options for measuring power   There are multiple options for measuring the power of a given computer. One way of classifying these options would be under them being either *logical measurements* or *physical measurements*.

> I feel like I should add a paragraph somewhere explaining what I want to measure

Logical ones would create a model on some metrics and derive the used power. One example would be using Linux' *perf* tool to read hardware performance counters.

> This needs some more here

Advantages of choosing a logical approach would be that no external hardware is needed and that the overhead of the measurement would be low, as the hardware counters are being kept track of anyway. Disadvantages on the other hand would be that such a model would have to be created or chosen and would include some form of error as all models do.

Physical measurements follow another route; measurement devices would be put between the operating hardware and the power supply. The point where a power measuring device is inserted would dictate what could and could not be measured, a wall mounted measurement device could only measure all power going into a computer and not differentiate between individual programs.

Advantages of physical measurements are that they can give a more holistic measurement of a system as would be the case for a wall mounted measurement device. Portability is an issue however, unlike operating-system supported tools such as perf, a measurement device would need more effort to be used on another system (or be entirely not useable, for example when such devices are only rated for a certain power level).

Due to having a power-measurement tool on-site in our university and it allowing whole-system measurements directly, I chose to follow the physical measurement option.

Measurement tool   The concrete tool used is the *Microchip MCP39F511N Power Monitor (henceforth called MCP)*, which can be inserted between the device to test and the wall

Figure 4.1: The MCP

mounted power supply. A picture of it can be found in figure 4.1. The MCP can report the current power consumption in 10 mW steps, each 5ms.

I then used *pinpoint*, a tool for energy profiling that can use different inputs, among them being the MCP, to read out its data.
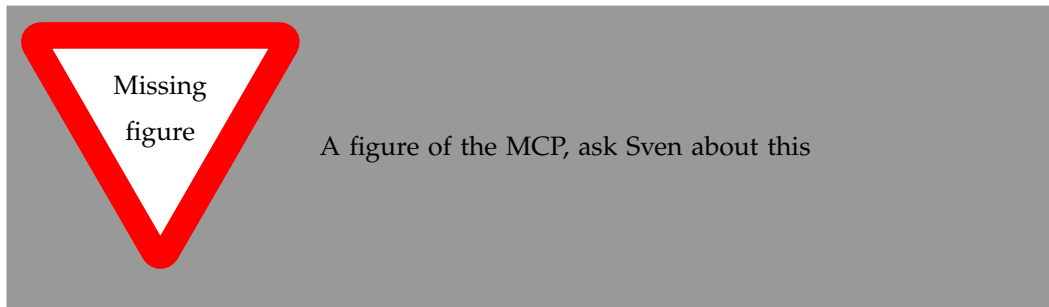
> I could include an extra paragraph on why the MCP is cool, and what it does differently, perhaps. Was there anything cool? I vaguely remember some measurement devices having two capacitors to more accurately determine usage

The test environment The experiments were run on my personal computer, the components of that are listed via the *hwlist* tool, with unnecessary columns and rows being redacted for brevity:

Listing 4.1: Hardware environment of the measurements

```
  $ lshw -short -C processor -C memory -C display -C bus
Class           Description
=========================
bus             AB350 Gaming K4
memory          16GiB System Memory
processor       AMD Ryzen 5 1600X Six-Core Processor
display         GP104 [GeForce GTX 1070]
```

Information about the operating system is given via *hostnamectl*, again some parts redacted:

Listing 4.2: Used operating system information

```
  $ hostnamectl
 Operating System: Ubuntu 24.04 LTS
           Kernel: Linux 6.8.0-39-generic
```

Measured Program Machine learning (ML) was used as the main motivation for checkpoint & resume scheduling in the related works[**wiesner_lets_2021**] and thus was also chosen by me to be measured and modeled.

The concrete model and framework is secondary for our measurement. In my case, a small model would be chosen in order to have fewer data points for processing as well as faster iterations on the measurement script.

There is a vast amount of machine learning frameworks. For a high-level model, the feature set of the framework only needed to support checkpointing, resuming, and some basic form of logging. Glancing at the documentation of popular frameworks such as *torch*, *tensorflow*, and *huggingface* shows that these features are commonly supported.

With not much bias towards any framework, huggingface was chosen because my supervisor Felix supplied a sample "hello-world"-esque machine learning script for python *roberta.py*[4]

The huggingface trainer supports callbacks, I thus modified the code by adding timestamped logs. These "Events" would be output into another .csv File I could later use.

> Later use for WHAT?!

Conducted Experiments A script[5] was created to execute each experiment.
On a high-level view, the following experiments were conducted:

1. Run the whole program start to finish

2. Run it partially, checkpointing after some step, sleeping, resuming from that step

3. Run it partially, checkpointing after some step but aborting before the next checkpoint. Then resume as above.

4. Run only the startup phase up until the ML would start

5. Do nothing, measure the system at rest

Experiment 1 would give a baseline for what the job would look like without checkpoint & resume. Number 2 and 3 would be used to determine the overhead of checkpointing the job. 4 would be used to validate the other ones. The last experiment is necessary to determine the baseline energy consumption of the environment.

To execute these experiments inside a repeatable bash script, additional command line parameters were added to the given python script. For example, there would be a boolean parameter `--resume_from_checkpoint`, or an integer parameter `--stop_after_epoch` would be used for experiment 1 to 2. The way of doing experiment 4 was to copy the script, and delete everything after the imports.

Creating repeatable measurements As this is being run on standard hardware on a standard operating system, all experiment are subject to noise. For example, *Dynamic frequency and voltage scaling (DFVS)*, the OS technique of increasing CPU "speeds" according to work load would add power in an uncontrolled way. Also, background tasks may happen "randomly", increasing power usage.

Thus, for the testing, any foreground apps would be closed. I also used the Linux tool `cpupower`, as shown in snippet below, to set the CPU frequency to a set value:

> Think about whether this is actually interesting, I guess keep it if I need more content

Listing 4.3: Used operating system information

```
MINFREQ=$(cpupower frequency-info --hwlimits | sed -n '1d;p' \
    | awk '{print $1}')
MAXFREQ=$(cpupower frequency-info --hwlimits | sed -n '1d;p' \
```

> What is the MAXFREQ of my Ryzen 5?

---

[4]https://github.com/Quacck/master-thesis/blob/main/power-measurements/roberta.py
[5]https://github.com/Quacck/master-thesis/blob/main/power-measurements/measure_roberta.sh

```
        | awk '{print $1}')

    cpupower frequency-set --min ${MAXFREQ} &>/dev/null
    cpupower frequency-set --max ${MAXFREQ} &>/dev/null


    # ... conduct experiments


    cpupower frequency-set --min ${MINFREQ} &>/dev/null
    cpupower frequency-set --max ${MAXFREQ} &>/dev/null
```

As machine learning makes use of available GPUs, the frequency should also be similarly set to a defined value. NVIDIA provides guide on how to do so[6] Sadly, my used GPU, the NVIDIA GTX 1070, is not capable of fixing the frequency as of the time of conducting these experiments. While it is supposed to be possible according to

> SOURCE, Reconstruct this argument, perhaps there is still something in my PC history | grep

> Find the forum post of people complaining

, but there seems to currently be drivers issue preventing this. Thus, the frequency of the GPU was not fixed. To reduce the effect of frequency scaling here, the time between experiments was increased generously so that any impact from such scaling would reoccur throughout each run and there would be reduced dependency between runs.

> Further explain how the experiments were conducted

Conducting each experiment   Each experiment was re-run 10 times. Between each run, there would be a `sleep` period of 10 seconds and one of two minutes in the partial executions. Additionally, `pinpoint`'s feature of measuring before and after the actual program-to-test would be used. This leads to a period of 30 seconds being measured around the actual experiment. Plotting these additional time frames would give a quick visual indicator whether experiments are sufficiently isolated from each other, ergo when the power draw is at the baseline as the actual program starts.

As there is some data being downloaded and persisted during the execution of the ML, before each run, the data would be cleaned up.

Collected data   For each experiment, a named and timestamped folder would be created in the `/power-measurements` folder of my repository. Each folder would then hold a `.csv` with pinpoint's timestamped power measurements. The added timestamped-logging would be saved into another `.csv`. While figuring out how to conduct the experiments, I would then plot these measurements early and visually spot if there were any obvious errors or mistakes.

Determining the baseline power draw   Beginning with the most exiting experiment, determining the baseline and testing the amount of the underlying environment. One sample run is shown in Figure 4.2. The blue dots in figure represent each data point. The red line is a smoothed Gaussian trend line with $\sigma = 2$. Dark-green vertical lines are the logged or derived "events" for each run. In this case, nothing happens, so it is only the start and end
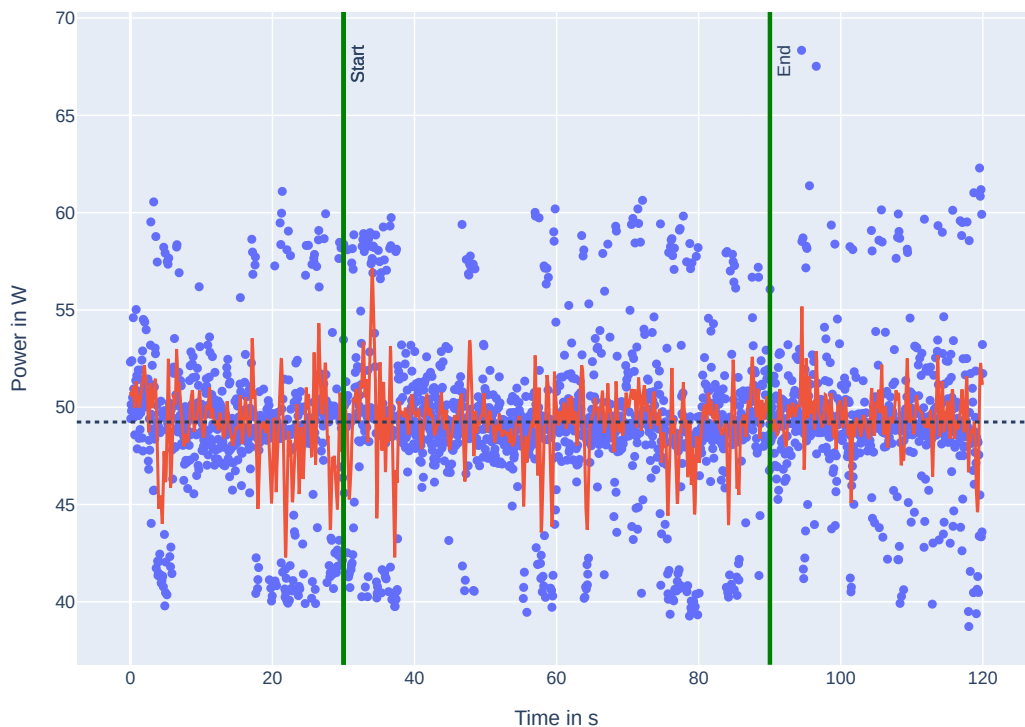
---

[6]`https://developer.nvidia.com/blog/advanced-api-performance-setstablepowerstate`

Figure 4.2: Sample run of the baseline experiment

of `sleep 120`. Notice how the trace starts 30 seconds before the start and continues for another 30 seconds because of the aforementioned `pinpoint` feature. Going further, these additional measurements will be redacted for brevity, unless something worth mentioning happens outside the actual experiments.

Across all 10 runs, the average baseline power draw is calculated via the mean of all data points. This comes out as an average of 49.8 W with a standard deviation of 4.4 W.

The baseline power draw will be less interesting going further, but will put perspective on the power draws of the other experiments. The standard deviation should give a broad idea of how much noise is in the system environment.

> Check later if something interesting happens or if I should reword this.

The non-interrupted run For the non-interrupted machine learning run, a figure of a sample run is provided in 4.3. Figure 4.4 shows the stacked trend lines of the 10 different runs. For simplicity's sake, I refrained from doing more elaborate statistical analysis on the different runs as the visual check of them being very similar seemed enough. There was an option to discuss the measurement results after normalizing each measurement point to its phase, but that would not change the result.

> What?

The main takeaways from these measurements are:

1. There is a long (about 25%) start-up phase, which is spent in starting python, loading libraries, and loading data to disc.
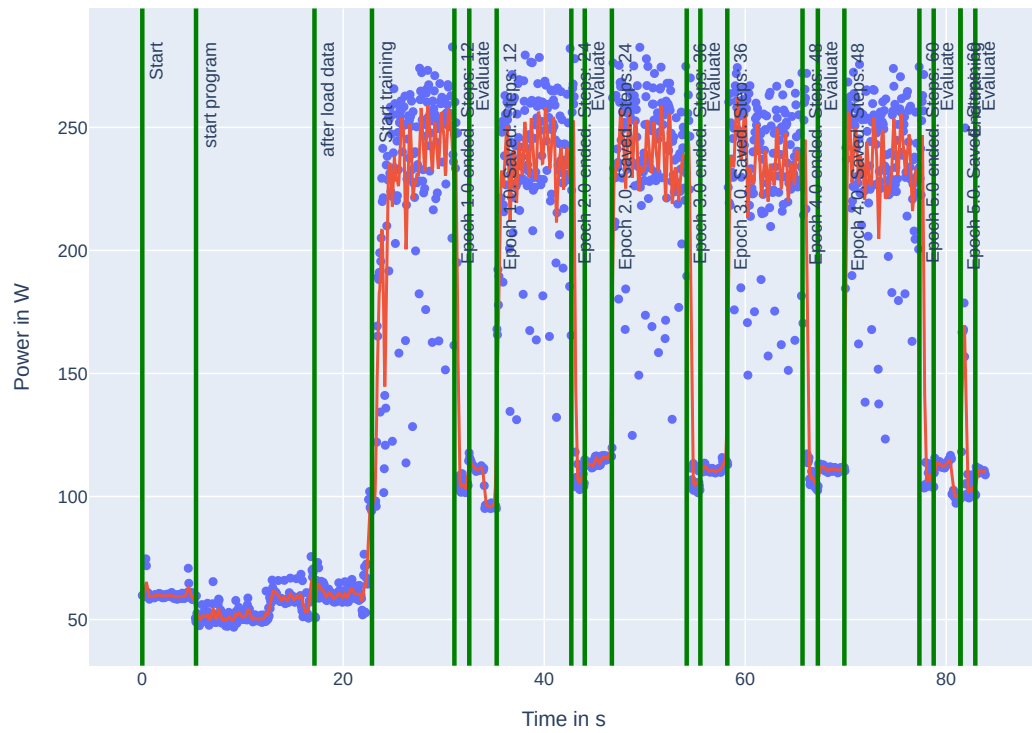
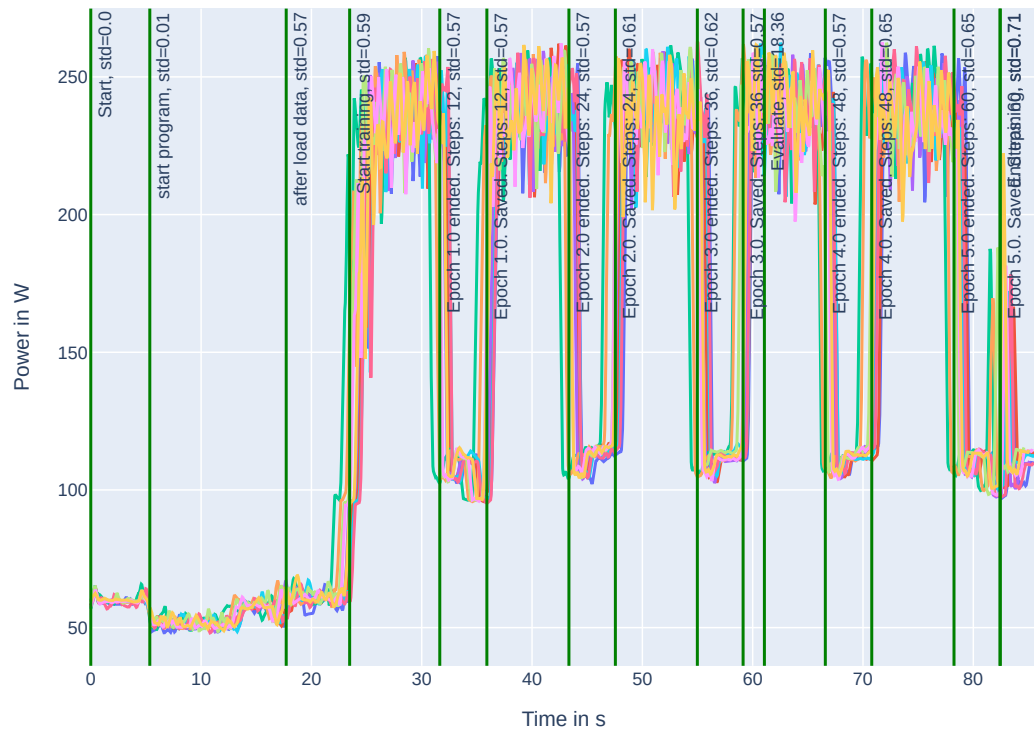**Figure 4.3:** Sample run of the full run experiment

Figure 4.4: Stacked trend lines of the power consumption for the full runs

These are not yet accurate, the multiple evaluate phases are being grouped into one, which is wrong.
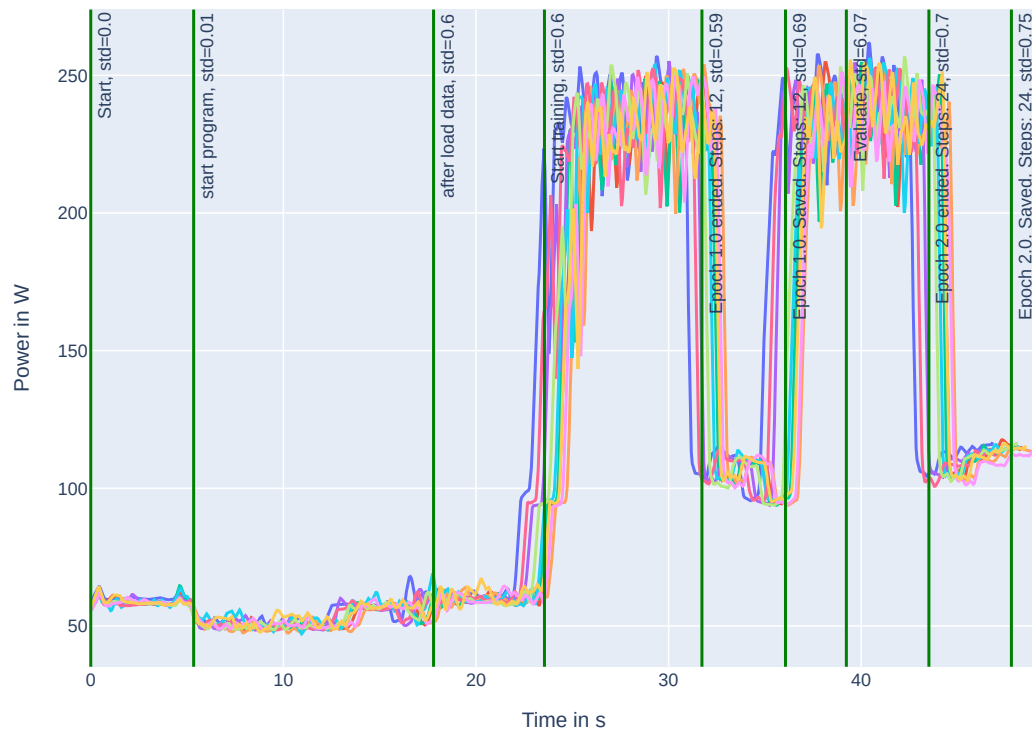
Figure 4.5: Power draws of the ML up until stopping after epoch 2

2. There are periodical work-phases; a high-power training phase would be followed by low-power evaluation phase and a low-power checkpointing.

3. A higher variance in measurements occurs during the training phases in comparison to the others.

This already shows, that improvements upon the constant-power model used in [**wiesner_lets_2021**] are possible. For example, in this case the start-up phase has a much lower power-draw than the work-phase.

> Uhm, where did my evaluation phase markers go?? They are mushed together as they share a label

Results of the checkpoint and restore experiment Similarly to before, results will be discussed using the stacked plots 4.5 and 4.6; each individual run is plotted in the repository, however.

Here we can observe that

1. The amount of work done is the same. Similarly to the full-run experiment, the ML still takes the full 5 epochs and has the same work-phases

2. There is no overhead from checkpointing itself, as the checkpoints are being created regardless of them being resumed from later.

3. Resuming the jobs results in an added start-up phase. This phase is slightly shorter by a few seconds than the ones in the full runs, likely due to not needing to download the dataset again.
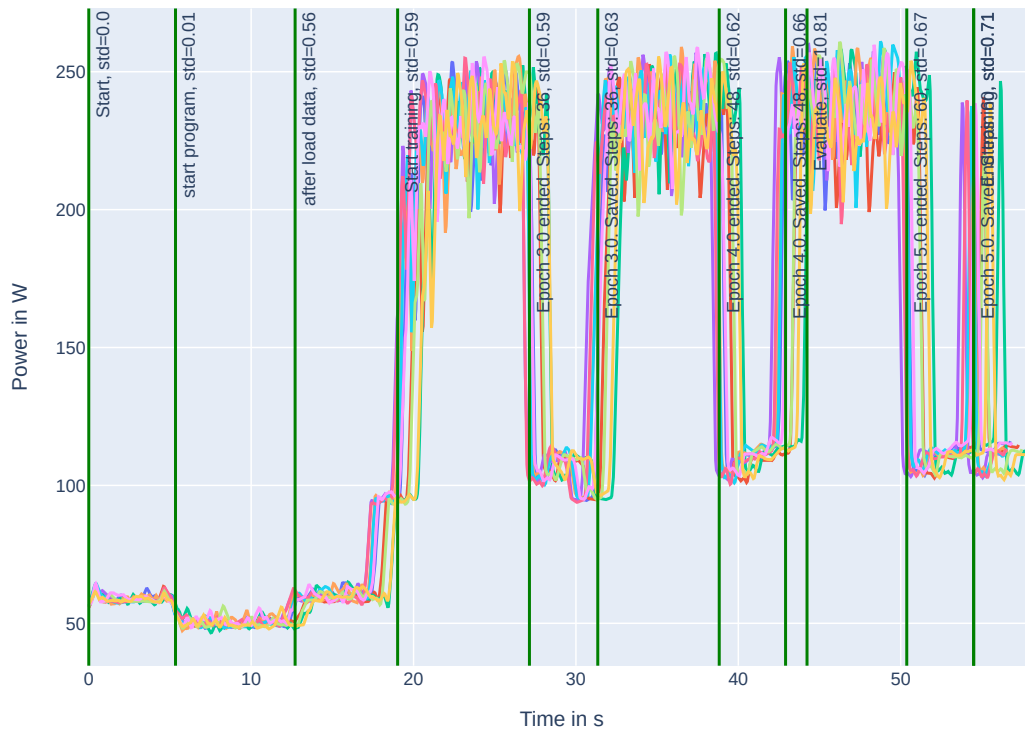
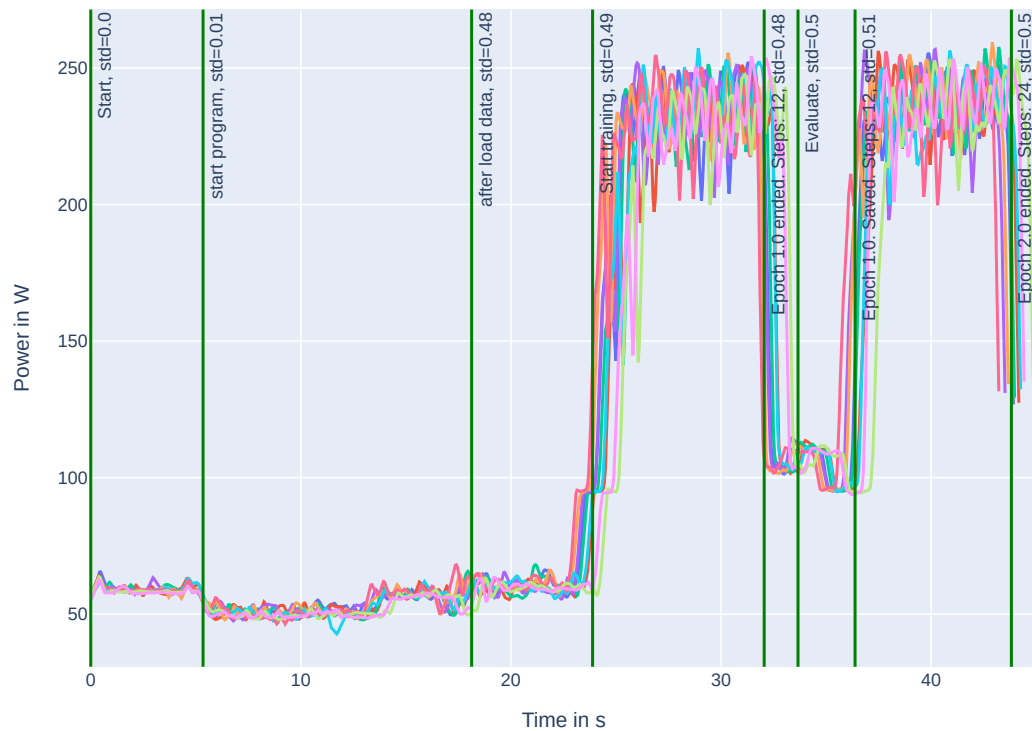**Figure 4.6:** Power draws after continuing from the second checkpoint

Figure 4.7: Power draws of the ML up until stopping after epoch 2

Additional considerations are that the amount of epoch that are worked off before checkpointing and resuming may matter, but it will be assumed that this is not the case.

> I could just run this again with another epoch parameter

Results from checkpoint and resume with abort   Unlike the previous experiment, where work is stopped as soon as checkpoint is created, this time the program will be stopped just before a checkpoint is created (in this case just the second checkpoint would be saved). This should show the maximum created overhead from a checkpoint & resume strategy.

While this may sound artificial, it could happen in environments where the interaction between the scheduler and the job is not well orchestrated, for example in an environment where jobs are stopped "at random" like in a cloud spot instance.

> Improve the wording here

Again, the results are visualized in figure 4.7 and 4.8. Attention should be paid to:

1. The behavior of the repeated start-up phase is kept
2. There is now a full additional training phase added to the overall work

Calculating the energy costs of each run   To support the argument that there is indeed an overhead from checkpointing & resuming, I calculated the energy needed via integral of each experiment:

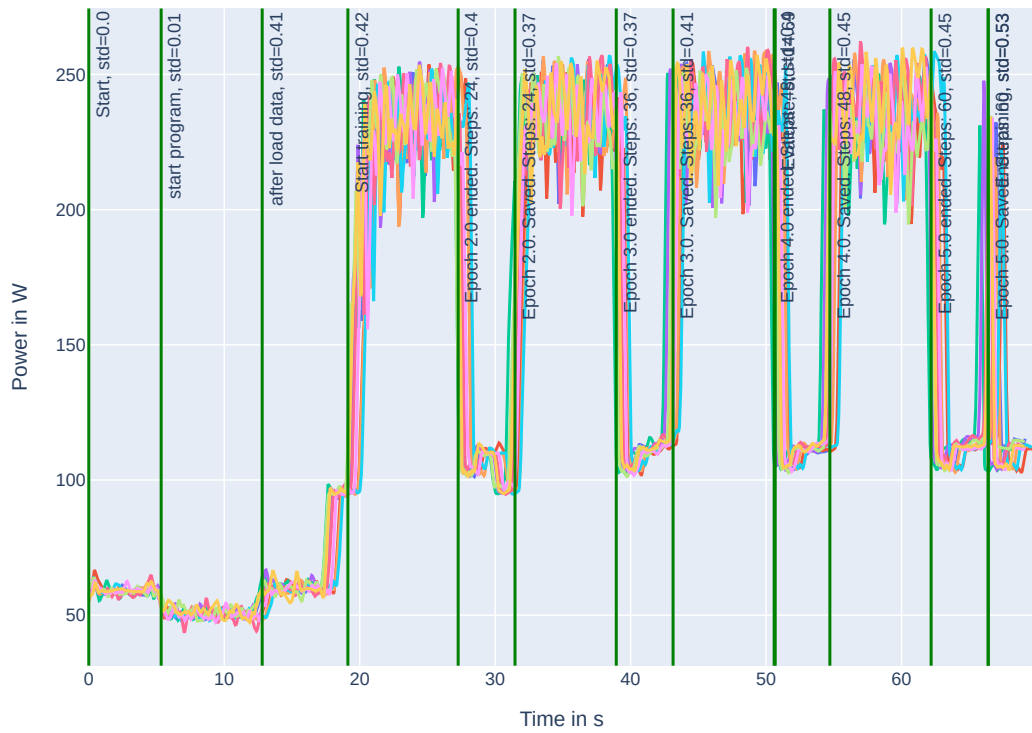- unstopped costs 12.97 kJ on average with an std of 0.04

Figure 4.8: Power draws after continuing from the second checkpoint

- save+resume costs 13.94 kJ on average with an std of 0.1
- save+abort+resume costs 15.72 kJ on average with an std of 0.07

4.1.2 Defining a new model

Now that we know what a high-level job looks like, we can pick it apart and reduce the real-world measurements of one program to a more generic model.

Summarizing the findings from the previous paragraphs; it was shown that

- The given job has phases that have different power draws
- Checkpointing & resuming carries overhead in the form of startup costs and possible wasted work.

The parameters for the improved job model are shown in form of the python implementation in 4.4.

Check whether this ref works

Probably need to improve the code here

Listing 4.4: Python Model definition

```python
class ModelParameters(TypedDict):
    startup: List[Phase]
    work: List[Phase]

class Phase(TypedDict):
    name: str
    duration: float
    power: float
    is_checkpoint: NotRequired[bool]
```

Some simplifications are made: the duration of each phase is well known and the power per phase is a constant. Phases can also be named for later reference. These phases essentially define a step function, i.e. piecewise constant function. Unlike a traditional step function, the start- and endpoints of each "piece" would be encoded implicitly by the previous phases. Using these specifications, a simple time-to-power function can be defined, that looks up the input time and traverses the phases in order.

Initially, I also considered allowing any expression instead of a constant value for power and then using Python's evaluate() to e.g. allow a function-per-phase model. In section 4.3.3, having a rather restrictive step function will be of advantage, however.

Add some more explanation to this in that section

What to do if the events are not known? How does this work for more complex jobs

The measurements that have been taken can now be fit into this new model. As each measurement-point can be associated to a phase via the aforementioned added logging, the average of each phase-associated measurement is used to determine the model parameters. The durations of the phases are calculated similarly by taking the average time the logging occurred during the measurements.

Using this strategy on the 10 complete runs results in figure 4.9, which shows the derived model on black with the previous figure 4.3 in less opacity. The startup phase looks well approximated, visually however there is some error during the work phases.
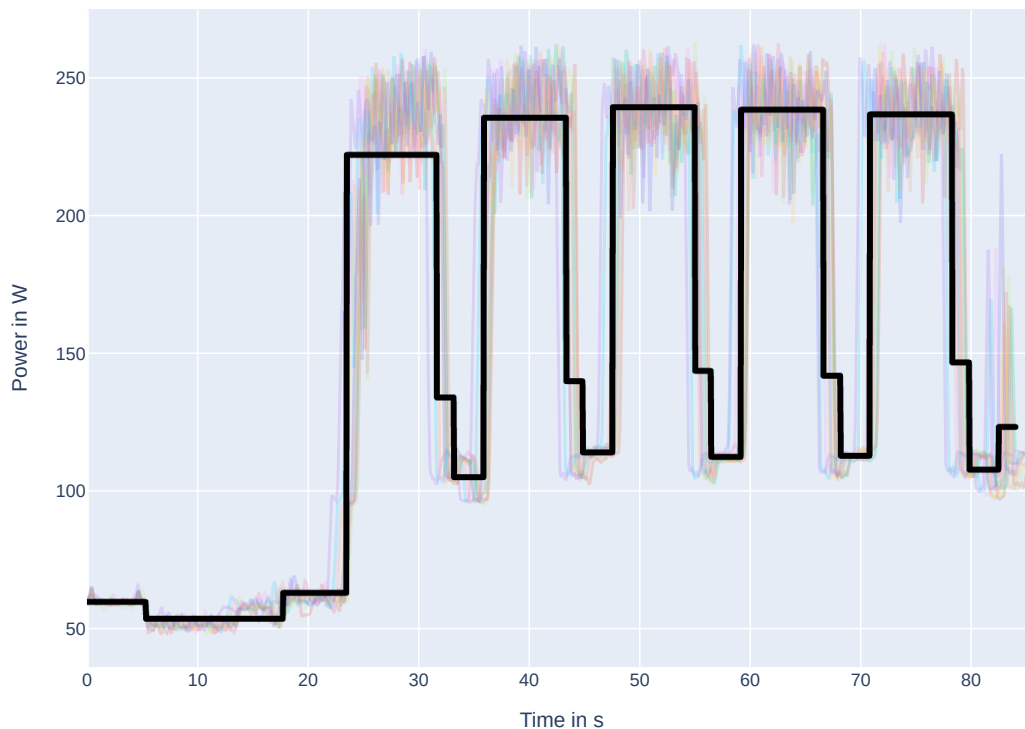
Figure 4.9: Model of roberta.py (black) vs. all measurements

The training phases each have a high variance, which is not captured by the constant power approximation. After each training phase, the power goes down seemingly liniarly, which is also approxiimated by the constant.

One notable point, this model is a superset of the previous constant-no-overhead model used in the related work. These jobs can be modeled with just one workphase, resulting in a constant power over its execution. Leaving the startup phases empty creates no overhead on resuming.

Should probably add the phase markers back in

Model error analysis   To analyse the error of this model, I cross validated the power's and total energy's RMSE using `scikit-learn`'s `LeaveOneOut` strategy. The first one would give a measure of the model's accuracy on a short-time (sub-second) scale, the latter would tell the long-time (whole job) scale accuracy of the model.

Each of the 10 runs would be taken as the ground truth while the other 9 would be used to create the model. The results are the following: t power between the prediction and remainder has an RSME of 39.3 W while the difference in total energy is calculated as -0.1 kJ.

Interpreting this, it seems that the model performs poorly as a predictor for die exact power used at some timepoint as the RMSE is rather large (think of the maximum power drawn being about 250W). However, in the context of carbon aware scheduling, this should not be too big of an issue as the time frames for carbon-emissions are orders of magnitudes larger (electricitymaps has a resolution of 1 hour for each intenstiy of carbon

emissions). The high error likely comes from the high variance during the training phases which is not captured in the model.

The total energy predicted by the model is very close to the actual real life experiment, this should mean that the total carbon calculated on the model should also be close to the carbon emitted by the real program.

4.2 Choosing an implementation approach

Now that an improvement on the job model has been made, the question, on how to evaluate the implications of said model, remains.

4.2.1 Carbon-aware scheduling via a Slurm plugin

My first idea was to use a non-simulation approach. The HPI's Data Lab[7] runs a *Slurm* cluster and also has some nodes with power measurement infrastructure included. Slurm is an "open source, fault-tolerant, and highly scalable cluster management and job scheduling system for large and small Linux clusters"[8] The job scheduling part is important here, it also supports a plugin infrastructure that includes scheduling plugins. One of the highlighted papers[o] in the related work section specifically used Slurm for its carbon-aware scheduler implementation and thus seemed like a good starting point for my own work.

Installing Slurm locally For my purposes, a local installation would suffice as I would not need to run heavy workloads but instead just the scheduling part of Slurm. While there is a Slurm `apt get` package for my Ubuntu version, this would not work as any plugins to be included during the Slurm compilation, meaning I would have to do the same.

Slurm's documentation provides some guidelines on how to install Slurm, which I followed. I tried cloning the main branch, but I got stuck during the compilation process. However, using the predefined released versions worked.

Installing `munge`[9] is also necessary, which is used for authentication in Slurm.

One problem arose as I tried to start the `Slurmd`- and `Slurmctld` services. The first one is the worker service that would later execute jobs submitted to Slurm. The latter is the main controller that, for example, schedules jobs on workers. While the command to start them would not fail, upon node inspection via Slurm's `scontrol` command, it would show that all nodes are `DOWN` instantly. | Dealing with Slurm's problems usually leads to inspecting its logs, in my case the logs showed the following:

Listing 4.5: Slurm error logs

```
$ less config.log

error: Couldn't find the specified plugin name for cgroup/v2
    looking at all files
```

---

[7]https://hpi.de/forschung/infrastruktur/hpi-data-engineering-lab.html
[8]https://Slurm.schedmd.com/overview.html
[9]https://github.com/dun/munge/wiki/Installation-Guide

```
error: cannot find cgroup plugin for cgroup/v2
error: cannot create cgroup context for cgroup/v2
error: Unable to initialize cgroup plugin
error: Slurmd initialization failed
```

Slurm uses Linux' cgroup feature to manage the submitted job's hardware ressources. The log hints at some problem related to Slurm's usage of it. The solution was this was to provide Slurm's `cgroup.conf` file. In my use-case of getting Slurm to simply start, this did not need to be very sophisticated so I just used an off-the-shelf (off-the-stackoverflow[10]) configuration file.

Running `scontrol` again, I was finally able to see idling nodes, meaning that Slurm was successfully installed form source:

Listing 4.6: Slurm running

```
$ scontrol
scontrol: update NodeName=vincent-Laptop STATE=RESUME
```

Creating a scheduler plugin   The Slurm documentation provides a short guide on how to add a plugin to Slurm.[11] As a start, I simply copied Slurm's default scheduler (which is also a plugin) to to the specified directory under a new name, and addings that new name to Slurms build files. It was then was time to recompile Slurm. Now however, during the recommended `autoreconf` step, an error occured:

Listing 4.7: Plugin recompilation errors

```
$ autoreconf
auxdir/x_ac_sview.m4:35: warning: macro 'AM_PATH_GLIB_2_0'
    not found in library
configure:25140: error: possibly undefined macro: AM_PATH_GLIB_2_0
      If this token and others are legitimate,
      please use m4_pattern_allow.
      See the Autoconf documentation.
autoreconf: error: /usr/bin/autoconf failed with exit status: 1
```

The solution, while not very obvious, was to install the `libgtk2.0-dev` library.[12] I then added a simple logging which then showed up in Slurm's log files too.

Adding more logic to the scheduler plugin   One very helpful step for developing inside Slurm is to enable the debugging flags. This must be decided before compilation by using the `--enable-developer` and `--disable-optimizations` flags during the `/configure` step. With that, debug symbols are added to the outgoing binaries. As I was using vscode, I could then attach its debugger to the running Slurm thread with full functionality.

---

[10]https://stackoverflow.com/a/74211989
[11]https://Slurm.schedmd.com/add.html
[12]https://stackoverflow.com/questions/7805815/autoconf-error-on-ubuntu-11-04

The code of the plugin runs in its own thread and there is no sandboxing or similar around it. Thus there are seemingly no limitation on what can be done inside the plugin. For testing, I read out information on the incoming jobs such as set constraints or the user supplied comments. Terminating the jobs was also possible inside the plugin.

Problems of a scheduler plugin   One big problem manifested in that not all jobs "showed up" inside the plugin's job queue. If I would submit 6 jobs, via Slurm's `squeue` command, only a part such as the last 3 could be logged inside the plugin. A possible explaination for this could be Slurms scheduler architecture: while there is a scheduler plugin, there also is a scheduler inside Slurm's main loop. That main scheduler loop also uses the same job queue as the plugin.

To hack around this, I tried disabling Slurm's main scheduling loop by setting `sched_interval=-1` inside the Slurm configuration file. While this had the effect of being able to access all incoming jobs inside the plugin, it also had the side-effect of disabling all logic concerning starting the jobs. So by choosing this route, the plugin would apparently also need to re-implement alot of extra logic, which conventionally would be not be put inside the scheduler plugin.

I also looked into whether there were any API hooks that are exposed to the plugin. Up until Slurm version 20.11, scheduler plugins had callbacks such as when jobs were submitted. There also was support for "passive" scheduler that would get invoked when determined by Slurm. The version I tested however, 23.11, removed all such functionality and documentation. All plugins are implemented via threads that only have callbacks on when they are started and stopped.

Thus, since there was no apparent way of getting around this scheduler race condition between the plugin and the main loop. The scheduler approach as a whole was dropped. While I would not say that a plugin approach is impossible, the effort to implement one from scratch subjectivly seems very high. The public documentation for developing on Slurm is scarce. There is a mailing list that can be searched, but it looks to be mostly aimed for administrating Slurm and not developing it.

Other avenues that could be explored are Slurm's Lua plugins. There is also a *Slurm simulator*[13] which could potentially be used for carbon-aware scheduling simulation, but that I did not look into much for reasons of little documentation and seeming lack of continued support.

4.2.2 Using a Simulation approach

Thankfully, just at that time, a new paper [0] was released. They made a prototype testbed for simulating job scheduling on cloud providers. These Jobs could be executed on spot instances (cheap VMs that seek to increase cloud utilization), on-demand instances (short-notices VMs that are thus more expensive) or pre bought VMs (medium cost, but may be wasted), the paper then discussed balancing carbon- and dollar costs. They included a small notion notion of hardwre requirements in the form of required CPUs per job, but that was only used to scale the cost; all hardware requirements were abstracted away in the form of the cloud always having computing ressources available.

---

[13]https://hpckp.org/articles/how-to-use-the-Slurm-simulator-as-a-development-and-testing-environment/
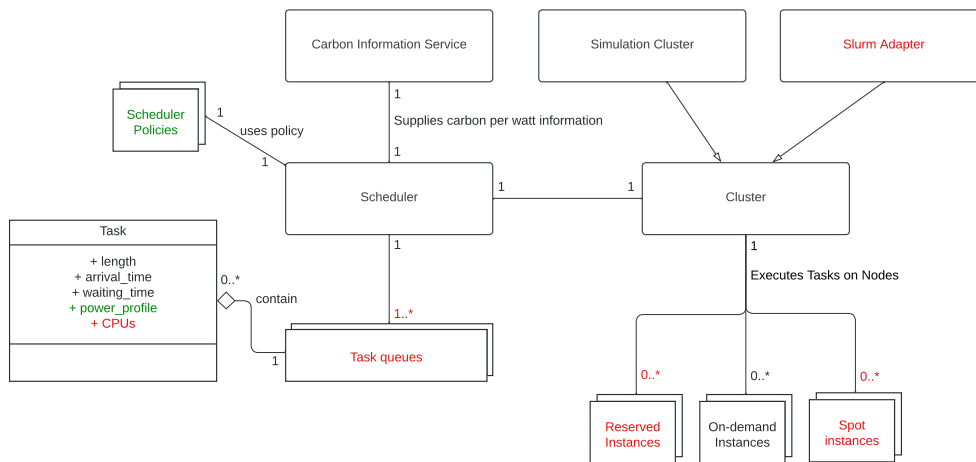
Figure 4.10: Class Diagram of GAIA, red indicates removal or reduction, green indicates additions

The important part is that they also included an implementation of some schedulers used in the highlighted related works. Among that an implementation for WaitAWhile[**wiesner_lets_2021**]. This meant that I could add the improved job model to that exisiting testbed and have something to compare against aswell.

Description of the GAIA simulator   I would first like to describe the existing testbed in detail to make it clear which part is my work and which is not. A class diagram is provided in 4.10 which is heavily inspired by the existing architecture diagram in the original paper.

The main part of GAIA is the scheduler. At program start, it takes parameters that determine the scheduling, such as whether tasks can be interrupted, how to use the carbon information (e.g. use a perfect-information / oracle approach or to use a running average), and how to balance the dollar cost for scheduling. The latter I removed for simplicity, which is marked in the figure via the red color of the reserved and spot instances. In my case of carbon-aware scheduling, I did not need that feature.

In the original implementation, the scheduler had multiple queues of tasks. The paper presented an approach of a short queue (tasks under 2 hours) and long tasks (all other), short tasks would get scheduled on spot instances. Again, as I already removed the spot instance, feature, I did not need the queue multiplicity and it was removed.

The tasks queues are based on historical traces. GAIA provided multiple traces that are described in the paper. To those I added a trace of the HPI's Data Lab, which will be analysed in section.

Tasks have a predetermined length (as saved in the trace), and they also hold some data that is used for scheduling such as their arrival time in the system, and how long they should wait until execution. Some properties such as required CPUs were removed. My contribution of the phases-and-power model was added to the tasks.

I should probably give an overview of which parameters are supported, so I have that terminology later

Link this

The Scheduler policies are also marked green, as I added scheduler policies that could use this new model. Specifically, I added a (non-) checkpoint & resume scheduler that works on oracle carbon prediction, this will be further explained in the latter sections.

Scheduled Tasks are submitted to a cluster. In my case, this is a simulated, already implemented, cluster that simply logs when each task is entered and finished. In the original paper, they also used an open source adapter that would submit the tasks to an actual Slurm cluster. While this approach could have been used, I decided against it on the basis of not adding further complexity. Thus I also removed the Slurm adapter from my implementation.

4.3 Implementing simulation-schedulers using the new model

I would first like to summarize assumption that GAIA makes on the problem of carbon aware scheduling:

1. job lengths are known

2. all considered jobs are batch jobs and can thus be shifted temporally based on user deadlines

3. carbon information is provided for near future time spans, no error is considered

4. there are no hardware limitations or considerations, all jobs are executed in an isolated manner

5. jobs have a constant power draw and can be checkpointed & resumed for free

Especially the last point will be modified going further. As shown in section 4.1, jobs now have a predefined, variable power draw according to the defined phases. Resuming a job also carries an additional startup phase with it.

4.3.1 Modifying the existing jobs to use the new model

The first step to be taken was to add the described model to the jobs as outlined in figure 4.10. So far, jobs were generated from `csv`-formatted traces, one example being provided in listing 4.8.

Listing 4.8: Excerpt from the Alibaba-PAI trace

```
arrival_time,    length,      cpus
0.0,             6302.0,      1
68.0,            1000.0,      1
463.0,           1570.0,      3
838.0,           23549.0,     1
```

In the original GAIA implementation, jobs have a `arrival_time`, which signify when the job should be added to the simulation in seconds. The `length` of a job similarly encodes the seconds a job needs to fully execute. The `cpu` column was not interesting for my work, as previously discussed.

The chosen way of supplying the model information was to add two new columns to the trace files, which would entail the type of job and a column for arguments. As of now, the following types are supported: `constant`, `mocked-constant-from-phases`, `phases`, and `ml`. The first two `constant` types are for backward-compatibility with GAIA, and would be used in the evaluation later.

Type `phases` is the main way of creating a job with phases such as the one used in the experiment. The supplied argument in that case would entail a python readable `dict`, essentially a `JSON`-like definition of the model as described in listing 4.4. As this was just a string, I would then use Python's `eval()` to read it back into a python object. As an example, a simplified `roberta.py`, the job that was measured in section 4.1.1, could look like the code in listing 4.9

Check how and if I should visualize this

Listing 4.9: Simplified definition for a job similar to the experiment

```
{
    'startup': [
        {'name': 'Start', 'duration': 5.34, 'power': 59.9},
        {'name': 'Finish Imports', 'duration': 12.36, 'power': 53.77},
        {'name': 'Data loaded', 'duration': 5.75, 'power': 63.17},
    ],
    'work': [
        {'name': 'Train', 'duration': 8.17, 'power': 221.93},
        {'name': 'Evaluate', 'duration': 1.54, 'power': 134.0},
        {'name': 'Save', 'duration': 2.72, 'power': 105.1,
            'is_checkpoint': True},
    ] * 5
}
```

In order to use this model definition and read out the power of a job at a given time, a function was crated that essentially traverses all phases in order, keeping track of the time, and returning the power of the phase when the requested time is reached. This was also used to create figure 4.9.

A generalizing helper type is `ml`, which takes a dictionary of parameters and converts that to model parameters for the `phases` type. A similar job as to the one above would be created with the following:

Listing 4.10: Generic model definition for machine learning jobs

```
{
    'start_duration': 23.45
    'start_power': 60
    'training_duration': 8.17
    'training_power': 221.93
    'evaluate_duration': 1.54
    'evaluate_power': 63.17
    'save_duration': 2.72
    'save_power': 105.1
```

```
        'epochs': 5
}
```

4.3.2 Uninterrupted oracle scheduling

There already was an existing version of this scheduling approach which assumed constant power and that the carbon trace would be fully known ("oracle"). Jobs would not be able to checkpoint & resume in this version. The algorithm for which is pseudocoded in listing 4.11.

Listing 4.11: Pseudocode for the original non-interrupt oracle scheduler

```
1  function schedule_job_no_checkpointing_resuming(job):
2      possible_starts = []
3      for every possible starttime until deadline:
4          calculate carbon_emissions_of_job at starttime
5          add carbon_emission to possible_starts
6
7      return starttime with least carbon emissions
8
9  function carbon_emissions_of_job(job, carbon_trace):
10     sum_of_emissions = 0
11
12     for each second of job:
13         sum_of_emissions += carbon_trace at timepoint * constant_watt
14
15     return sum_of_emissions
```

In order to adjust this to the new model where power is a function of time, only line 13 needed to be changed. Thus, I implemented a python function whose input is the model parameters (see listing **??**), and which would return the power at a specified time. Evaluating this scheduling approach will take place in section 4.4, after another scheduling algorithm is introduced.

4.3.3 Checkpoint & resume scheduling for heterogeneous jobs

Under the constant-power, no startup-overhead assumption of the already existing implementation, the algorithm for this scheduler worked like the following:

- order all time slots until the job deadline by their emissions ascending
- execute the job on those time slots until done

This would minimize the carbon emissions, as only the best time slots would be used, but would also create unrealistic schedules sometimes. For example, in figure 4.11, if a job's deadline is in the distant future, due to the diurnal nature of the electric grid, the job would be scheduled on the "peaks" of each day. Sometimes this would lead to a job
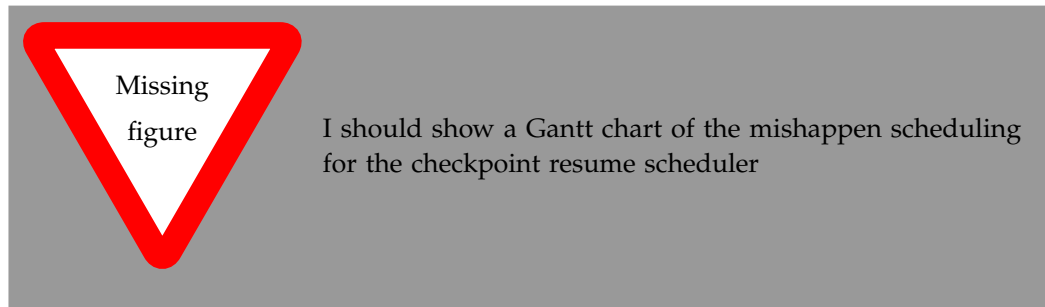
Figure 4.11: Problems in the checkpoint & resume scheduling under the previous assumptions

being simulated as being executed for very short timeframes at a time. As shown in the power measurement chapter, this kind of scheduling would create a lot of overhead from starting so many times.

In order to implement a scheduler for the improved job model, I chose to use *linear programming* (also: LP). In a nutshell, LP is an optimization method, that given linear equations and constraints, finds a set of variables (or a vector) that would minimize (or maximize) an optimization goal. The reason for choosing this approach over, for example coming up with a "standard" algorithm, was that I had never used LP before and that due to the "inherent optimization", the burden of proof for the correctness would be lower.

Translating this to the context of carbon-aware scheduling, the resulting vector would decode when a job should be executed, the optimization goal would be to minimize the emitted carbon. A constraint for example could be that all time slots being executed should add up to the job length. The big challenge is then to model all of this in the form of mathematical equations, which will be most part of this section's remainder.

Personal experience with linear programming   Linear programming is its own programming paradigm. Unlike, for example, imperative programming, where each instruction would be coded explicitly, enabling classic debugging and such, in LP, a mathematical model would be written which is then solved by a *solver*. Different implementations for these solvers exist, but atleast in my case, the result output by a solver would either be an error, or the result set. As the solver uses the whole model simultaneously, "debugging" individual parts of the model is not possible outside removing them from the overall model.

Thus, an iterative approach to LP proved useful. I would encode some part of my overall problem into the model, solve it, and immediately plot the variables of the result set and check them visually. The visual check is very important. Many times the solver would solve the problem "so well" that jobs would get scheduled in a way that the emitted carbon is minimized, but the jobs would be executed in edge cases that I did not intend, but that are possible under the model, examples of this will be given in the following parts.

Another part of programming LP is "just knowing the tricks". Many common programming operations, especially ones for control flow, cannot be expressed directly (as they need to be a linear equation). There are some mappings for such operations, but finding out how seems to be harder than in other paradigms, since the LP community

appears to be smaller in comparison and online resources are limited. Some "tricks" will be highlighted in the latter parts as well.

Modelling carbon-aware scheduling in a linear program   In this part, I would like to preset the steps taken to model the scheduler as an LP problem, highlight some implementation details and visualizing the results of each step. I used python's PuLP library. It allows creating LP models to standard file types and also helps in calling external solvers as well as querying the results.

Executing the job   Firstly, as the job has a certain length and a set deadline, I chose to use an array of time slot-variables as my result set. Each such variable would be a boolean signifying whether the job would be executed at that time. For the first constraint, the sum of all boolean variables (which are represented as 0 and 1) should add up to the job length, effectively executing the job for length-many time slots. The necessary objective function is to be defined as each time slot-being-executed multiplied by the carbon-per-watt at that time slot.

As an example, the code for this is shown in listing 4.12.

Listing 4.12: LP Implementation for basic scheduling

```
1  prob = LpProblem("CarbonAwareScheduling", pulp.LpMinimize)
2  work = LpVariable.dicts("work", (t for t in range(DEADLINE)), cat="Binary")
3
4  prob += lpSum([work[t] * carbon_cost_at_time[t] for t in range(DEADLINE)])
5  prob += lpSum(work[t] for t in range(DEADLINE)) == WORK_LENGTH
6
7  solver = pulp.Gurobi_CMD(timeLimit=timelimit)
8  prob.solve(solver)
```

The first line creates an LP problem and defines the optimization goal to be a minimizing one. Then, a variable "work" is defined as being DEADLINE-many (in this case 300) integer-indexed boolean variables. These will be modeled as the time slots. Line 4 defines the optimization goal; each time slot will be multiplied by the carbon emitted there. As one factor is a boolean, this will only increase the sum if the time slot is scheduled. The last two lines start the solving library. PuLP offers an open source solver by default, but during development this proved to be very slow and also did not offer features such as time limits and retrieving intermediate results. I thus chose the *Gurobi* solver, a commercial solver that also offers academic licenses. That one supported the previously lamented features and increased development time by a lot.

The running example will be a deadline of 300 time slots, the job has a startup phase of 20 units and has 100 work units. The above code leads to a result set that is visualized in figure 4.12, which on the bottom part shows the carbon emissions at each time slot and the upper graph shows the chosen time slots. Looking at the figure, the results are not too surprising: the chosen time slots are just the points where emissions are lowest, essentially being equal to the result of the WaitAWhile-Algorithm.
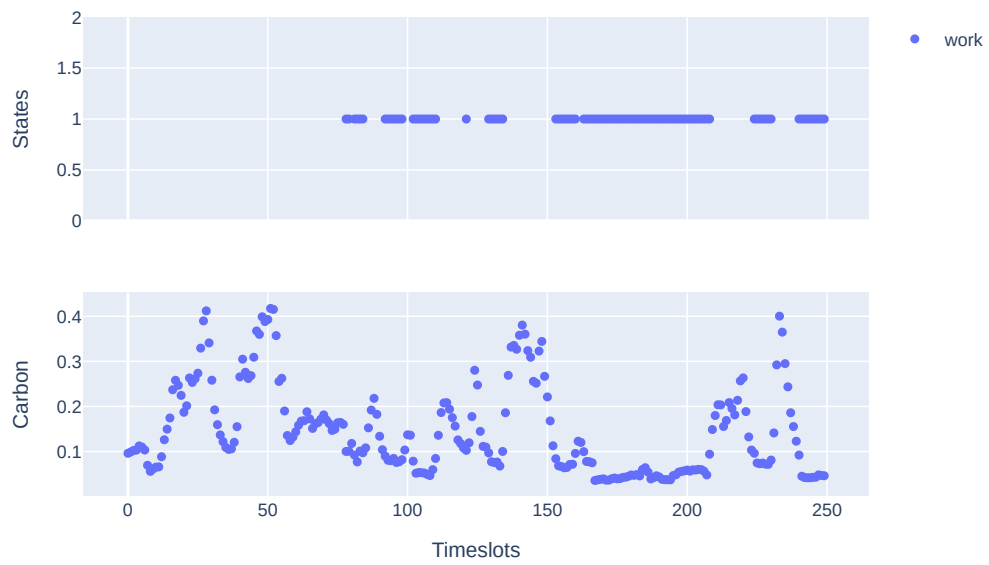
Figure 4.12: Visualizing the result set of executing the job for its length

Adding overhead via startup phases   In order to add a cost to starting a job, the code following in listing 4.13 is complemented, some parts are excluded for brevity.

Listing 4.13: LP Implementation for overhead

```
1  for t in range(DEADLINE - 1):
2      prob += startup_finished[t] >= work[t + 1] - work[t]
3      prob += startup_finished[t] + work[t] <= 1
4      prob += starting[t] + work[t] <= 1
5
6  for i in range(STARTUP_LENGTH - 1, DEADLINE):
7      prob += pulp.lpSum([starting[i - j] for j in range(STARTUP_LENGTH)])
8          >= STARTUP_LENGTH * startup_finished[i]
```

In this snippet, two extra dictionary-variables are introduced, `startup_finished` and `startup`. For every time slot (line 1), set `startup_finished` to true if and only if there is a 0 to 1 transition along the `work` dictionary. This becomes apparent when looking at the following truth table 4.1. Notice how the numerical booleans help in this case, as negative integers get mapped to 0, or `false` respectively.

$work[t]$	$work[t+1]$	$work[t+1]$ - $work[t]$	$startup\_finished[t]$
0	0	0	0
0	1	1	1
1	0	$max(-1,0) = 0$	0
1	1	0	0

Table 4.1: Truth table for finding when working time slots begin

Line 3 and 4 ensure that "working" time slots and "startup" time slots are mutually exclusive. The last loop defined that if (`* startup_finsihed[i]`) a startup must be finished by some time slot, the previous `STARTUP_LENGTH`-many time slots must be used for starting the job.

At this point, the solver scheduled jobs in a way that would sometimes execute the job at the very first time slots, as no startup could happen before time slot 0, thus minimizing carbon but obviously producing a bogus result. I thus added an extra constraint that work can only be scheduled after atleast the length of the startup phase. The emitted carbon goal is changed to also include these new startup time slot, similarly to the previous listing 4.13. With this step, the result already looks more like a reasonable schedule, as shown in figure 4.13. This time, the optimal schedule includes executing the job in one go. Doing a visual check, the job is also executed on seemingly the lowest carbon intensities.

Adding a notion of progress   So far, the assumption of constant power has been continued. Changing this assumption under the previous other scheduler using the greedy algorithm in section 4.3.2, was relatively easy, as changing the constant expression to python function of the model sufficed. This cannot be reused in LP however, as the problem definition may only include linear equations, which a generic function is not. In
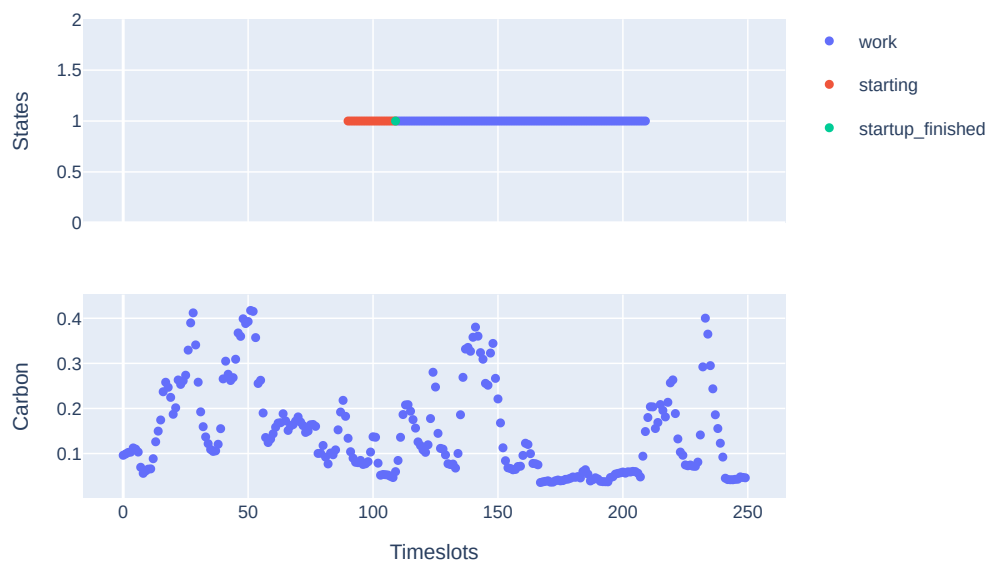
Figure 4.13: LP Scheduling with overhead in form of a startup phase

order to add dynamic power into the linear program, I decided to *linearize* the function, meaning the model needed to be split up into multiple linear approximations.

As the model already is essentially a step function of time to power, each phase being one step, the mapping is inherently pretty close. As such, *a lot* of equations were needed that each express "if the progress in the job is *t*, set power to *model(t)*". For that a notion of progress and time is needed inside the model. The progress inside each startup-phase needs to reset, as that can happen multiple times during the schedule. On the other hand, the progress for the productive work must not be reset between execution blocks.

I added the following code to express this:

Listing 4.14: Progress Variables in LP

```
1   # define "work_time_progressed" and "startup_time_progressed" as
2   # DEADLINE-many integer variables
3
4   M = DEADLINE * 2
5   for t in range(DEADLINE-1):
6       if (t>0):
7           prob += startup_time_progressed[t] >= startup_time_progressed[t-
                1] + 1 - (1 - starting[t]) * M
8           prob += startup_time_progressed[t] <= startup_time_progressed[t-
                1] + 1 + (1 - starting[t]) * M
9       prob += startup_time_progressed[t] <= starting[t] * M
10      prob += work_time_progressed[0] == 0
11      if (t > 0):
12          prob += work_time_progressed[t] == work_time_progressed[t-1] +
                work[t]
```

On a base level, the idea is to count up each progress variables by 1, if a time slot is being determined for work or startup respectively (see line 12 for this).

This snippet also includes an LP "trick", namely the *Big M Method*. In line 4, a constant `M` is defined as "a *large* integer, that cannot otherwise occur in the result set", in this case "large" being twice the amount of time slots but it could also be some other arbitrarily-chosen large number.

Take line 9 as an example: remember that `starting[t]` is either 0 or 1, multiplying this by a large number means the right side is either 0 or "*large*". Constraining a variable to be less that `M` effectively does nothing (is "*relaxed*"), as every value of that variable is less than `M` by definition of `M`. The whole can expression be translated to "if a time slot is not used for starting the job, set the progress to 0, otherwise ignore this constraint", the Big M Method enables a way to add conditional constraints to a model!

While line 9 this defines the `startup_progress` outside the startup phases, line 7 and 8 are needed to increase the progress by exactly 1. Notice how depending on the type of inequality, *M* is either added or subtracted to the equation, a conditional "greater than"-relation is relaxed by setting the constraint to 0.

All in all, there is now a way to keep track of a job's progress inside the model, as shown in figure 4.14's upper graph. Attention should be drawn to the `work_progress` which keeps its value even when time slots are not used for work. The schedule found by
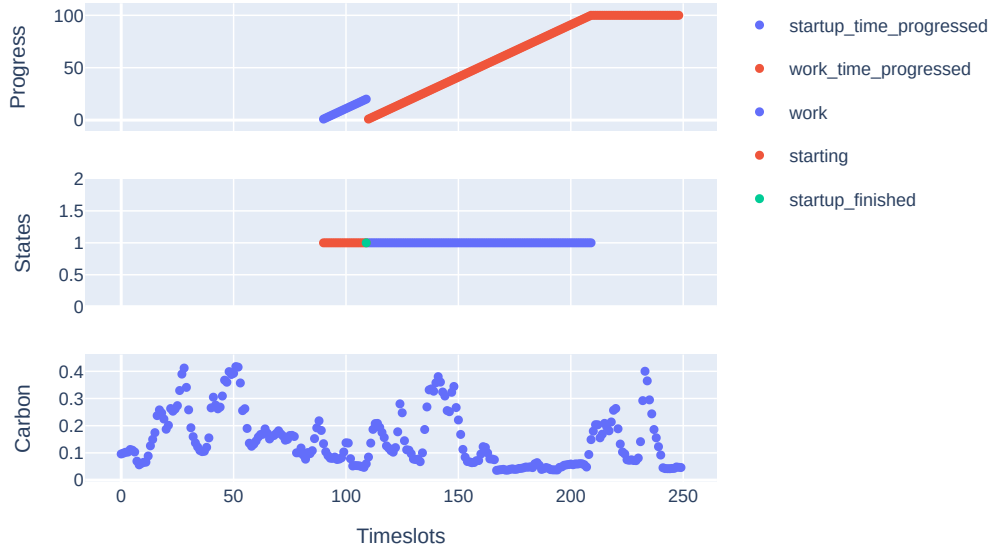
Figure 4.14: The result set now contains the progresses of the startup and work phase

the solver is not different to the previous one which added overhead, as the optimization goal was not changed and the progress indicators have no impact on the scheduling (yet).

Adding dynamic power according to the new model   The goal of this part will be to have an LP variable for each phase, which indicates when the job is in that phase. When such indicators exist, the formula for calculating a schedule's carbon emissions can be changed to the following (4.1):

$$carbonEmitted(t) = \sum_{p \in Phases} isActive(p,t) * powerOfPhase(p) * carbonEmission(t) \quad (4.1)$$

With that goal in mind, we add the pseudocode listed in 4.15 to determine when a phase is active.

Listing 4.15: Phase detection in LP

```
1  # for each phase
2  # let phase_indicator, phase_indicator_upper, phase_indicator_lower be
       DEADLINE-many boolean variables
3
4  # set lower_bound to be the minimum progress this phase can occur in
5  # set upper_bound to be the maximum similarly
```

```
 6
 7  # do the following for each phase
 8  for t in range(DEADLINE):
 9      prob += progress[t] - lower_bound <= M*phase_indicator_lower[t]
10      prob += lower_bound - progress[t] <= M*(1-phase_indicator_lower[t])
11
12      prob += upper_bound - progress[t] <= M*phase_indicator_upper[t]
13      prob += progress[t] - upper_bound <= M*(1-phase_indicator_upper[t])
14
15      prob += phase_variable[t] >= phase_indicator_lower[t] +
                  phase_indicator_upper[t] - 1
16      prob += phase_variable[t] <= phase_indicator_lower[t]
17      prob += phase_variable[t] <= phase_indicator_upper[t]
```

Unwrapping this, two helper variables are added per phase per time slot. A lower variable indicates that the previously established progress is above the threshold for a phase, while the upper variable indicates the opposite. The `phase_variabel` is then "active" where these two overlap (line 14 to 17 define a logical "AND").

The constraint of line 8 is only applied if the indicator is `false`. If it is false, the progress at the time slot must be below the lower bound (as negative numbers are equal to 0). Line 9 works on the negated indicator, applying the constraint if it is `true`. If the indicator is `true`, progress must be higher than the lower bound. Combining this, the expression `phase_indicator_lower[t] <=> progress[t] > lower_bound` is added to the model. The upper bound is formulated in the following two lanes similarly.

Using this addition, the schedule now looks like the one shown in figure 4.15. Unlike the previous times, splitting the job up into two parts is now the optimal solution. Attention should be drawn to the circumstance that the high-powered phase (the green one) is scheduled on the lowest carbon emissions while the low-powered one is scheduled on the higher emission time slots.

Issues of the implementation   As of now, checkpointing may happen at any point in the scheduler, as the `work_progress` is never reset. Checkpointing at specific points, such as after specific phases like in the entry ML example in section, will be left for future work.

Another issue is the runtime and hardware requirements for finding a solution. While the upper example of 250 time slots and a job length of 120 were found within minutes on my laptop (a Lenovo T470 with 8GB RAM and an i5-7200U CPU @ 2.50GHz), bigger problem sizes such as 5000 time slots and a length of 800 would barely finish within 30 minutes with a *gap*-value of 98%. As the LP solver computes the problem, the gap value is an indicator of how close the solver is to finding the optimal solution, the optimal solution is found when the gap is at 0%.

Solvers are able to take advantage of multiple CPU cores, but in my case, the issue was probably a lack of memory. Glancing into the system monitor utility on Ubuntu would show that all 8 GB are in use and that swap space is being used a lot.
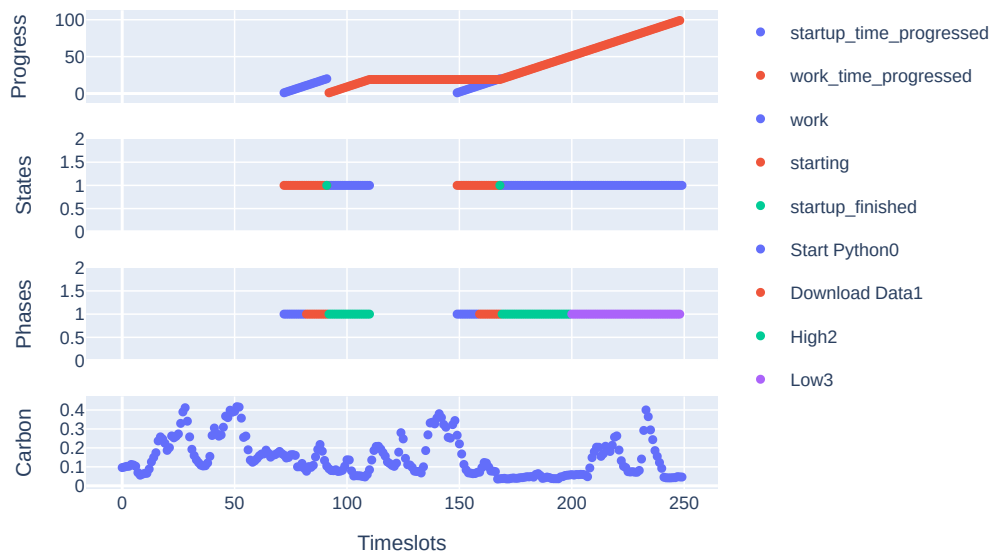
Figure 4.15: The final scheduling including dynamic power via phases

Decreasing the Problem Size   In the previously shown Figures, each carbon-emission data point would correspond to one time slot, which in turn corresponds to one unit of time in the job. Going by the resolution of the carbon-emissions, each data point describes the emissions for one hour. In the original `GAIA` implementation, job lengths are given in seconds, however. The example workload used for measuring in Section 4.1.1 also showed that timescales in seconds are useful.

Using a 1:1 mapping between those would result in 3600 (60s * 60) time slots for each hour, resulting in very large problem sizes in turn needing long execution times and high amounts of memory.

In order to improve on the issues mentioned above, the following optimization is made: by calculating the *greatest common divisor (gcd)* between all phase durations and the time resolution of the carbon-emissions (3600), all durations can be scaled down by the `gcd`. Each time slot in the model would then represent gcd-many seconds.

The effect of this optimization heavily depends on the input phases. If there are very short phases, the `gcd` would likewise be low and problem size would not be decreased much.

> I could perhaps do a tiny evaluation on runtime and hardware usage, doing a cute lil graph with x being problem time, z being job length, y being runtime / memory usage

4.4 Evaluating carbon-aware scheduling with the new job model

In order to evaluate the carbon savings made possible by the previously established dynamic power model, the following approach is proposed: As the already existing job traces hold no information regarding the power or their phases, some test cases will be presented and used for the models. In a rather explorative process, we use the following parameters and run the simulation on all possible permutations of them. This is done using the `generate_evaluation_jobs.sh` script, but a high-level view of the used parameters is given thus:

1. Checkpoint & restore scheduling or non-interrupted scheduling

2. Different phase configurations, in general, we assume there to be a (long or short) high-powered phase and a (long or short) low-powered phase periodically up to the given job length.

3. Startup-lengths between none and 5 minutes

4. Startup power levels between 100 W and 300 W

5. Different deadlines picked from 4 hours, 12 hours, and 1 day

6. Different Job lengths, from 1 hour to 3 hours.

Another dimension will be comparing these scenarios against having no information on phases, instead only having an averaged constant wattage of the otherwise existing phases. This would represent the previous `GAIA` implementation, where jobs had a constant amount of power at all points in time.

4.4.1 Running the Evaluation on a Cluster

As previously discussed in Section 4.3.3, calculating the checkpoint & resume scheduling tends to have high runtime and memory requirements. For that reason, the simulation was executed on the *SCORE Lab*, standing for "scientific compute resources", of HPI.

After requesting and gaining access, `rsync` was used to transfer the simulation to the cluster. Slurm could then be used to schedule all experiments individually (that were generated using the mentioned `generate_all_jobs.sh` script), which would parallelize the evaluation, leading to faster results.

One problem arose in the licensing of the used *Gurobi* solver. Under the used academic license, only 2 *"sessions"* are allowed simultaneously. A session is defined via the hostname of the executing machine, which is communicated to the solver's licensing servers live. As such, scheduling each experiment by itself lead to many sessions being started, as Slurm would distribute the jobs on the available nodes. While there is some leeway in the amount of sessions, experiments would crash beyond the 5th instance as the solver would not start.

We work under this restriction by distributing the experiments across two workers (via a script called `evalute_dynamic_power.sh`); as each experiment has an index, one worker executes the even numbered jobs and the other executes the odd ones. Using the even-odd strategy results in both workers having about the same amount of work.

The workers in this case are python docker containers that were created with the help SCORE Lab's online knowledge base. The command for launching one example worker, in this case the one for even jobs, is given in Listing 4.16.

Listing 4.16: Executing the Evaluation inside the SCORE Lab's Slurm environment

```
1  sbatch -A polze -p magic \
2      --container-image=python \
3      --container-name=test \
4      --container-writable \
5      --mem=128G \
6      --cpus-per-task=128 \
7      --time=24:0:0 \
8      --output=slurmlogs/output_%j.txt \
9      --error=slurmlogs/error_%j.txt \
10     --container-mounts=/hpi/fs00/home/vincent.opitz:/home/vincent.opitz \
11     --container-workdir=/home/vincent.opitz/master-thesis/GAIA \
12     run_all_even_jobs.sh
```

Now the simulation can be run with 128 GB RAM as specified in line 5. The `-p magic` parameter results in us using a compute node. Line 3, `--container-writable`, means that the container will be reused if called again under the same name, this lets us conduct set up using (`pip install`).

4.4.2 Results for uninterrupted scheduling

4.4.3 Results for checkpoint & resume scheduling

5 Results

- here we would try to show off the difference between power-and-phase-oblivious scheduling and my new implementation which can make use of that

-

6 Discussion

welche schlüsse können wir aus den ergebnissen ziehen?

7 Future Work

lol

Bibliography

[0] Walid A. Hanafy, Roozbeh Bostandoost, Noman Bashir, David Irwin, Mohammad Hajiesmaili, and Prashant Shenoy. "The War of the Efficiencies: Understanding the Tension between Carbon and Energy Optimization". en. In: *Proceedings of the 2nd Workshop on Sustainable Computer Systems*. Boston MA USA: ACM, July 2023, pages 1–7. ISBN: 9798400702426. DOI: 10.1145/3604930.3605709 (cited on page 10).

[0] Walid A. Hanafy, Qianlin Liang, Noman Bashir, Abel Souza, David Irwin, and Prashant Shenoy. "Going Green for Less Green: Optimizing the Cost of Reducing Cloud Carbon Emissions". In: *Proceedings of the 29th ACM International Conference on Architectural Support for Programming Languages and Operating Systems, Volume 3*. Volume 3. ASPLOS '24. New York, NY, USA: Association for Computing Machinery, Apr. 2024, pages 479–496. ISBN: 9798400703867. DOI: 10.1145/3620666.3651374 (cited on page 26).

[1] Andrew S. Tanenbaum and Albert Woodhull. *Operating systems: design and implementation: [the MINIX book]*. en. 3. ed. The MINIX book. Upper Saddle River, NJ: Pearson Prentice Hall, 2006. ISBN: 978-0-13-142938-3 978-0-13-505376-8 978-0-13-142987-1 (cited on page 7).

[0] Íñigo Goiri, Kien Le, Md. E. Haque, Ryan Beauchea, Thu D. Nguyen, Jordi Guitart, Jordi Torres, and Ricardo Bianchini. "GreenSlot: scheduling energy consumption in green datacenters". en. In: *Proceedings of 2011 International Conference for High Performance Computing, Networking, Storage and Analysis*. Seattle Washington: ACM, Nov. 2011, pages 1–11. ISBN: 978-1-4503-0771-0. DOI: 10.1145/2063384.2063411 (cited on pages 10, 24).

Eidesstattliche Erklärung

Hiermit versichere ich, dass meine Arbeit zur Erlangung des Grades "Master of Science" der Digital-Engineering-Fakultät der Universität Potsdam mit dem Titel "A parameterized test bed for carbon aware job scheduling" ("Ein parametrisierbares Testbed für kohlenstoffbewusste Jobplanung") selbständig verfasst wurde und dass keine anderen Quellen und Hilfsmittel als die angegebenen benutzt wurden. Diese Aussage trifft auch für alle Implementierungen und Dokumentationen im Rahmen dieses Projektes zu.

Potsdam, den 29. September 2024

_____
(Vincent Opitz)