Exploring the Energy Consumption of Highly Parallel Software on Windows

Mads Hjuler Kusk*, Jeppe Jon Holt*
and Jamie Baldwin Pedersen*
Department of Computer Science, Aalborg University, Denmark
*{mkusk18, jholt18, jjbp18}@student.aau.dk

April 25, 2023

Abstract

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

1 Introduction

In recent years there has been rapid growth in Information and Communications Technology (ICT) which has led to an increase in energy consumption. Furthermore, it is expected that the rapid growth of ICT will continue in the future. [1, 2] As the use of ICT rises the demand for computational power rises as well, therefore energy efficiency has or perhaps should become more of a concern for companies and software developers alike.

In this paper, we investigate energy consumption of various benchmarks on Windows 11, comparing the efficiency and tradeoffs between sequential and parallel execution. Our experiments involve two Device Under Tests (DUTs): an Intel Coffee Lake CPU with a traditional P-core setup and an Intel Raptor Lake CPU with P- and E-cores. We analyze the impact of Asymmetric Multicore Processors (AMPs) on parallel execution compared to traditional Symmetric MultiCore Processors. We conduct three experiments, each building upon the previous one. The first experiment focuses on selecting the C++ compiler for the benchmarks in the second experiment. The second experiment aims to identify the best measuring instruments for our use case, using only C++ benchmarks to avoid noise from e.g. a garbage collector or just-in-time compilation. In the third experiment, we expand the scope beyond C++ benchmarks, as the preferred measuring instruments have been chosen, and focus on analyzing energy consumption behavior when utilizing different numbers of cores. The following research questions are formulated to assist with the process:

- **RQ1**: How does the C++ compiler used to compile the benchmarks impact the energy consumption?

- **RQ2**: What are the advantages and drawbacks of the different types of measuring instruments in terms of accuracy, ease of use, and availability?

- **RQ3**: What effect does parallelism have on the energy consumption of the benchmarks?

- **RQ4**: What effect do P- and E-cores have on the parallel execution of a process, compared to a traditional desktop CPU?

To answer these research questions a command line framework is created to assist with running a series of different experiments.

In Section **2** the related work which lay the foundation for our work is covered, including our previous work. This is followed by Section **3** which includes the necessary background information about e.g. CPUs and schedulers. Thereafter in Section **4** our experimental setup is presented. In **??** the results are presented whereafter they are discussed in Section **6** and finally a conclusion is made in Section **7**.

2 Related Work

This section provides an overview of related work in energy consumption, parallel software, compilers, and asymmetric multicore processors. It also builds upon our previous work in comparing measuring instruments.

2.1 Previous Work

In our previous work *"A Comparison Study of Measuring Instruments"*[3] where different measuring instruments were compared to explore whether a viable software-based measuring instrument was available for Windows. It was found that Intel Power Gadget (IPG) and Libre Hardware Monitor (LHM) on Windows have similar correlation to hardware-based measuring instruments as Intel's Running Average Power Limit (RAPL) has on Linux. The remainder of this chapter builds upon the related work chapter in [3] and as such will not be repeated, however, it will be expanded upon.

2.2 Parallel Software

Amdahl's law describes the maximum potential speedup that can be achieved through the parallelization of an algorithm based on the proportion of the algorithm that can be parallelized and the number of cores used.[4] In [5] Amdahl's law, was extended to also estimate the energy consumption. Then three different many-core designs were compared with different amounts of cores using the extended Amdahl's law. The comparison showed that a CPU can lose its energy efficiency as the number of cores increases and it was argued that knowing how parallelizable a program is before execution allows for calculating the optimal number of active cores for maximizing performance and energy consumption. However, the comparison was based on an analytical model and not real measurements.[5]

[6] compares the observed speedup of computing Laplace equations with one, two, and four cores, with estimates given by Amdahl's law and Gustafson's law. Gustafson's law evaluates the speedup of a parallel program based on the size of the problem and the number of cores. Unlike Amdahl's law which assumes a fixed problem size and a fixed proportion of the program that can be parallelized, Gustafson's law takes into account that larger problems can be solved when more cores are available and that the parallelization of a program can scale with the problem size. Comparing the observed speedup and the estimates it was clear that Gustafson's law is more optimistic than Amdahl's law, however, both estimate smaller speedups than the observed speedup on two and four cores. [6]

In [7], three different thread management constructs from Java were explored and analyzed. It was found that the energy consumption increased with the number of threads used. However, after a certain point energy consumption would start to decrease as the number of threads approached the number of cores in the CPU. The peak of the energy consumption was application-dependent. The study also found that in eight out of nine benchmarks, there was a decrease in execution time when transitioning from sequential execution on one thread to using multiple threads. It should be noted, though, that four of their benchmarks were embarrassingly parallel, while only one was embarrassingly serial. Moreover, decreased execution time does not necessarily imply decreased energy consumption, because in six out of nine benchmarks, the lowest energy consumption was found in the sequential version. Furthermore, the study used Energy-Delay-Product (EDP), the product of energy consumption and execution time and found that in general parallel execution was favorable. However,increasing the number of threads was not an improvement for all of the benchmarks.[7]

In [8], found that a larger number of cores in the execution pool results in a lower running time and energy consumption, and conclude that parallelism can help reduce energy consumption for genetic algorithms. When considering parallel software, it also found asynchronous implementations to use less energy, because there are no idle cores waiting for data in asynchronous implementations, while in synchronous implementations cores can be blocked during runtime, while waiting for responses from other cores.

In [9], four different language constructs which can be used to implement parallelism in C# are tested. Furthermore, they uses varying amounts of threads and a sample of micro- and macro-benchmarks. They found that workload size has a large influence on run time and energy efficiency and that a certain limit must be reached before improvements can be observed when changing a sequential program into a parallel one. Additionally, it was found that execution time and energy consumption of parallel benchmarks do not always correlate. Comparing micro- and macro-benchmarks the findings remain consistent, although the impact becomes low for the macrobenchmarks due to an overall larger energy consumption. Furthermore, it has included some recommendations, which are considered in our setup:[9]

- Static clock: Make the clock rate of the CPU as static as possible

- Turn off CPU turbo boost

- Turn off hyperthreading

2.3 Compilers

In [10], several C++ compilers were compared, with the goal of finding a balance between performance and energy efficiency. The different coding styles introduced examined the impact of splitting CPU and IO operations and interrupting CPU-intensive instructions with sleep statements. The C++ compilers used in [10] included MinGW GCC, Cygwin GCC, Borland C++, and Visual C++, and the energy measurements were taken using Windows Perfor-

mance Analyzer (WPA). The compilers were used with their default settings, and no optimizations options were used. They found that when choosing a compiler and coding style, energy reduction depended on the specification of the target machine and the individual application. Based on the benchmark used, which involved an election sort algorithm, the lowest execution time was achieved with the Borland compiler, and the lowest energy consumption was observed with the Visual C++ compiler. When considering the coding styles, the study found that separating IO and CPU operations and interrupting CPU-intensive instructions with sleep statements both decreased energy consumption.

2.4 Asymmetric Multicore Processors

AMPs are CPUs in which not all cores are treated equally. One example of this is the combination of performance cores and efficiency cores, as seen in Intel's Alder Lake and Raptor Lake. Intel's Thread Director (ITD) was introduced alongside Intel's Alder Lake. The purpose of ITD is to assist the operating system in deciding on which cores to run a thread. In [11], support for utilizing ITD in Linux was developed, and some SPEC benchmarks were conducted to analyze the estimated Speedup Factor (SF) from the ITD compared to the observed SF. SF is the relative benefit a thread receives from running on a P-core. The study examined which classes were assigned to different threads in the benchmark and found that 99.9% of class readings were class 0 or 1. Class 0 is for threads that perform similarly on P- and E-cores, while Class 1 is for threads where P-cores are preferred.[12] Furthermore, class 3, which is for threads that are preferred to be on an E-core, was not used. The experiment indicated that the ITD overestimated the SF of using the P-cores for many threads but also underestimated it for some threads. Overall, it was found that the estimated SF had a low correlation coefficient (< 0.1) with the observed values. Furthermore, a performance monitoring counter (PMC) based prediction model was trained. The model outperformed ITD, but it still produced some errors. However, the correlation coefficient was higher at (> 0.8). The study then implemented support for the IDT in different Linux scheduling algorithms and compared the results from using the IDT and the PMC-based model. It found that the PMC-based model provided superior SF predictions compared to ITD.[11] Official support for ITD has since been released.

3 Background

3.1 CPU States

This section provides an overview of CPU-states. The concept of CPU-states is concerned with how a system manages its energy consumption during different operational conditions. The C-states are a crucial aspect of CPU-states, as they dictate the extent to which a system shuts down various components of the CPU to conserve energy. The C0 state represents the normal operation of a computer under load.[13, 14] As the system moves from C0 to C10 [3], progressively more components of the CPU are shut down until, in C10, the CPU is almost inactive. It is important to note that the number of C-states supported may vary depending on the CPU and motherboard in use, in [3] the DUT supported C0 to C10 states.

The C-states can have a large impact on the energy consumption of the benchmarks, especially the idle case as was found in [3].

3.2 Performance and Efficiency cores

For the CPU architecture x86, the core layout has comprised of identical cores. However, the ARM architecture introduced the big.LITTLE layout in 2011[15]. It is an architecture that utilizes two types of cores, a set for maximum energy efficiency and a set for maximum computer performance.[16]. Intel introduced a hybrid architecture in 2021[17] codenamed Alder lake, which is similar to ARM's big.LITTLE architecture. Alder lake also has two types of cores: performance cores (P-cores) and efficiency cores (E-cores). These types of cores are optimized for different tasks, where P-cores are standard CPU cores focusing on maximizing performance. In contrast, the E-cores are designed to maximize performance per watt and are intended to handle smaller non-time critical jobs, such as background services[18].

3.3 CPU Affinity

Affinity is a feature in operating systems(OSs) that enables processes to be bound to specific cores in a multi-core processor. In OSs, jobs and threads are constantly rescheduled for optimal system performance, which means that the same process can be assigned to different cores of the CPU. Processor affinity allows applications to bind or unbind a process to a specific set of cores or range of cores/CPUs. When a process is pinned to a core, the OS ensures it only executes on the assigned core(s) or CPU(s) each time it is scheduled.[19] Processor affinity is particularly useful for scaling performance on multi-core processor architectures that share the same global memory and have local caches referred to as the Uniform memory access architecture. Processor affinity is also useful for out

study, as this allows the framework to assign a single or a set of cores and threads to a process.[19]

When setting the affinity for a process in C#, which the framework was written in, it is done through a bitmask, where each bit represents a CPU core. An example of how it is done in C# can be seen in Listing **1**, where the process is allowed to execute on core #0 and #1.

```
1  void ExecuteWithAffinity(string path)
2  {
3      var process = new Process();
4      process.StartInfo.FileName = path
5      process.Start();
6
7      // Set affinity for the process
8      process.ProcessorAffinity =
9          new IntPtr(0b0000_0011)
10 }
```

Listing 1: An example of how to set affinity for a process in C#

3.4 Scheduling Priority

Scheduling threads on Windows, is done based on each thread's scheduling priority level and the priority class of the process. The priority class can be either `IDLE`, `BELOW NORMAL NORMAL`, `ABOVE NORMAL`, `HIGH` or `REALTIME`, where the default is `NORMAL`. It is noted that `HIGH` priority should be used with care, as other threads in the system will not get any processor time while that process is running. If a process needs `HIGH` priority, it is recommended to raise the priority class temporarily. The `REALTIME` priority class should only be used for applications that "talk" to hardware directly, as this class will interrupt threads managing mouse input, keyboard inputs, etc.[20]

The priority level can be either `IDLE`, `LOWEST`, `BELOW NORMAL`, `NORMAL`, `ABOVE NORMAL`, `HIGHEST` and `TIME CRITICAL`, where the default is `NORMAL`. A typical strategy is to increase the level of the input threads for applications to ensure they are responsive, and to decrease the level for background processes, meaning they can be interrupted as needed.[20]

The scheduling priority is assigned to each thread as a value from zero to 31, where this value is called the base priority. The base priority is decided using both the thread priority level and the priority class, where a table showing the scheduling priority given these two parameter can be found in [20]. When assigning a base priority where both the priority class and thread priority are the default values, e.i. `NORMAL`, the base priority is 8.[20]

```
1  void ExecuteWithPriority(string path)
2  {
3    var process = new Process();
4    process.StartInfo.FileName = path
5    process.Start();
6
7    // Set priority class for process
```

```
8    process.PriorityClass =
9      ProcessPriorityClass.High;
10
11   // Set priority level for threads
12   foreach (var t in process.Threads)
13   {
14     thread.PriorityLevel =
15       ThreadPriorityLevel.Highest;
16   }
17 }
```

Listing 2: An example of how to set priorities for a process in C#

Note when setting priority class and priority level for a process through C#, the priority class is supported for both Windows and Linux, while the priority level is only supported for Windows. An example of how both the priority class and priority level can be set for a process and its threads can be seen in Listing **2**.

3.5 OpenMP

OpenMP (Open Multi-Processing) is a parallel programming API consisting of a set of compiler directives and runtime library routines, with support for multiple OSes and compilers.[21] The directives provide a method to specify parallelism among multiple threads of execution within a single program, while the library provides mechanisms for managing threads and data synchronization. OpenMP allows writing parallel code and taking advantage of multiple processors without having to deal with low-level details.[21]

When executing using OpenMP, the parallel mode used is the Fork-Join Execution Model. This model begins with executing the program with a single thread, called the master thread. This thread is executed serially until parallel regions are encountered, in which case a thread group is created, consisting of the master thread, and additional worker threads. This process is called a fork. After splitting up, each thread will execute until an implicit barrier at the end of the parallel region. When all threads have reached this barrier, only the master thread continues.[21]

```
1  #pragma omp directive-name [
2      clause[ [,] clause]...
3      ]
```

Listing 3: The basic format of OpenMP directive in C/C++

The basic format of using OpenMP can be seen in Listing **3**. By default, the parallel regions are executed using the number of present threads in the system, but this can also be specified using `num_threads(x)`, where x represents the number of threads.[21]

4 Experimental Setup

4.1 Measuring Instruments

This section present the different measuring instruments utilized in our work. The measuring instruments utilized in our previous work will only be briefly introduced, however more detail can be found in [3].

Intel's Running Average Power Limit (RAPL): is often seen in the literature as a software-based measuring instrument.[3] It uses model-specific-registers (MSRs) and Hardware performance counters to calculate how much energy the processor uses. The MSRs RAPL uses include *MSR_PKG_ENERGY_STATUS*, *MSR_DRAM_-ENERGY_STATUS*, *MSR_PP0_ENERGY_STATUS* and *MSR_PP1_ENERGY_STATUS*. RAPL is only directly accessible on Linux and Mac. In [3] we found that RAPL had a high correlation of 0.81 with our ground truth on Linux.[3]

Intel Power Gadget (IPG): is a software tool created by Intel, which can estimate the power of Intel processors. It uses the same hardware counters and MSRs as RAPL[22], therefore it is expected to have similar measurements to RAPL. Which was also found in [3], where we found that IPG on Windows had a high correlation of 0.78 with the ground truth on Windows as well as a high correlation of 0.83 with RAPL on Linux.[3]

Libre Hardware Monitor (LHM): is a fork of Open Hardware Monitor, where the difference is that LHM does not have a UI.[23] Both projects are open source. LHM uses the same hardware counters and MSRs as RAPL and IPG.Therefore, a similar measurement is expected between LHM, IPG and RAPL. We found in [3] that LHM on Windows correlated 0.76 with our ground truth on Windows and a high correlation of 0.85 with IPG.

MN60 AC Current Clamp (Clamp): Serving as our ground truth a setup comprised of an MN60 AC clamp, an Analog Discovery 2 and a Raspberry Pi 4. The MN60 AC clamp is connected to the phase of the wire that goes into the PSU and the Analog Discovery 2 which is used as an oscilloscope. The Analog Discovery 2 is connected to the Raspberry Pi 4. This setup allows us to continuously measure and log our data.[3] The accuracy is reported to be 2%[24].

CloudFree EU smart Plug (Plug): is used, as an alternative lower-priced hardware-based measuring instrument, which also has greater ease of use than the Clamp setup. The accuracy and sampling rate of the plug is unknown.[25]

Scaphandre (SCAP): is described as a monitoring agent that can measure energy consumption.[26] It is designed for Linux where it can use Powercap RAPL, a Linux kernel subsystem that reads data from RAPL. Additionally, SCAP can measure the energy consumption of some virtual machines, specifically Qemu and KVM hypervisors. A kernel driver also exists that allows getting RAPL measurements and using SCAP on Windows[27]. The Windows version of SCAP can report the energy consumption of the power domain PKG using the MSR *MSR_PKG_ENERGY_STATUS*. It can also estimate the energy consumption for individual processes by storing CPU usage statistics alongside the energy counter values and then calculating the ratio of CPU time for each Process ID (PID). Using the calculated ratio it estimates the subset of energy consumption that belong to a specific PID.

4.2 Dynamic Energy Consumption (DEC)

Dynamic Energy Consumption (DEC) was utilized in [3, 28] to enable comparison between the software-based measuring instruments and the hardware-based measuring instruments, where the former measures energy consumption of the CPU only and the latter the entire DUT. DEC was also used in our work. A brief explanation of DEC based on [28] is given:

$$E_D = E_T - (P_S * T_E) \tag{1}$$

In Equation (1) E_D is the DEC, E_T is the total energy consumption of the system, P_S is the energy consumption when the system is idle and T_E is the duration of the program execution. With this equation the energy consumption of the benchmark is isolated. Using DEC requires also measuring the energy consumption on an idle case. [28]

4.3 Statistical Methods

In this sections the statistical method used to analyze our results are presented. This section is based on what was found in [3] and can be referred to for further detail.

Shapiro-Wilk Test: was used to examine if the data followed a normal distribution. We expected or data to not be normally distributed, because that was found to be the case is [3]. Understanding the distribution of the data was essential when choosing subsequent statistical methods.[29]

Mann-Whitney U Test: to evaluate if there is a statistical significant difference between samples the Mann-Whitney U Test was used, because it is a non-parametric test that does not assume normality in the data.[30]

Kendall's Tau Correlation Coefficient: was used to asses the correlation between our measurements. It is a non-parametric measure of association that can evaluate the strength and direction of relationships between ordinal variables, when the underlying data does not adhere to a normal distribution.[31] The correlation can be evaluated using the Guilford scale [32, p. 219] as can be seen in Table **1**.

Values	Label
$< .20$	Slight; almost negligible relationship
$.20 - .40$	Low correlation; definite but small relationship
$.40 - .70$	Moderate correlation; substantial relationship
$.70 - .90$	High Correlation; marked relationship
$.90 - 1$	Very high correlation; very dependable relationship

Table 1: The values for the scale presented by Guildford in [32, p. 219]

Cochran's Formula: To determine an appropriate sample size for our measurements, Cochran's formula was used. With this formula a required sample size to achieve a desired level of statistical power can be calculated.[33]

In summary, the selection of the Shapiro-Wilk test, Mann-Whitney U test, Kendall's Tau correlation coefficient, and Cochran's formula allowed us to effectively analyze our data, taking into account its non-normal distribution and ordinal nature while determining statistically significant differences, correlations, and an appropriate sample size for our measurements.

4.4 Device Under Tests

Two workstations were used as DUTs in the experiments. These were chosen to enable comparison between CPUs with and without P- and E-cores. When the two DUTs were set up, they were updated to have the same version of Windows and Linux. In Tables **2** and **3** the specifications of the two workstations can be seen. They will be referred to as DUT 1 and DUT 2.

Workstation 1 (DUT 1)	
Processor:	Intel i9-9900K
Memory:	DDR4 16GB
Disk:	Samsung MZVLB512HAJQ
Motherboard:	ROG STRIX Z390 -F GAMING
PSU:	Corsair TX850M 80+ Gold
Ubuntu:	22.04.2 LTS
Linux kernel:	5.19.0-35-generic
Windows 11:	10.0.22621 Build 2262

Table 2: The specifications for DUT 1

Workstation 2 (DUT 2)	
Processor:	Intel i5-13400
Memory:	DDR4 32GB
Disk:	Kingston SNV2S2000G
Motherboard:	ASRock H610M-HVS
PSU:	Cougar GEX 80+ Gold
Ubuntu:	22.04.2 LTS
Linux kernel:	5.19.0-35-generic
Windows 11:	10.0.22621 Build 22621

Table 3: The specifications for DUT 2

When running the experiments, the recommendations presented in [9] were followed. These included that the WiFi, CPU turbo boost and hyperthreading was disabled. Lastly, the CPU was set to static, which was achieved by disabling the C-states in the bios.

4.5 Compilers

This section introduces the various C++ compilers that were used in the first experiment. Some of the chosen compilers were based on [10], which found that applications compiled by Microsoft Visual C++ and MinGW exhibited the lowest energy consumption. Additionally, the Intel OneApi C++ compiler and Clang were included as both can be found on lists of the most popular C++ compilers[34–36].

Microbenchmarks	
Name	Version
Clang	15.0.0
MinGW	12.2.0
Intel OneAPI C++	2023.0.0.20221201
MSVC	19.34.31942

Table 4: C++ Compilers

Clang: is an open source compiler that builds on the LLVM optimizer and code generator. It is available for both Windows and Linux[37]

Minimalist GNU for Windows (MinGW): is an open-source project which provides tools for compiling code using the GCC toolchain on Windows. It includes a port of GCC. Additionally, MinGW can be cross-hosted on Linux.[38]

Intel's oneAPI C++ (oneAPI): is a suite of libraries and tools aimed at simplifying development across different hardware. One of these tools is the C++ compiler, which implements SYCL, this being an evolution of C++ for heterogeneous computing. It is available for both Windows and Linux.[39]

Microsoft Visual C++ (MSVC): comprises a set of libraries and tools designed to assist developers in

building high-performance code. One of the included tools is a C++ compiler, which is only available for Windows[40].

4.6 Benchmarks

Our work employed microbenchmarks and macrobenchmarks to asses the measuring instruments. This section outlines the selected benchmarks and the rationale behind their selection.

Microbenchmarks: are small, focused benchmarks that test a specific operation, algorithm or piece of code. They are useful for measuring the performance of some particular code precisely while minimizing the impact of other factors. However microbenchmarks may not provide an accurate representation of overall performance.[41]

The microbenchmarks are from the Computer Language Benchmark Game (CLBG)[1]. The selected benchmarks include both single- and multi-threaded microbenchmarks, which are compatible with the chosen compilers, as well as with both Windows and Linux. Certain libraries, such as `<sched.h>`, were used in many implementations and was not available on Windows, which limited the pool of compatible microbenchmarks. The microbenchmarks were executed using the highest parameters specified in the CLBG as input for each benchmark. The chosen microbenchmark benchmarks and their abbreviation are presented in Table **5**. During compilation, the only parameter given is `-openmp` for the multi-core benchmarks, ensuring optimization for all cores of the DUT.

Microbenchmarks		
Name	Parameter	Focus
NBody (NB)	$50 * 10^6$	single core
Spectra-Norm (SN)	5.500	single core
Mandelbrot (MB)	16.000	multi core
Fannkuch-Redux (FR)	12	multi core

Table 5: Microbenchmarks

Macrobenchmarks: are large-scale benchmarks testing the performance of an entire application or system. They provide a more comprehensive overview of how the system performs in real-world scenarios. Macrobenchmarks are more suitable for understanding the overall performance of an application or system rather than focusing on specific operations.[41] Application-level benchmarks are a type of marco benchmarks that test an application, which provides a more realistic benchmark scenario. Two macro benchmarks developed by UL were used. The first one was 3DMark

(3DM) which is a set of benchmarks for scoring both GPU's and CPU's based on gaming performance. We only used the 3DM benchmark CPU Profile, because we were only interested in loading the CPU and not the GPU, which the other benchmarks does. The CPU Profile benchmarks runs a 3D graphic, but the main component of the workloads is from a boids flocking behavior simulation.[42]. The second one was PCMark 10 (PCM) which is a benchmark meant to test various different task which could be seen at a workplace. It has three test groups that includes e.g. web browsing, video conferencing, working in spreadsheets and photo editing, the full list can be seen in Tables **10** and **11**. This benchmark simulated common task in office workspace.[43] The versions of both macrobenchmarks can be seen in Table **6**.

Macrobenchmarks	
Name	Version
3DM	2.26.8092
PCM	1.1

Table 6: Macrobenchmarks

4.7 Background Processes

To limit background processes on Windows, a few step were taken. When the DUTs were set up, all startup processes in the Task Manager on Windows were also disabled, in addition to non-Microsoft background services found in System Configuration. Exceptions were however made to processes related to Intel.

During runtime, different background processes were also stopped. These processes were found by looking at the running processes using command `Get-Process`. A list of processes was found which are killed using the `Stop-Process` command before running the experiments. The list can be found in Table **7**.

---

[1]https://benchmarksgame-team.pages.debian.net/ benchmarksgame/index.html

Background Processes
Name
searchapp
runtimebroker
phoneexperiencehost
TextInputHost
SystemSettings
SkypeBackgroundHost
SkypeApp
Microsoft.Photos
GitHubDesktop
OneDrive
msedge
AsusDownLoadLicense
AsusUpdateCheck

Table 7: Background Processes

5 Experiments

In the following section, the conducted experiments are described. All experiments carried out in this section will utilize the framework detailed in Appendix **A**, with the results stored in the database introduced in Appendix **B**. During the experiments, the `ProcessPriorityClass` for the measuring instrument, framework, and benchmarks was set to `High`, unless specified otherwise by the particular experiment.

5.1 Experiment One

The first experiment investigated RQ **1**. This experiment employed both multi-core benchmarks presented in Section **4.6**, and the measurements were performed using IPG. IPG was chosen based on its performance in [3], where it was found to produce similar measurements to LHM. Since the objective of this experiment was to identify the most energy-efficient compiler, the expectation was that a similar conclusion would be made if multiple measuring instruments were used. This experiment was conducted on DUT 1.

Initial Measurements: As was presented in Section **4.3**, Cochran's formula was used to ensure confidence in the measurements made. The initial measurements were taken to gain insight into the number of measurements required before making additional measurements if required. The number chosen for the initial measurements was 30, as the central limit theorem suggests that a sample size of at least 30 is usually sufficient to ensure that the sampling distribution of the sample mean approximates normality, regardless of the underlying distribution of the population[44]. In this experiment, the process' priority class for the framework, the benchmark, and the measuring instrument were set to `HIGH`.

After 30 measurements, the results from Cochran's formula can be seen in Table **8**, where it was evident that the required samples varied between compilers and benchmarks. When the benchmarks were analyzed it was found that MB deviates less than FR, with MB requiring as little as 3 samples with MinGW, while FR requires up to $62,086$ samples with Clang. Given these results, more measurements were necessary. When the compilers were analyzed interestingly oneAPI had the lowest energy consumption for FR, but the highest for MB. oneAPI also displayed the lowest energy consumption. As a result, 550 additional measurements were conducted for the next step.

Initial Measurements		
Name	Fannkuch Redux	Mandelbrot
Clang	61.086	40
MinGW	1.644	3
oneAPI	550	222
MSVC	2.994	10

Table 8: The required samples to gain confidence in the measurements made by IPG on Windows

Results: After 550 measurements were obtained, the reported values by Cochran's formula still indicated that MSVC, MinGW, and Clang needed more measurements. Between the different compilers, Clang stands out where 61.086 measurements are required. Because this number is so much higher than other compilers, additional measurements were taken using this compiler. After 10.000 measurements, Cochran's formula now indicated that 1.289 measurements were required, which is more in line with other compilers.
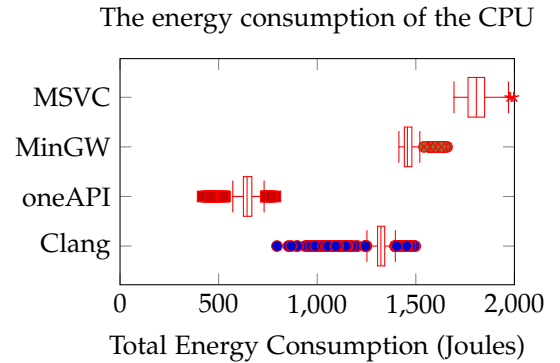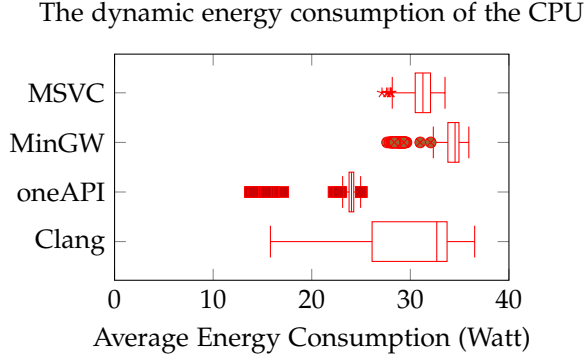

Figure 1: CPU measurements by IPG on DUT 1 for benchmark(s) FR

When looking at the results for FR in Figures **1** and **2**, and for MB in Appendix **D**, oneAPI had the lowest DEC and total energy consumption for both benchmarks. Clang deviated the most in Figure **2**.

In the first experiment, it was concluded that the different compilers have a huge impact on the energy consumption but also how many measurements were

required to be confident in the results. In the end, oneAPI had the lowest energy consumption and was used in the remaining experiments, unless otherwise specified.

The dynamic energy consumption of the CPU

**Figure 2:** CPU measurements by IPG on DUT 1 for benchmark(s) FR

5.2 Experiment Two

The second experiment investigated RQ **2**, in order to identify our preferred measuring instrument on Windows. The measuring instrument was chosen based on a combination of different factors, including its correlation with our ground truth, ease of use and cost.

A couple of changes were made in the experimental setup for experiment two. Firstly, due to some issues with SCAP, where its sampling rate significantly decreased when the DUT was under full load, the process priority class of the benchmark was set to `Normal`. Secondly, due to an execution time of less than a second for `MB` when compiled with Intel's oneApi, `MB`'s input parameter was changed from 16.000 to 64.000 which increased the duration of the benchmark execution time to $\sim$ 14 seconds. This avoided a scenario where the Plug only had a single data point per measurement. For this experiment, `FR` was executed 550 times, while `MB` was executed 222 times, based on Table **8**.

Initial Measurements: When analyzing how many measurements is required when applying Cochrans to the results can be seen in Appendix **F**. The Clamp requires significantly more measurements in this case compared to other measuring instruments, which is why a more in depth analysis was conducted. In Figure **3** boxplots showing the evolution of the DEC when performing between $200 - 3.000$ measurements. The median decreased by 5.84% from 200 measurements to 3.000 measurements, and by 0.3% between 2.800 and 3.000 measurements. A pattern was observed, where the median decreased as more measurements are made, until measurements 1.000, after which the DEC increases until measurement 1.400 by 2%, af-

ter which it decreases again. In the last 1.400 measurements the DEC has converged where the DEC increases by 0.2%. The DEC at 1.000 measurements is 0.29% from the DEC at 3.000, and due to the excessive time required to run the experiments, we have capped the maximum amount of measurement at 1000 for this experiment. When looking at the evolution of Cochran's formula for the different measurements, 15.137 ends up being the amount of measurements required, where the evolution of this number can be found in Appendix **G**. This number is higher compared to other measuring instruments, and this will be analyzed further in the discussion.
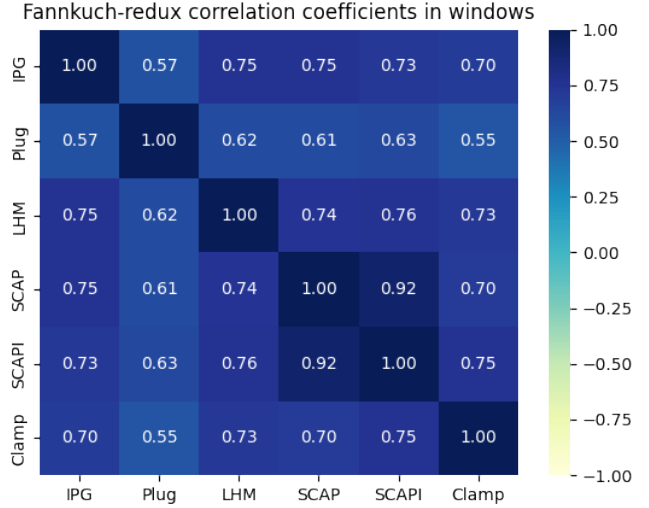
The evolution of energy consumption
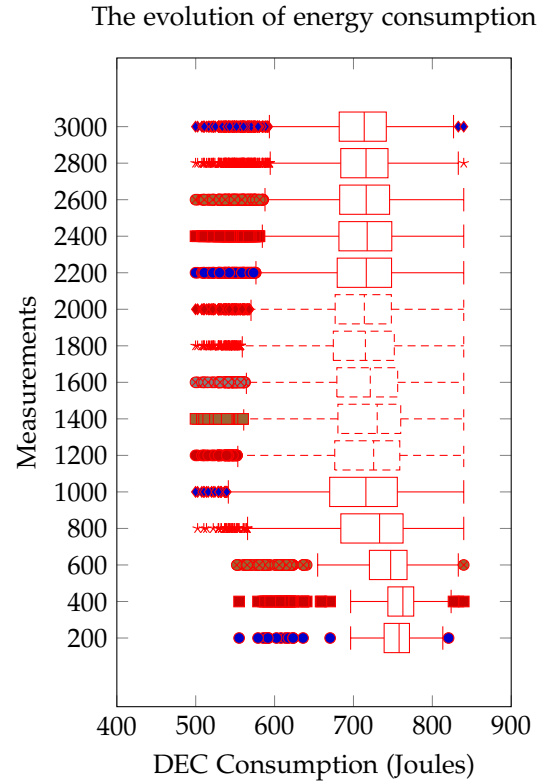
Figure 3: A visual representation of how the energy measurements evolve as more measurements are made by clamp on DUT 2 for benchmark MB

Results: When analyzing the results, it will be done for DUT 1 using barcharts in Figure **4** as the deviation in the results in limited, where boxplots for boths duts can be found in Appendix **E**. In Figure **4** `MB` has a lower energy consumption than `FR` for all measuring instrument except RAPL, and SCAP, LHM and IPG performs measuremenst within 25 joules of each other for both benchmarks. When looking at the Clamp, this measuring instrument reports a lower DEC than the Plug for both benchmarks, IGP, LHM and SCAP for `MB` and a higher DEC on `FR`. When comparing between OSs, Windows can be observed to have a lower DEC and Linux.
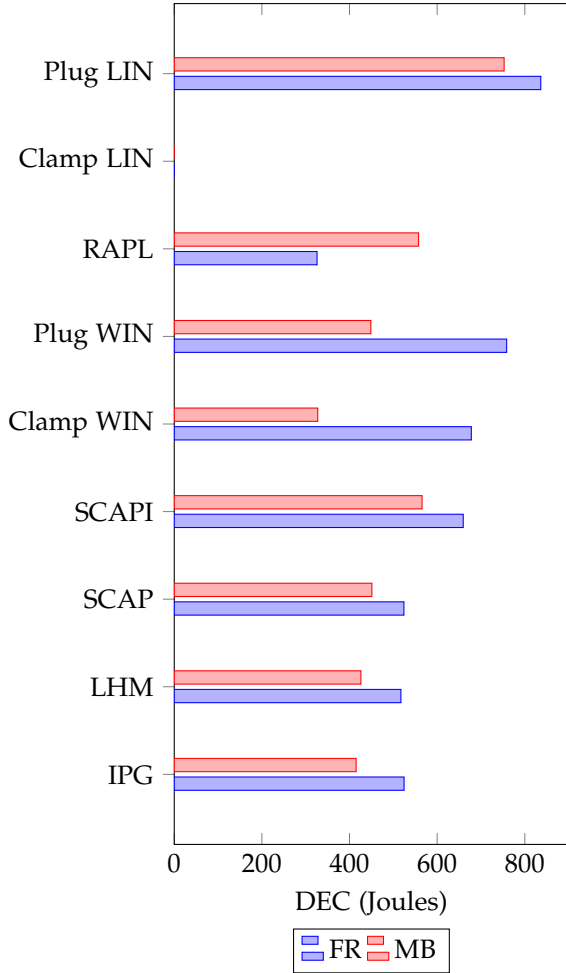
Figure 4: The average DEC for DUT 1, where both benchmarks are compiled on oneAPI

Figure 5: Heatmap showing the correlation ceoffecient betwween all of the measurement instrument on windows for the fannkuch-redux Benchmark

All DUTs showed moderate to high correlation with the ground truth (Clamp) when assessed with the Guildford Scale. The measuring instruments varied in their correlation performance, with SCAPI being the best but with very few data points logged, this is also the case with SCAP. LHM and IPG being essentially equal in performance for both benchmarks which Slight diviations. Since usability is also a factor, IPG was chosen as the best measuring instrument and will be used for future experiments on Windows.

5.3 Experiment Three

The third experiment investigated RQs **3** and **4**, by taking a look at the per-core performance. In this experiment only IPG and the Clamp was used to conduct measurements. The benchmark was executed on one core at a time using the single-core benchmarks introduced in Section **4.6**. This allowed a comparison between the energy consumption of the P- and E-cores on DUT 2 and the P-cores on DUT 1. When performing measurements, the limit of 1.000 measurements set in Appendix **E** is still used.

When applying statistical methods from Section **4.3**, it was discovered that some of the data did not follow a normal distribution and were significantly different from eachother, previous studies [3, 45] have had simliar results. Thus, Kendalls Tau Correlation Coefficient was used, and the results for the two benchmarks can be seen in Figure **5** and Appendix **F**.

Per-Core Initial Measurements: An initial 250 measurements were made for each benchmark on each core. Then Cochran's formula was calculated to determine if more measurements were required as shown in Appendix **I**.

SN measurements on DUT 2			
Metric	E-core	P-core	Difference
Duration	58.96 s	13.96 s	-76.32%
Energy	336.88 j	99.53 j	-70.45%
DEC	253.85 j	16.26 j	-93.59%
DEC per second	0.53 w	1.88 w	$+254.71\%$

Table 9: The performance difference between E and P cores on DUT 2, SN

Figure 6: The evolution of the DEC (blue), DEC per second (red) and duration (green) as more cores are allocated to 3DM on DUT 2

Per-Core Results: The results, presented here are based on DUT 2, where the results will be shown in tables, given the low deviation in the results. Boxplots for both DUTs can be found in Appendix **H**. For SN, as seen in Table **9**, the run time was on average 76.26% lower on the P-cores compared to the E-cores and The total DEC was on average 70.44% lower on P cores, however the E cores had a 72.88% lower energy consumption per second. The largest difference between two cores of the same type was found on DUT 1 with benchmark NB, where the performance was 11.61% worse on core 1 than core 6. The smallest difference was found on DUT 2, benchmark NB on a E core, where the energy consumption was 1.17% higher on core 6 than core 9.

Figure 7: The evolution of the DEC (blue), DEC per second (red) and duration (green) as more cores are allocated to PCM on DUT 2. Note that the y-axis does not start at zero.

Macrobenchmark Initial Measurements: An initial 30 measurements were made for both 3DM and PCM on an increasing number of cores starting from two, to the maximum amount of cores. The initial idea was to start at one core, but the web browsing in PCM did not support this, which was deemed an important part of PCM by us. It was also found that spreadsheet and photo editing could not be executed on DUT 2, but will still be executed on DUT 1. 30 measurements was chosen as the per-core experiment illustrated how 250 was too much for DUT 2. The order of cores used in this experiment was done by using the cores with the lowest DEC found in Appendix **H**. The required measurements from the first 30 according to Cochran's can be found in Appendix **J**.

Macrobenchmark Results: The results for DUT 1 can be seen in Figure **6** and Figure **7** for 3DM and PCM respectively, and for DUT 2 in Appendix **J**, while the results has been combined into a table for all DUTs and benchmarks in Appendix **K**. For both PCM and 3DM on both DUTs, similar observations can be made, where when more cores are allocated, the duration and DEC is exponentially decreasing, while the DEC per second is increasing. It can be seen in Table **18** that the duration decrease more than the DEC which shows a diminishing return in terms of energy savings. A difference between 3DM and PCM is how the dura-

tion and energy consumption decrease more for 3DM. This is because a large portion of PCM is single thread tasks, meaning only some parts of the benchmarks can benefit from the additional allocated cores, and even for those parts benefitting, the performance gained from the last few allocated cores is very limited, as can be seen in Table **18**.

6 Discussion

In the following section, results from Section **5** will be discussed.

6.1 Outliers

In this work Cochran's formula was used to determine how many measurements were required in order to gain confidence in our results. When analyzing the results from Cochran's formula, it was found that the amount of measurements could deviate a lot between benchmarks, measuring instrument, DUTs and even cores on the same DUT.

Results can deviate from core to core as a result of the variability in the fabrication process, where the exact characteristics of each core can change, despite being assembled in the same way.[46]

6.2 Energy usage mystery

The trend shown in Section **5.2** where the median DEC decreased as more measurements were taken until 1000 measurements after which it increased until 1400 after which it decreased again, could be seen on both the Clamp and Plug, which indicates that it is not caused by faulty measurements. However, the same trend could not be observed on the software-based measuring instruments. Therefore we hypothesized that the observed reduction in energy consumption may be caused by changes in the reactive energy consumption occurring between the power outlet and the power supply of the DUTs.

In a circuit, two types of energy can be identified: active energy, which performs useful work, and reactive energy, which does not. The combination of these two energies is called apparent energy, which is what is measured by our hardware-based measuring instruments. Reactive energy occurs because of inductive or capacitive loads in a circuit, resulting in an energy loss that is not utilized by the circuit[47]. The ratio between active and reactive energy is known as the power factor[47].

Based on this, two hypotheses have been constructed to explain why the energy consumption of the DUTs are changing over measurements. Firstly, noise on the electrical network could interfere with the phase synchronization. This may be due to many machines being connected to the same electrical network,

and disrupting the harmonics of the network[48]. However, if the power supply generates reactive energy because it is out of phase with the electrical network, a reduction in noise could help synchronize them again. Therefore, the observed changes in energy consumption may be related to the time of the day and week where the measurements are taken, with consumption decreasing when there is less devices connected to the electrical network, during the night and weekends.

Alternatively, the DUTs' power supply unit (PSU) may be correcting the phase over time. PSU's can contain a power factor correction (PFC) circuit that attempts to reduce the amount of reactive power by correcting the phase. There are two main types of PFCs, passive power factor correction (PPFC) and active power factor correction (APFC)[49]. The behavior seen in the results may be the result of an APFC, but we could not determine whether such a circuit is present in our DUTs.

We are unable to determine the exact cause of the changes in energy consumption.

6.3 Time synchronization

In our work, four different devices were used to take the measurements - the DUTs, a Raspberry Pi, and an Analog Discovery 2. Each of these devices kept its own time, which could cause issues if they were not synchronized. This was particularly problematic for external measurement instruments, as even small differences in time could result in inaccurate data.

To address this issue, the data acquisition process was changed to ensure that the devices were synchronized every second. However, some problems may still exist, as small time drifts can occur over time. For example, the Raspberry Pi did not have a real-time clock(RTC)[50] and would therefore become increasingly inaccurate over time. Additionally, the execution time of IO events for the clamp and plug could result in a slight time difference, although this is expected to have minimal impact on the results, since resynchronization happens every second.

7 Conclusion

Acknowledgements

8 Future Works

References

1. Jones, N. *et al.* How to stop data centres from gobbling up the world's electricity. *Nature* **561,** 163–166 (2018).

2. Andrae, A. S. & Edler, T. On global electricity usage of communication technology: trends to 2030. *Challenges* **6,** 117–157 (2015).

3. Holt, J., Kusk, M. H. & Pedersen, J. B. *A Comparison Study of Measuring Instruments* (Aalborg University Department of Computer Science, 2023).

4. Amdahl, G. M. *Validity of the single processor approach to achieving large scale computing capabilities* in *Proceedings of the April 18-20, 1967, spring joint computer conference* (1967), 483–485.

5. Woo, D. H. & Lee, H.-H. S. Extending Amdahl's law for energy-efficient computing in the many-core era. *Computer* **41,** 24–31 (2008).

6. Prinslow, G. Overview of performance measurement and analytical modeling techniques for multi-core processors. *UR L: http://www. cs. wustl. edu/˜ jain/cse567-11/ftp/multcore* (2011).

7. Pinto, G., Castor, F. & Liu, Y. D. Understanding Energy Behaviors of Thread Management Constructs. *SIGPLAN Not.* **49,** 345–360. issn: 0362-1340. https://doi.org/10.1145/2714064.2660235 (2014).

8. Abdelhafez, A., Alba, E. & Luque, G. A component-based study of energy consumption for sequential and parallel genetic algorithms. *The Journal of Supercomputing* **75,** 1–26 (Oct. 2019).

9. Lindholt, R. S., Jepsen, K. & Nielsen, A. Ø. *Analyzing C# Energy Efficiency of Concurrency and Language Construct Combinations* (Aalborg University Department of Computer Science, 2022).

10. Hassan, H., Moussa, A. & Farag, I. Performance vs. Power and Energy Consumption: Impact of Coding Style and Compiler. *International Journal of Advanced Computer Science and Applications* **8** (Dec. 2017).

11. Saez, J. C. & Prieto-Matias, M. *Evaluation of the Intel thread director technology on an Alder Lake processor* in *Proceedings of the 13th ACM SIGOPS Asia-Pacific Workshop on Systems* (2022), 61–67.

12. Intel. *Intel performance hybrid architecture & software optimizations Development Part Two: Developing for Intel performance hybrid architecture* https : / / www . google . com / url ? sa = t & rct = j & q = &esrc = s & source = web & cd = &ved = 2ahUKEwj1j9no9c79AhX9␣EDHXGiDMgQFnoECA8QAQ & url = https % 3A%2F%2Fcdrdv2-public.intel.com%2F685865% 2F211112␣Hybrid␣WP␣2␣Developing␣v1.2.pdf&

usg = AOvVaw2dfqExqLBgFMeS5To1sjKM. 09/03/2023.

13. Intel. *Energy-Efficient Platforms* https : / / www. intel.com/content/dam/develop/external/us/ en / documents / green - hill - sw - 20 - 185393.pdf. 2011. 07/03/2023.

14. hardwaresecrets. *Everything You Need to Know About the CPU Power Management* https : / / hardwaresecrets.com/everything-you-need-to-know - about - the - cpu - c - states - power - saving-modes/. 2023. 07/03/2023.

15. ARM. *MEDIA ALERT: ARM big.LITTLE Technology Wins Linley Analysts' Choice Award* https:// www . arm . com / company / news / 2012 / 01 / media - alert - arm - biglittle - technology - wins-linley-analysts-choice-award. 2012. 09/03/2023.

16. ARM. *Processing Architecture for Power Efficiency and Performance* https : / / www . arm . com / technologies/big-little. 09/03/2023.

17. Intel. *Intel Unveils 12th Gen Intel Core, Launches World's Best Gaming Processor, i9-12900K* https: / / www. intel . com / content / www / us / en / newsroom / news / 12th - gen - core - processors. html. 2021. 09/03/2023.

18. Rotem, E. *et al.* Intel alder lake CPU architectures. *IEEE Micro* **42,** 13–19 (2022).

19. *1.3.1. processor affinity or CPU pinning* https:// www.intel.com/content/www/us/en/docs/ programmable / 683013 / current / processor - affinity-or-cpu-pinning.html. 03/03/2023.

20. Karl-Bridge-Microsoft. *Scheduling priorities - win32 apps* https://learn.microsoft.com/en-us / windows / win32 / procthread / scheduling-priorities. 03/03/2023.

21. Michael Womack, A. W. *Parallel Programming and Performance Optimization With OpenMP* https:// passlab.github.io/OpenMPProgrammingBook/ cover.html. 03/03/2023.

22. Mozilla. *tools/power/rapl* https://firefox-source-docs . mozilla . org / performance / tools␣power␣ rapl.html. 24/02/2023.

23. source, O. *Libre Hardware Monitor* https : / / github . com / LibreHardwareMonitor / LibreHardwareMonitor. 03/03/2023.

24. Arnoux, C. *AC current clamps user's manual* 2013.

25. CloudFree. *CloudFree EU Smart Plug* https : / / cloudfree.shop / product / cloudfree - eu - smart-plug/. 10/03/2023.

26. Hubblo. *Scaphandre* https://github.com/hubblo-org/scaphandre. 23/02/2023.

27. Hubblo. *windows-rapl-driver* https://github.com/hubblo-org/windows-rapl-driver. 23/02/2023.

28. Fahad, M., Shahid, A., Manumachu, R. R. & Lastovetsky, A. A comparative study of methods for measurement of energy of computing. *Energies* **12,** 2204 (2019).

29. Razali, N. M., Wah, Y. B., *et al.* Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests. *Journal of statistical modeling and analytics* **2,** 21–33 (2011).

30. Mann, H. B. & Whitney, D. R. On a test of whether one of two random variables is stochastically larger than the other. *The annals of mathematical statistics,* 50–60 (1947).

31. Han, A. K. Non-parametric analysis of a generalized regression model: the maximum rank correlation estimator. *Journal of Econometrics* **35,** 303–316 (1987).

32. Guilford, J. P. Fundamental statistics in psychology and education (1950).

33. Cochran, W. G. *Sampling Techniques, 3rd edition* ISBN: 0-471-16240-X (John Wiley & sons, 1977).

34. Saqib, M. *What are the Best C++ Compilers to use in 2023* 2023. https://www.mycplus.com/tutorials/cplusplus-programming-tutorials/what-are-the-best-c-compilers-to-use-in-2023/. 20/03/2023.

35. Pedamkar, P. *Best C++ Compiler* 2023. https://www.educba.com/best-c-plus-plus-compiler/. 20/03/2023.

36. *Top 22 Online C++ Compiler Tools* 2023. https://www.softwaretestinghelp.com/best-cpp-compiler-ide/. 20/03/2023.

37. *Clang Compiler Users Manual* https://clang.llvm.org/docs/UsersManual.html. 20/03/2023.

38. *MinGW FAQ* https://home.cs.colorado.edu/~main/cs1300/doc/mingwfaq.html. 20/03/2023.

39. *Intel oneAPI Base Toolkit* https://www.intel.com/content/www/us/en/developer/tools/oneapi/base-toolkit.html#:~:text=The%20Intel%C2%AE%20oneAPI%20Base,of%20C%2B%2B%20for%20heterogeneous%20computing.. 20/03/2023.

40. *C and C++ in Visual Studio* 2022. https://learn.microsoft.com/en-us/cpp/overview/visual-cpp-in-visual-studio?view=msvc-170. 20/03/2023.

41. appfolio. *Microbenchmarks vs Macrobenchmarks (i.e. What's a Microbenchmark?)* https://engineering.appfolio.com/appfolio-engineering/2019/1/7/microbenchmarks-vs-macrobenchmarks-ie-whats-a-microbenchmark. 24/03/2023.

42. UL. *3DMark* https://www.3dmark.com/. 14/04/2023.

43. UL. *PCMark* https://benchmarks.ul.com/pcmark10. 14/04/2023.

44. *Central Limit Theorem* https://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_probability/BS704_Probability12.html. 20/03/2023.

45. Koedijk, L. & Oprescu, A. *Finding Significant Differences in the Energy Consumption when Comparing Programming Languages and Programs* in *2022 International Conference on ICT for Sustainability (ICT4S)* (2022), 1–12.

46. Mauzy, R. Parallelizing Neural Networks to Break Physical Unclonable Functions (2020).

47. *MORE POWER WITH LESS COPPER* = https://fortop.co.uk/knowledge/white-papers/reactive-power-reducing-compensating/,

48. Kullarkar, V. T. & Chandrakar, V. K. Power quality analysis in power system with non linear load. *Int. J. Electr. Eng* **10,** 33–45 (2017).

49. McDonald, B. & Lough, B. *Power Factor Correction (PFC) Circuit Basics* in *Texas Instruments Power Supply Design Seminar* (2020).

50. *Syncing Time from the Network on the Raspberry Pi* = https://pimylifeup.com/raspberry-pi-time-sync/, 2022.

A The Framework

The framework used in this work is an extension to [3], where one key difference is it a command line tool, supporting all languages. The framework is called Biks Diagnostics Energy (BDE) and can be executed in two ways, as seen in Listing **4**, where one is with a configuration, and one is with a path to an executable file.

```
1    .\BDEnergyFramework --config path/to/config.json
2
3    .\BDEnergyFramework --path path/to/file.exe --parameter parameter
```

Listing 4: An example of how BDE can be started

When using `--config`, the user specifies a path to a valid json file of the format seen in Listing **5**. Through Listing **5**, it is possible to specify paths to executable files and assign each executable file with a parameter in `BenchmarkPaths` and `BenchmarkParameter` respectively. Information like the `compiler`, `language`, etc can also be specified about the benchmark in the configuration. It is also possible to specify the affinity of the benchmark through `AllocatedCores`, where an empty list represents the use of all cores and the list `1,2` specifies how the benchmark can only execute on core one and two. When multiple affinities are specified, each benchmark will be run on both. Limits for the temperature the benchmarks should be executed within can also be specified, and lastly, `AdditionalMetadata` can be used to specify relevant aspects about the experiment, which cannot already be specified through the configuration.

```
1    [
2      {
3        "MeasurementInstruments": [ 2 ],
4        "RequiredMeasurements": 30,
5        "BenchmarkPaths": [
6            "path/to/one.exe", "path/to/two.exe"
7        ],
8        "AllocatedCores": [
9            [], [1,2]
10       ],
11       "BenchmarkParameters": [
12           "one_parameter", "two_parameter",
13       ],
14       "UploadToDatabase": true,
15       "BurnInPeriod": 0,
16       "MinimumTemperature": 0,
17       "MaximumTemperature": 100,
18       "DisableWifi": false,
19       "ExperimentNumber": 0,
20       "ExperimentName": "testing-phase",
21       "ConcurrencyLimit": "multi-thread",
22       "BenchmarkType": "microbenchmarks",
23       "Compiler": "clang",
24       "Optimizations": "openmp",
25       "Language": "c++",
26       "StopBackgroundProcesses" : false,
27       "AdditionalMetadata": {}
28     }
29   ]
```

Listing 5: An example of a valid configuration for BDE

When using the parameters `--path`, the `--parameter` is an optional way to provide the executable with parameters. When using BDE this way, a default configuration is set up, containing all fields in the configuration, except `BenchmarkPath` and `BenchmarkParameter`.

```
1    public interface IDutService
2    {
3        public void DisableWifi();
4        public void EnableWifi();
5        public List<EMeasuringInstrument> GetMeasuringInstruments();
6        public string GetOperatingSystem();
7        public double GetTemperature();
8        public bool IsAdmin();
9        public void StopBackgroundProcesses();
10   }
```

Listing 6: The DUT interface which allows BDE to work on multiple OSs

Both Windows and Linux is supported on BDE. This is supported through the `IDutService` seen in Listing **6**, where all OS dependent operations are located. This includes the ability to enable and disable the WiFi, stop background processes, ect. The `IDutService` has a Windows and Linux implementation on BDE where depending on the OS of the machine BDE is executed on, one of these will be initialized and used.

```
1    public class MeasuringInstrument
2    {
3
4        public (TimeSeries, Measurement) GetMeasurement()
5        {
6            var path = GetPath(_measuringInstrument, fileCreatingTime);
7            return ParseData(path);
8        }
9
10       public void Start(DateTime fileCreatingTime)
11       {
12           var path = GetPath(_measuringInstrument, fileCreatingTime);
13
14           StartMeasuringInstruments(path);
15
16           StartTimer();
17       }
18
19       public void Stop(DateTime date)
20       {
21           StopTimer();
22           StopMeasuringInstrument();
23       }
24
25       internal virtual int GetMilisecondsBetweenSamples()
26       {
27           return 100;
28       }
29
30       internal virtual (TimeSeries, Measurement) ParseData(string path) { }
31
32       internal virtual void StopMeasuringInstrument() { }
33
34       internal virtual void StartMeasuringInstruments(string path) { }
35
36       internal virtual void PerformMeasuring() { }
37   }
```

Listing 7: The implementation of the different measuring instruments on BDE

BDE also supports multiple measuring instruments, through a parent class `MeasuringInstrument` in Listing **7** the measuring instruments can inherit from. `MeasuringInstrument` implements a start (line 10) and stop (line 19) method, and a method to get the data measured between the start and stop in line 4. In terms of the virtual methods, each measuring instrument needs to override, these are measuring instruments specific. This includes a start (line 34) and stop (line 32) method, a method to parse the measurement data in line 30 and a method in line 36 which performs a measurement by default every 100ms by default. The method in line 36 is made for measuring instruments line RAPL, where an action is required to read the energy consumption.

```
1    public void PerformMeasurement(MeasurementConfiguration config)
2    {
3        var measurements = new List<MeasurementContext>();
4        var burninApplied = SetIsBurninApplies(config);
5
6        if (burninApplied)
7            measurements = InitializeMeasurements(config, _machineName);
8
9        do
10        {
11            if (CpuTooHotOrCold(config))
12                Cooldown(config);
13
14            if (config.DisableWifi)
15                _dutService.DisableWifi();
16
17            PerformMeasurementsForAllConfigs(config, measurements);
18
19            if (burninApplied && config.UploadToDatabase)
20                UploadMeasurementsToDatabase(config, measurements);
21
22            if (!burninApplied && IsBurnInCountAchieved(measurements, config))
23            {
24                measurements = InitializeMeasurements(config, _machineName);
25                burninApplied = true;
26            }
27
28        } while (!EnoughMeasurements(measurements));
29    }
```

Listing 8: An example of how BDE performs measurements

Listing **8** shows how BDE performs measurements given the configuration. In the configuration, the burn-in period can be set to any positive integer, where if this value is one, the boolean `burninApplied` will be set to `true`, and the measurements will be initialized in line 7. This initialization will, if the results should be uploaded to the database, mean BDE will fetch existing results from the database, where the configuration is the same, and continue where it was left off. Otherwise, an empty list will be returned. If `burninApplied` is set to `false`, the amount of burn-in specified in the configuration will be performed before initializing the measurements.

Next, a do-while loop is entered in line 9, which will execute until the condition EnoughMeasurements from line 28 is met. Inside the do-while loop, a cooldown will occur in line 12, until the DUT is below and above the temperature limits specified in the configuration. Once this is achieved, the WiFi/Ethernet is disabled, and `PerformMeasurementsForAllConfigs` will then iterate over all measuring instruments and benchmarks specified, and perform one measurement for all permutations. Afterward, a few checks are made. If the burn-in period is over, and the configuration states that the results should be uploaded to the database, `UploadMeasurementsToDatabase` is called. If the burn-in period is not over yet, but `IsBurnInCountAchieved` is true, the measurements are initialized similarly to line 7, and the boolean *burninIsApplied* is set to `true`, indicating that the burn-in period is over, and the measurements are about to be taken.

B   The Database

In [3], a MySQL database was used to store the measurements made by the different measuring instruments. In this work, a similar database will be used, but with some modifications to accommodate the different focus compared to [3]. The design of the database can be seen in Figure **8**, where the `MeasurementCollection` table defines under which circumstances the measurements were made. This includes which measuring instrument was used, which benchmark was running, which DUT the measurements were made on, whether or not there was a burn-in period, etc. Compared to [3], a few extra columns have been added to `Benchmark`, this includes metadata like compiler, optimizations, and parameters used.

In the `MeasurementCollection`, the columns `CollectionNumber` and `Name` represents which experiment the measurement is from, and the name of the experiment respectively. A column found in both `MeasurementCollection`, `Measurement` and `Sample` is `AdditionalMetadata`. This column can be used to set values unique for specific rows, where an example could be how some metrics are only measured by one measuring instrument.

The `Measurement` contains values for the energy consumption during the entire execution time of one benchmark, while the `Sample` represents samples taken during the execution of the benchmark. This means for one row in the `MeasurementCollection` table, there can exist one to many rows in `Measurement`. Each row in `Measurement` is associated with multiple rows in the `Sample` table, where the samples will be a time-series illustrating the energy consumption over time.
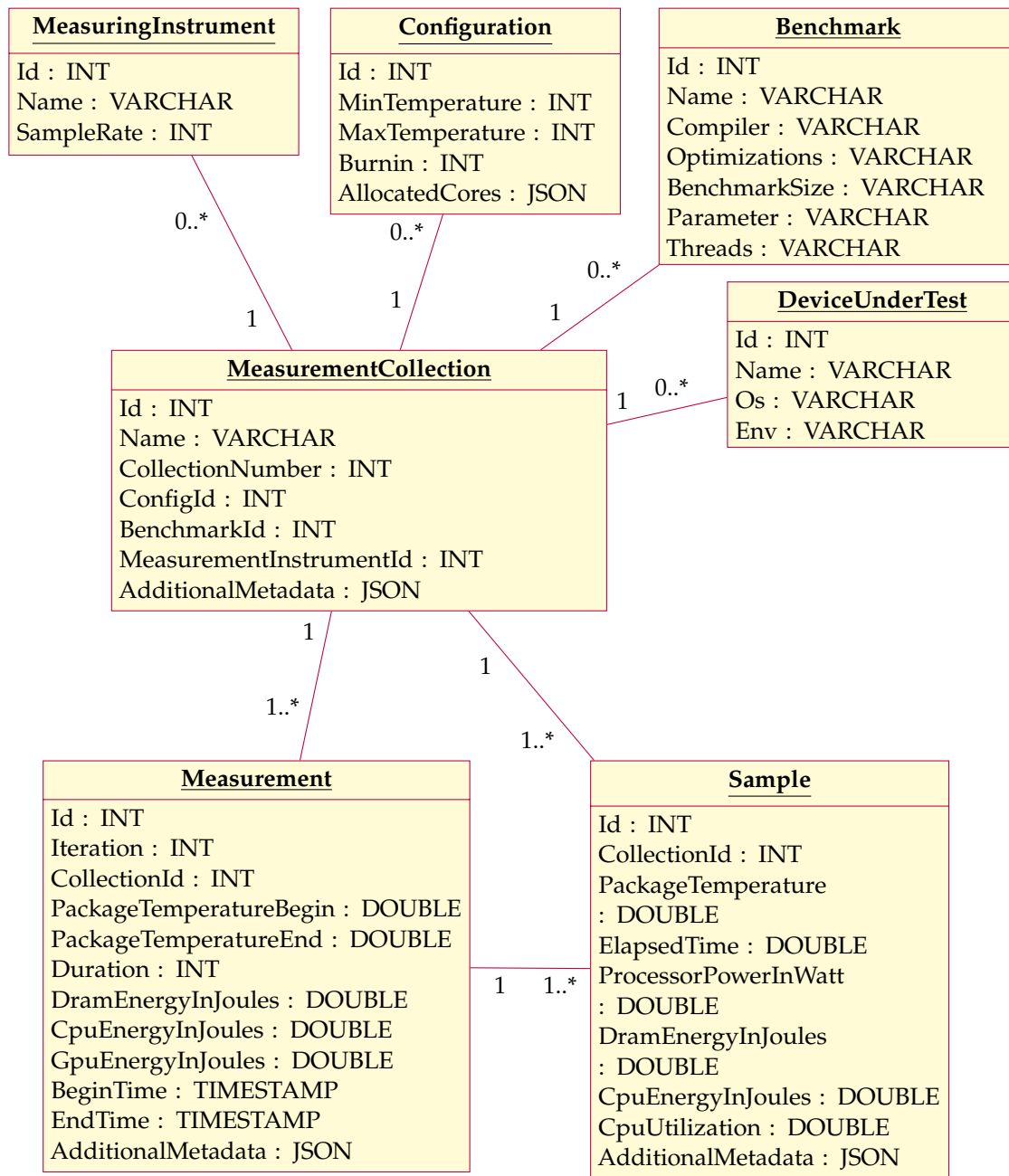
Figure 8: An UML diagram representing the tables in the SQL database

C PCMark 10

Not all of the benchmarks are executed on our DUTs, because some of them would crash. The different workloads and whether they are included or not are shown on Tables **10** and **11**. Further detail about the workloads can be found in [43].

18

Essentials	DUT1	Productivity	DUT1	Digital Content Creation	DUT1
App Start-up		**Writing**		**Photo Editing**	
Chromium	×				
Firefox	×	Writing simulation	×	Editing one photo	✓
LibreOffice Writer	×			Editing a batch of photos	✓
GIMP	×				
Web Browsing		**Spreadsheets**		**Video Editing**	
Social media	✓				
Online shopping	✓	Common use	✓	Downscaling	✓
Map	✓	Power use (More complex)	✓	Sharpening	✓
Video 1080p	✓			Deshaking filtering	✓
Video 2160p	✓				
Video Conferencing				**Rendering and Visualization**	
Private call	✓			Visualization of a 3D model	✓
Group call	✓			Calculating a simulation	✓

Table 10: List of PCMark10 benchmarks used on DUT1.

Essentials	DUT2	Productivity	DUT2	Digital Content Creation	DUT2
App Start-up		**Writing**		**Photo Editing**	
Chromium	×				
Firefox	×	Writing simulation	×	Editing one photo	×
LibreOffice Writer	×			Editing a batch of photos	×
GIMP	×				
Web Browsing		**Spreadsheets**		**Video Editing**	
Social media	✓				
Online shopping	✓	Common use	×	Downscaling	✓
Map	✓	Power use (More complex)	×	Sharpening	✓
Video 1080p	✓			Deshaking filtering	✓
Video 2160p	✓				
Video Conferencing				**Rendering and Visualization**	
Private call	✓			Visualization of a 3D model	✓
Group call	✓			Calculating a simulation	✓

Table 11: List of PCMark10 benchmarks used on DUT2.

D   Experiment One

Measurements made on benchmark Mandelbrot for the first experiment, found in Section **5.1**.

The average duration
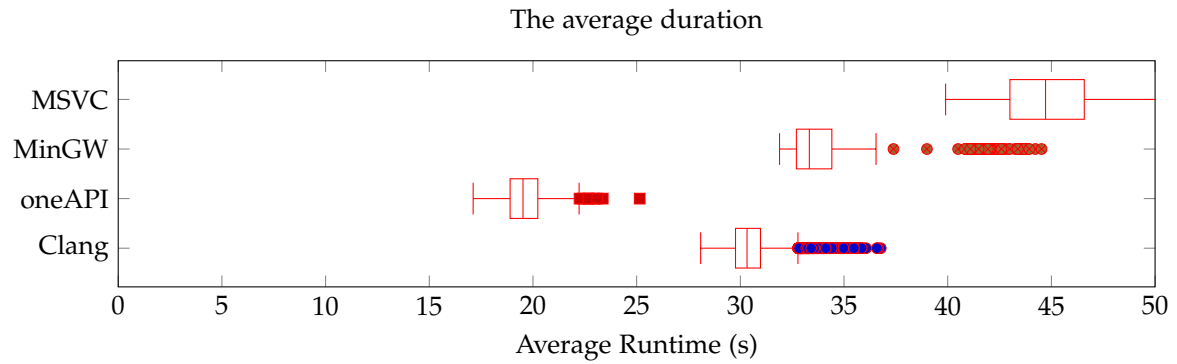
Figure 9: Runtime measurements by IPG on DUT 1 for benchmark(s) FR

The dynamic energy consumption of the CPU
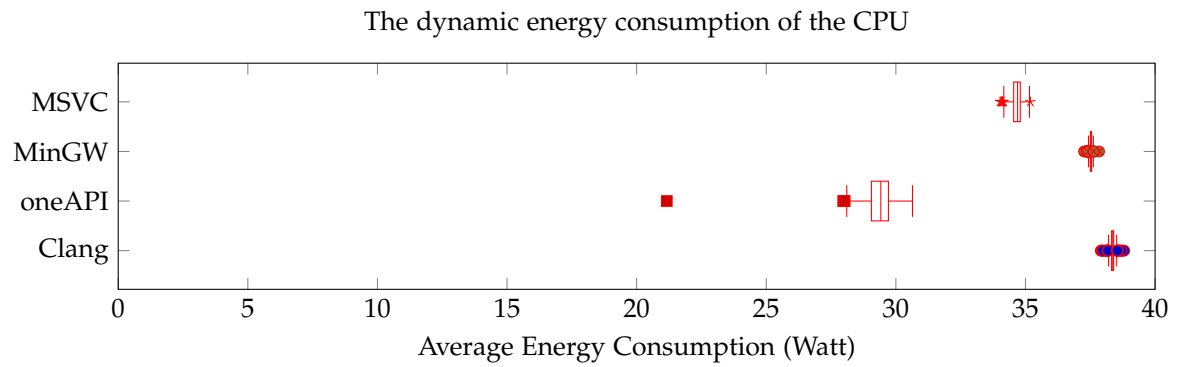
Figure 10: CPU measurements by IPG on DUT 1 for benchmark(s) MB

The energy consumption of the CPU
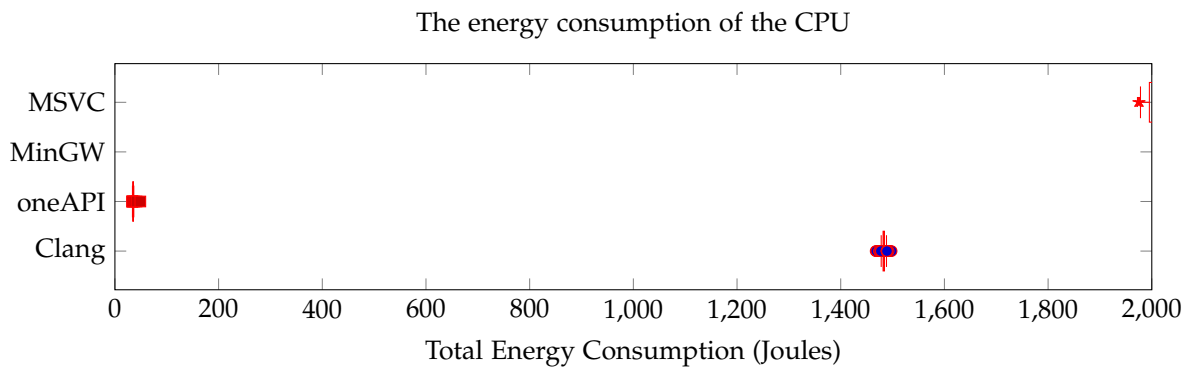
Figure 11: CPU measurements by IPG on DUT 1 for benchmark(s) MB

The duration of the Runtime
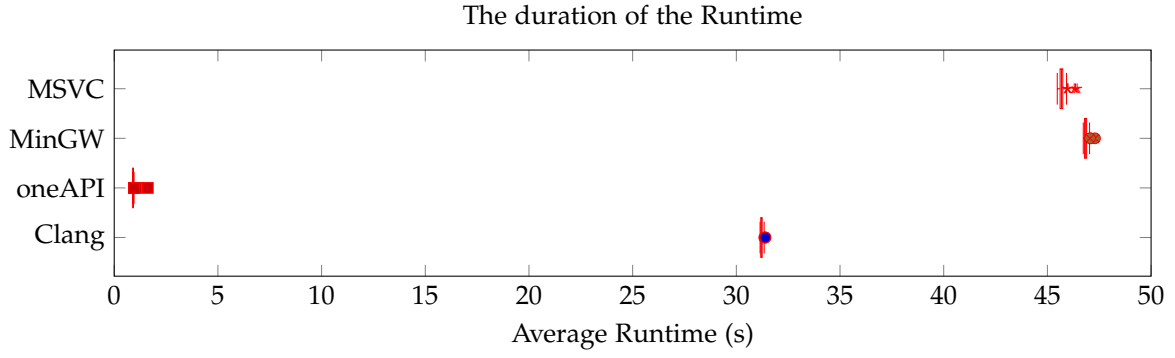
Figure 12: Runtime measurements by IPG on DUT 1 for benchmark(s) MB

E   Experiment Two

Measurements made on for the second experiment, aiming to find the best measuring instrument, found in Section **5.2**.

The DEC of the CPU
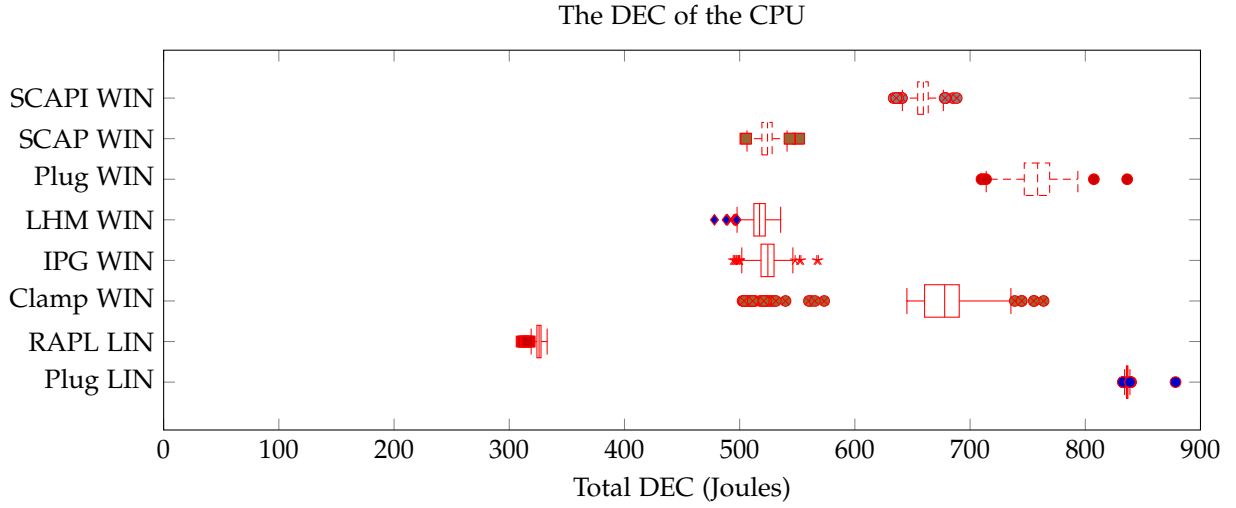
Figure 13: CPU measurements on DUT 1 for benchmark(s) FR compiled on oneAPI

The DEC per second of the CPU
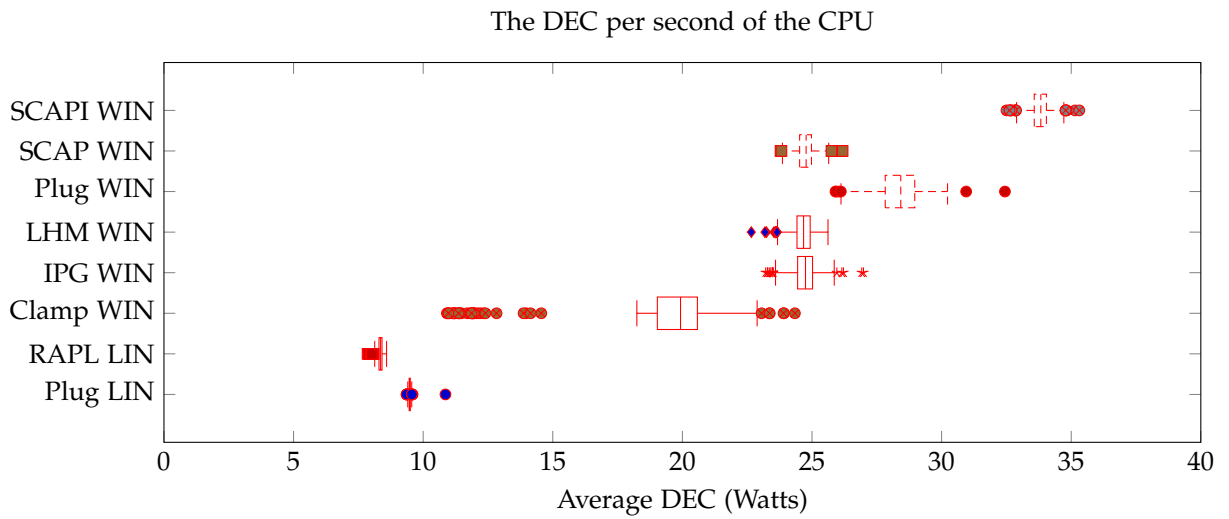
Figure 14: CPU measurements on DUT 1 for benchmark(s) FR compiled on oneAPI

The average duration
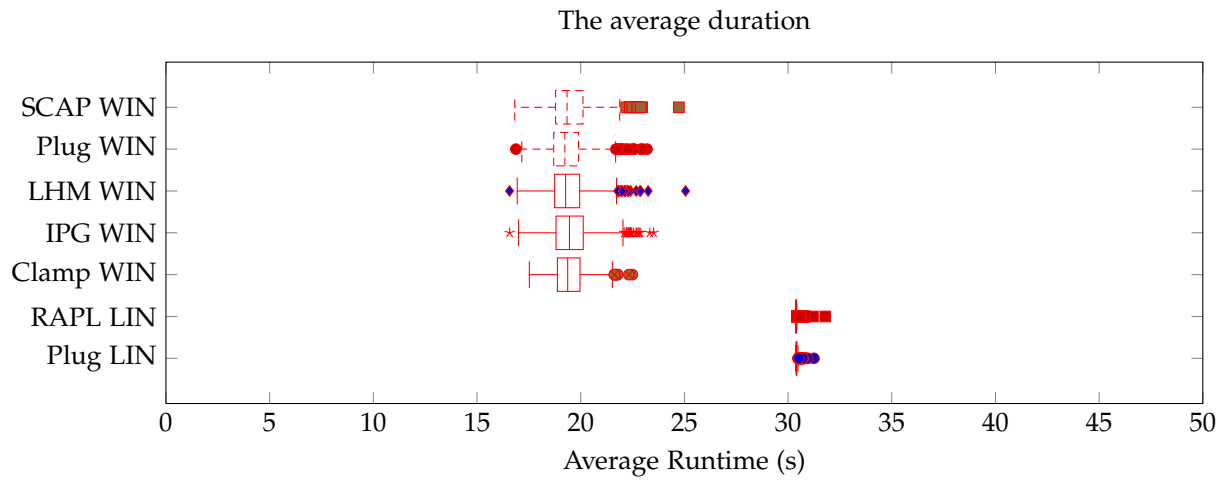
Figure 15: Runtime measurements on DUT 1 for benchmark(s) FR compiled on oneAPI

The DEC of the CPU
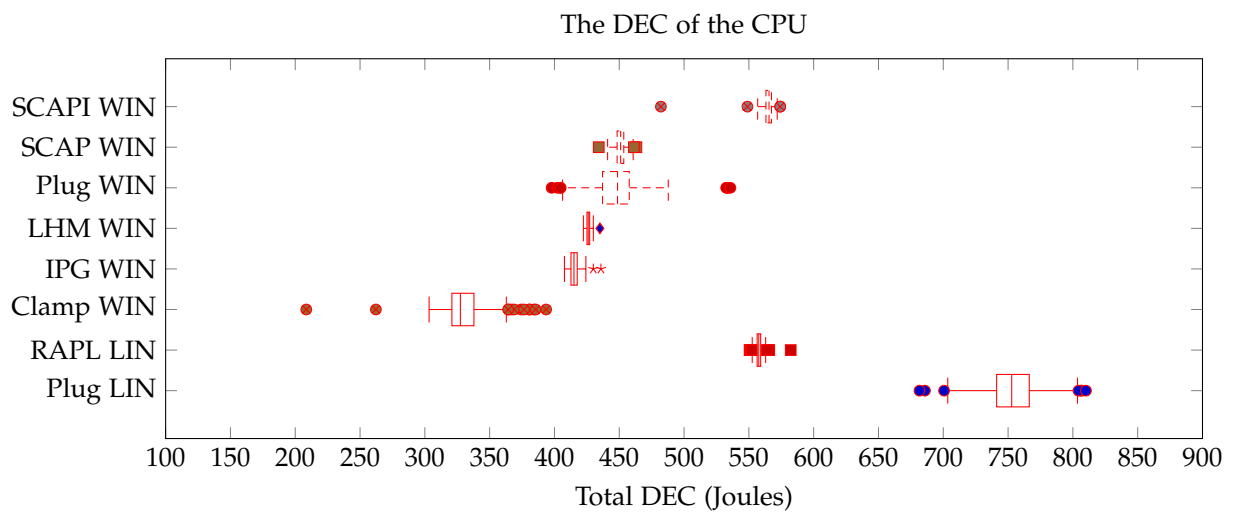
Figure 16: CPU measurements on DUT 1 for benchmark(s) MB compiled on oneAPI

The DEC per second of the CPU
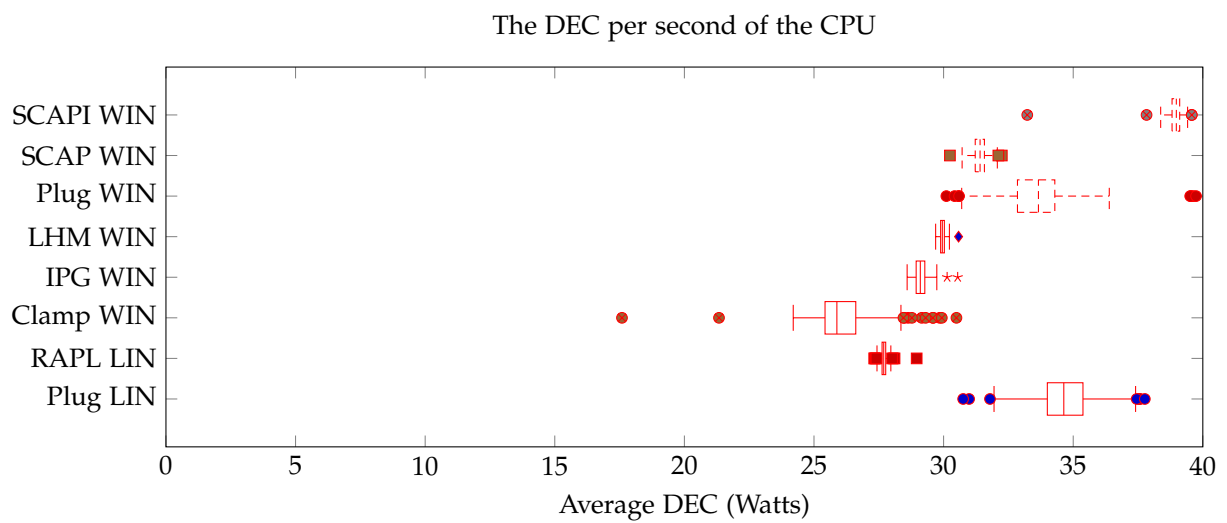
Figure 17: CPU measurements on DUT 1 for benchmark(s) MB compiled on oneAPI
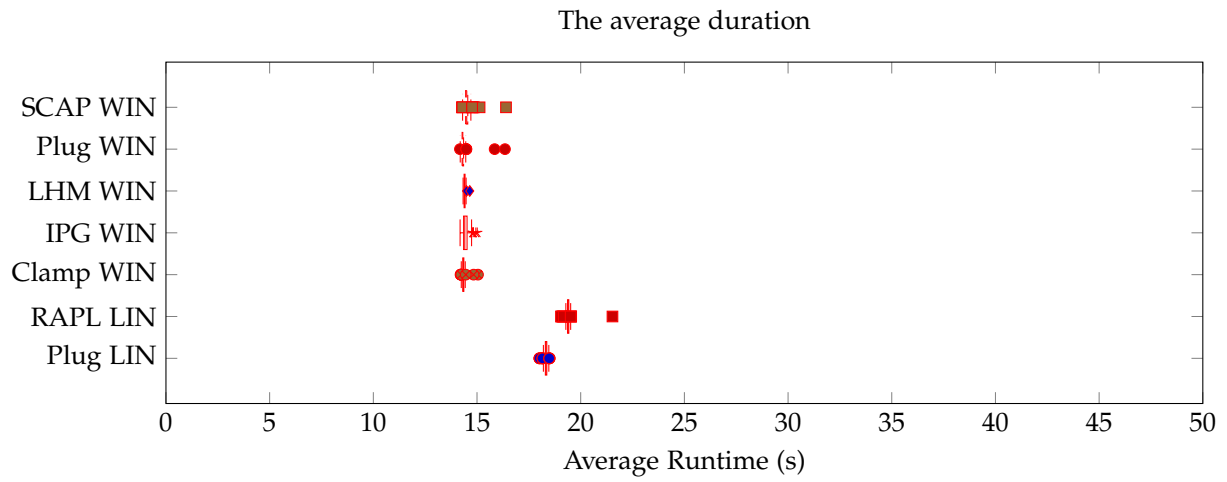
Figure 18: Runtime measurements on DUT 1 for benchmark(s) MB compiled on oneAPI
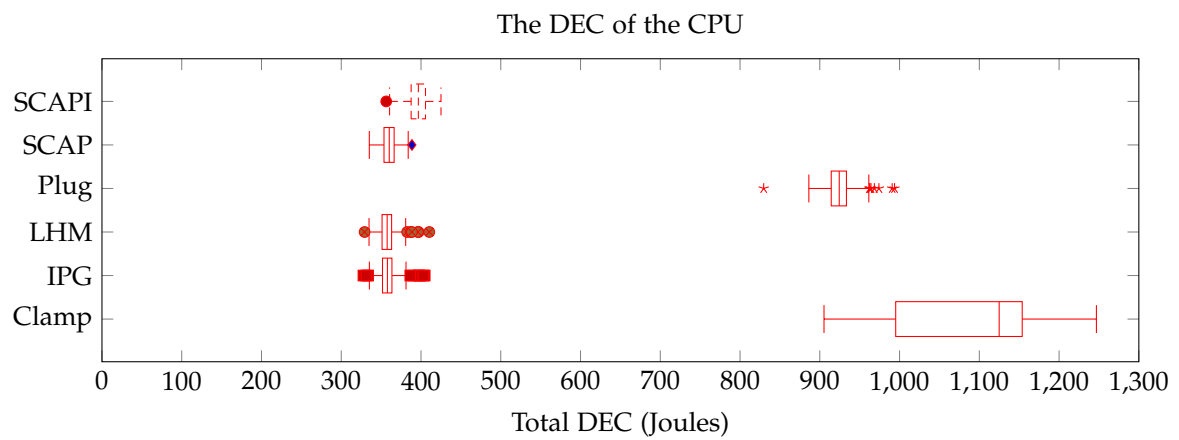
Figure 19: CPU measurements on DUT 2 for benchmark(s) FR compiled on oneAPI
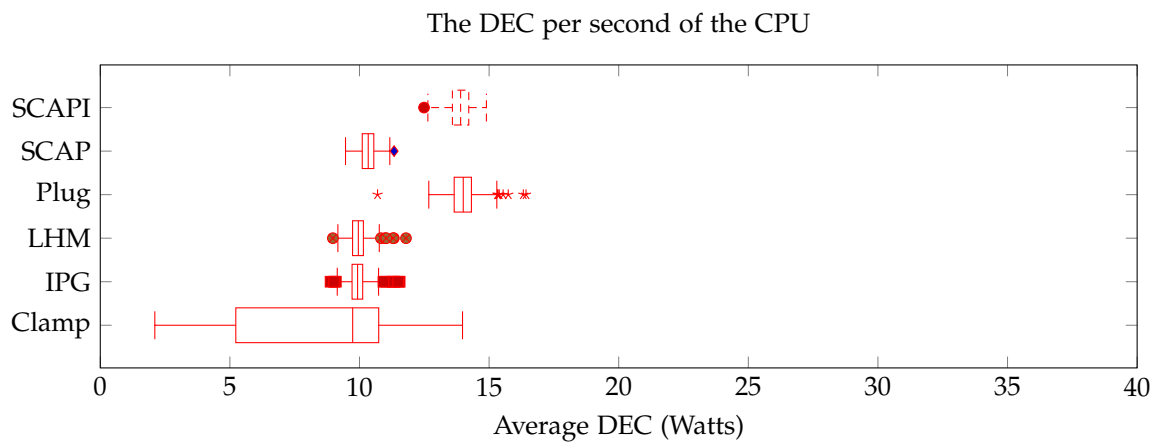
Figure 20: CPU measurements on DUT 2 for benchmark(s) FR compiled on oneAPI

The average duration
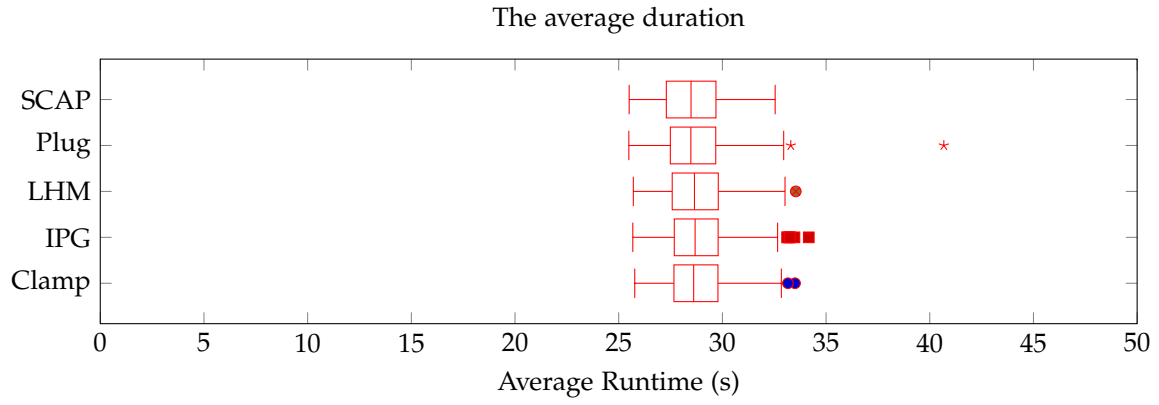
Figure 21: Runtime measurements on DUT 2 for benchmark(s) FR compiled on oneAPI

The DEC of the CPU
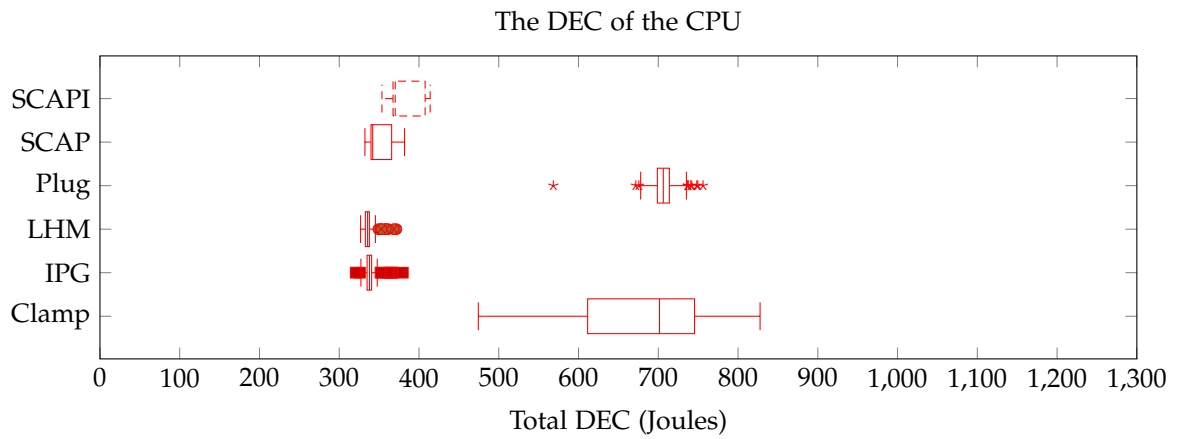
Figure 22: CPU measurements on DUT 2 for benchmark(s) MB compiled on oneAPI
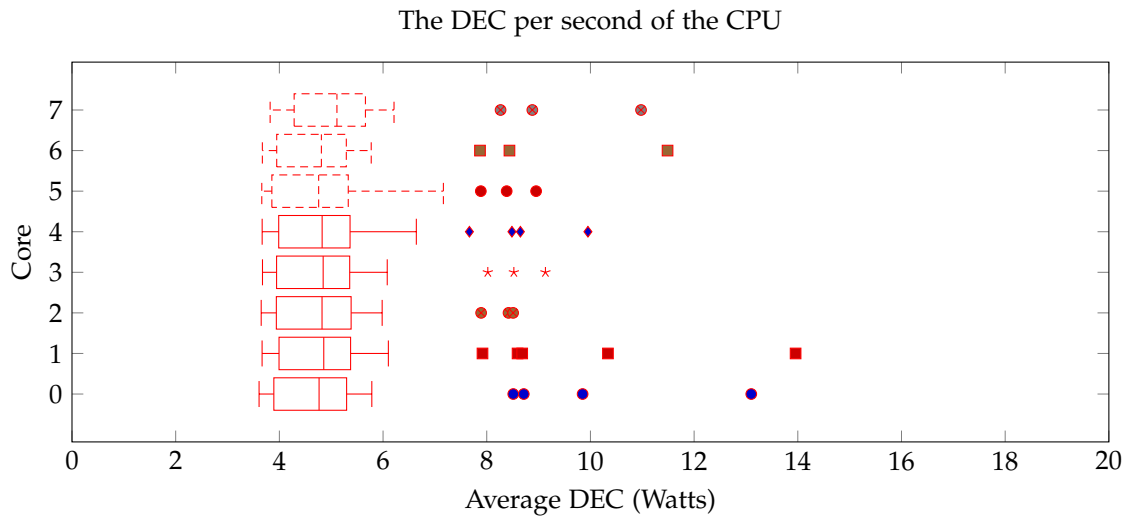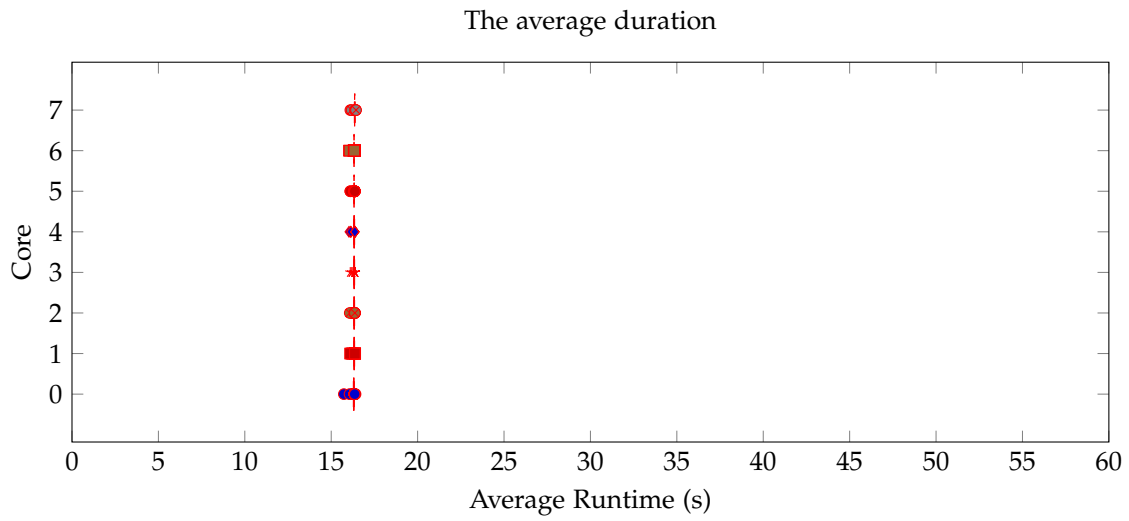

The DEC per second of the CPU
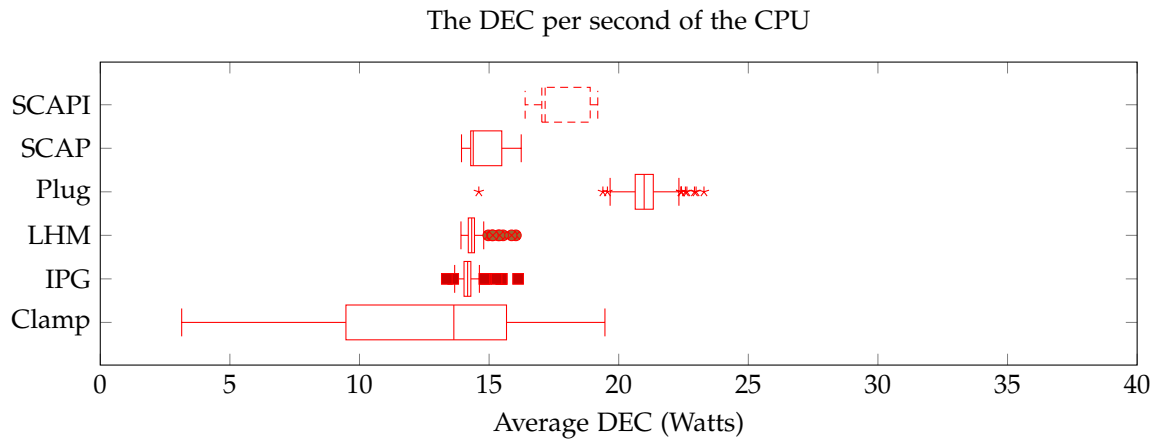
Figure 23: CPU measurements on DUT 2 for benchmark(s) MB compiled on oneAPI
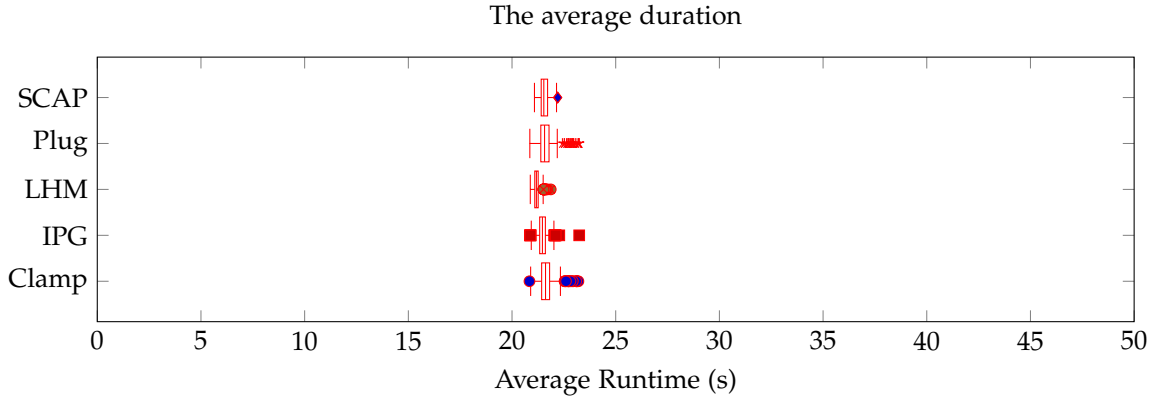
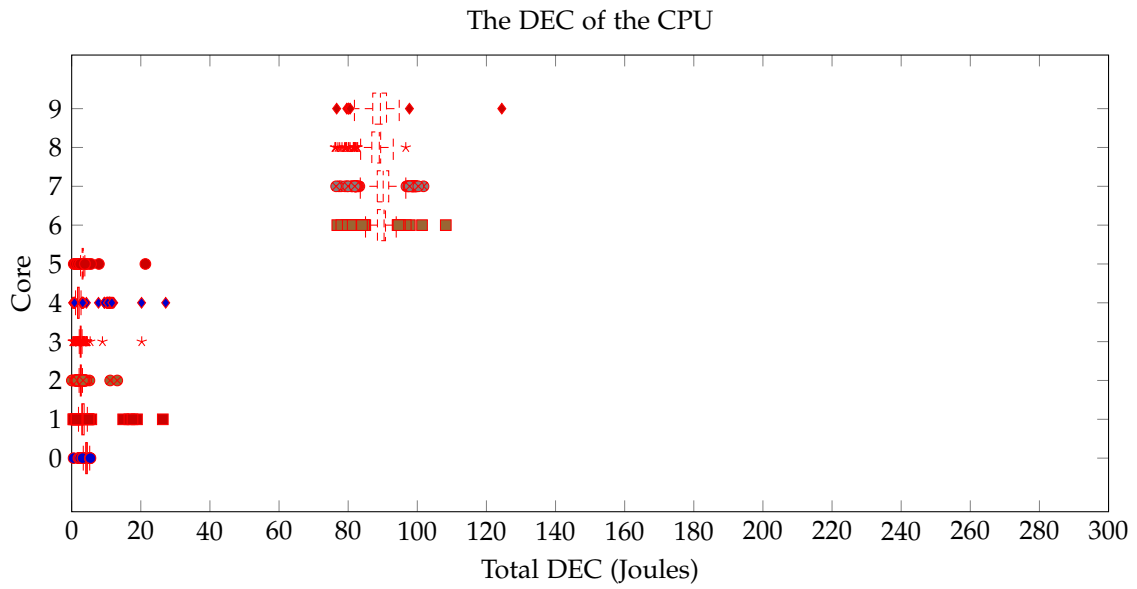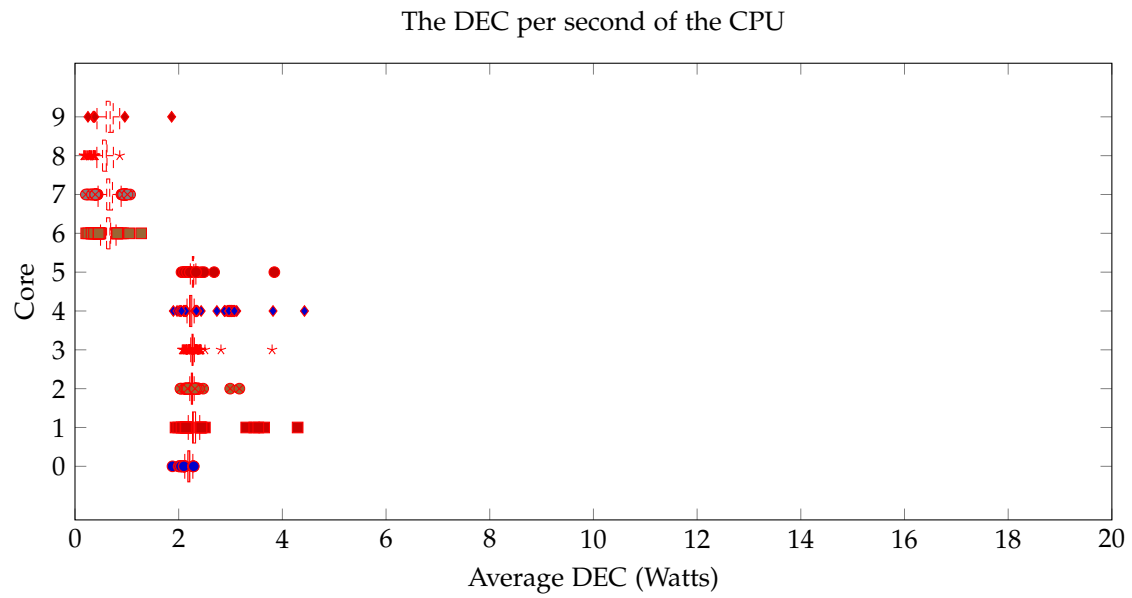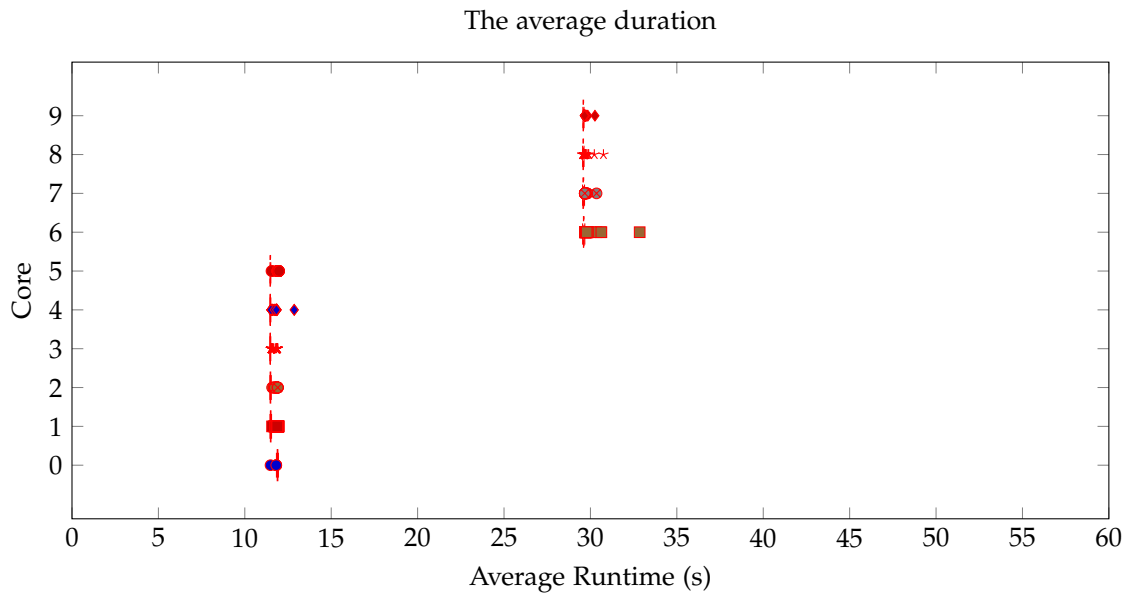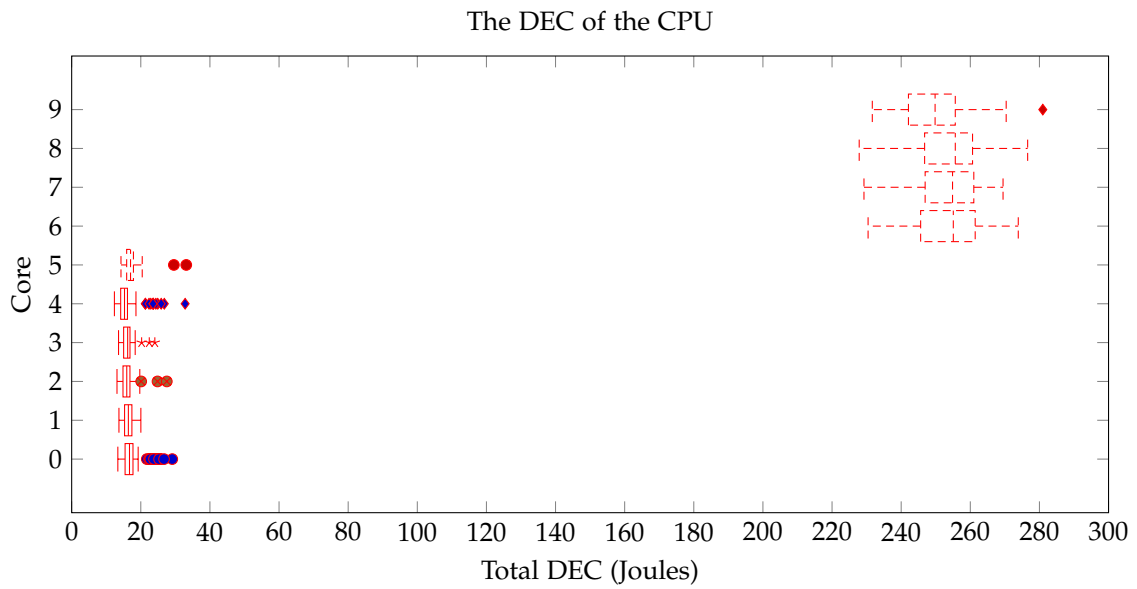**Figure 24:** Runtime measurements on DUT 2 for benchmark(s) MB compiled on oneAPI

F Initial Measurements in Experiment Two

This section illustrates how many measurements are required from the different measuring instruments in order to gain confidence in them, and are used in Section **5.2**.

Initial Measurements		
Name	Fannkuch Redux	Mandelbrot
Plug (W)	2.474	1.790
Plug (L)	5	4818
Clamp (W)	16.908	2855
Clamp (L)	???	???
RAPL	52	53
SCAP	459	74
SCAPI	453	153
IPG	714	216
LHM	604	45

Table 12: The required samples to gain confidence in the measurements made by the different measuring instruments, on both OSs for DUT 1

Initial Measurements		
Name	Fannkuch Redux	Mandelbrot
Plug (W)	916	1.088
Plug (L)	738	1056
Clamp (W)	36.558	44.106
Clamp (L)	???	???
RAPL	1298	4.340
SCAP	416	1.478
SCAPI	840	3.095
IPG	379	88
LHM	379	31

Table 13: The required samples to gain confidence in the measurements made by the different measuring instruments, on both OSs for DUT 2

Correlation from Experiment Two

This section shows the correlation heatmap from Section **5.2**.
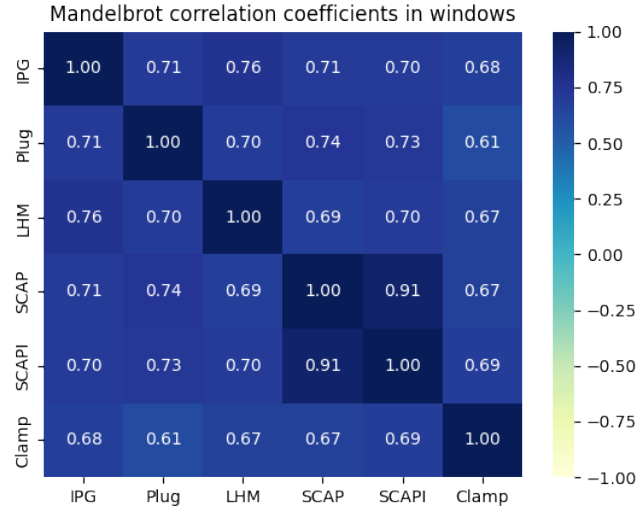
Figure 25: Heatmap showing the correlation coefficient between all of the measurement instruments on windows for the Mandelbrot benchmark.

G   Cochran's Formula Evolution for Experiment Two

This section shows the evolution of how many measurements are required, calculated using Cochran's formula on different amount of measurements, as used in Section **5.2**.
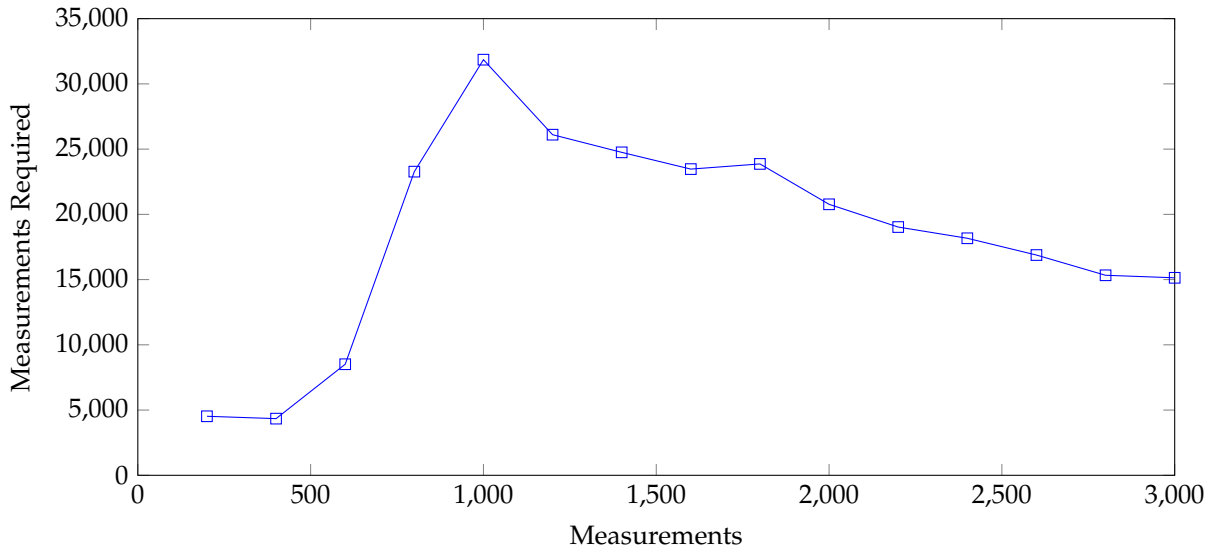
H   Experiment Three

This section includes the results from the third experiment, as can be found in Section **5.3**
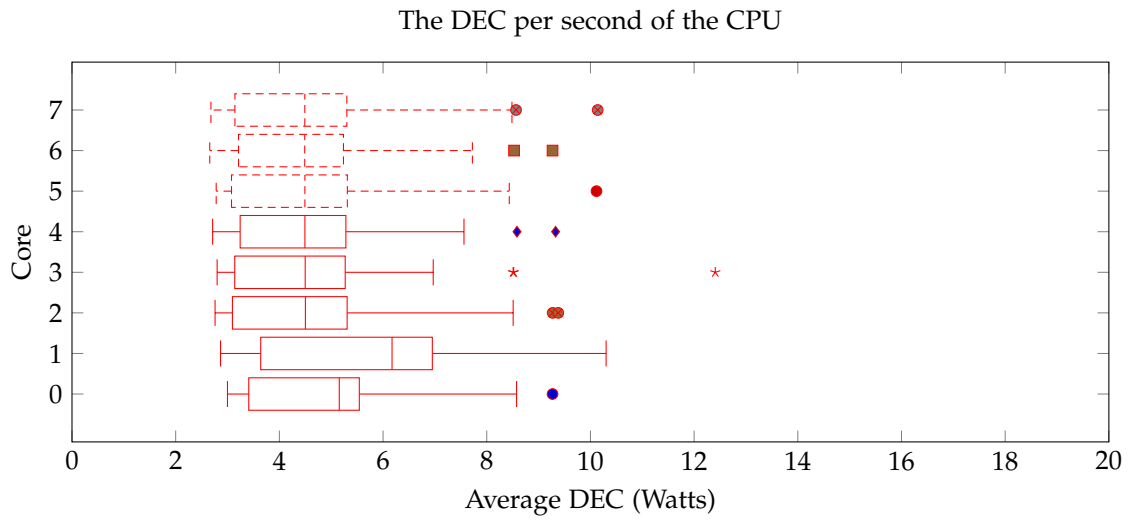
Figure 26: CPU measurements by IPG on DUT 1 for benchmark(s) NB compiled on oneAPI
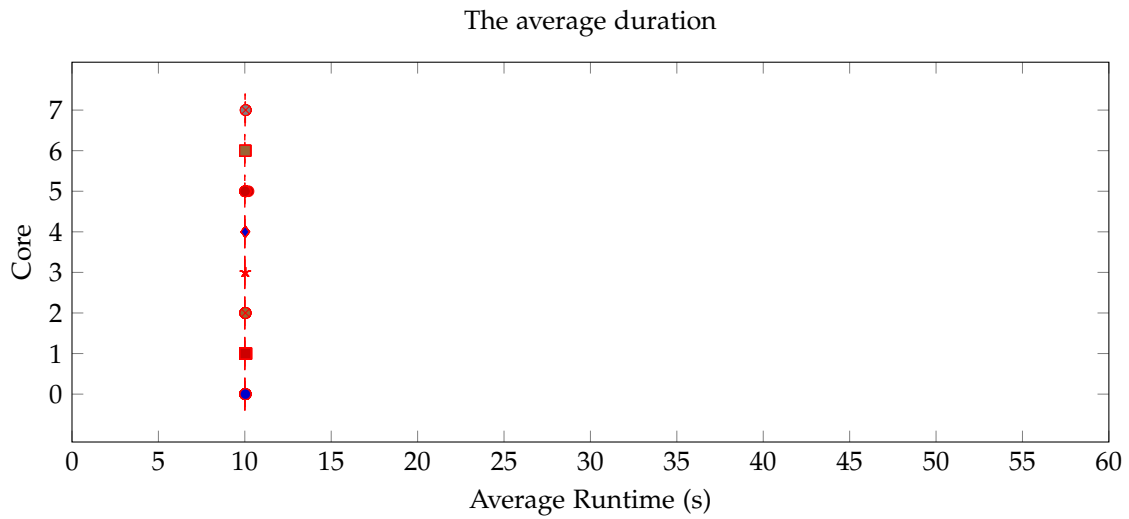
Figure 27: Runtime measurements by IPG on DUT 1 for benchmark(s) NB compiled on oneAPI
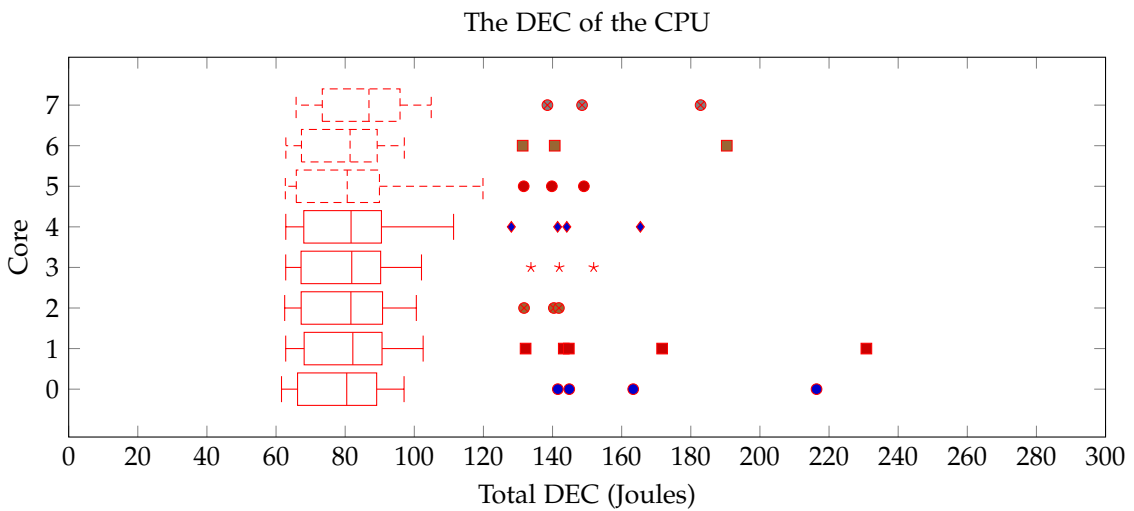
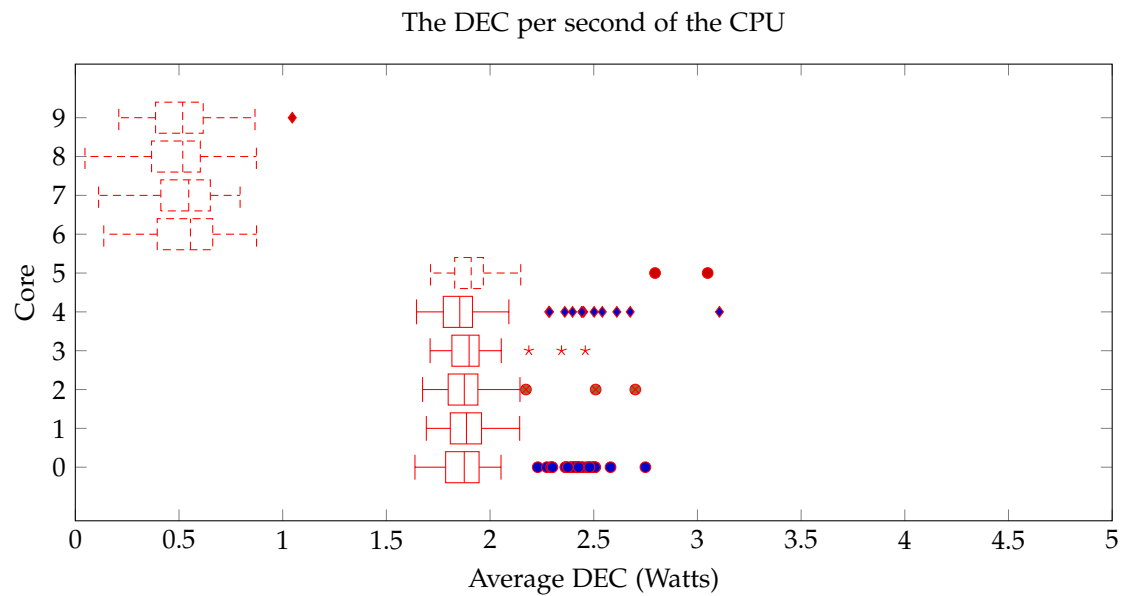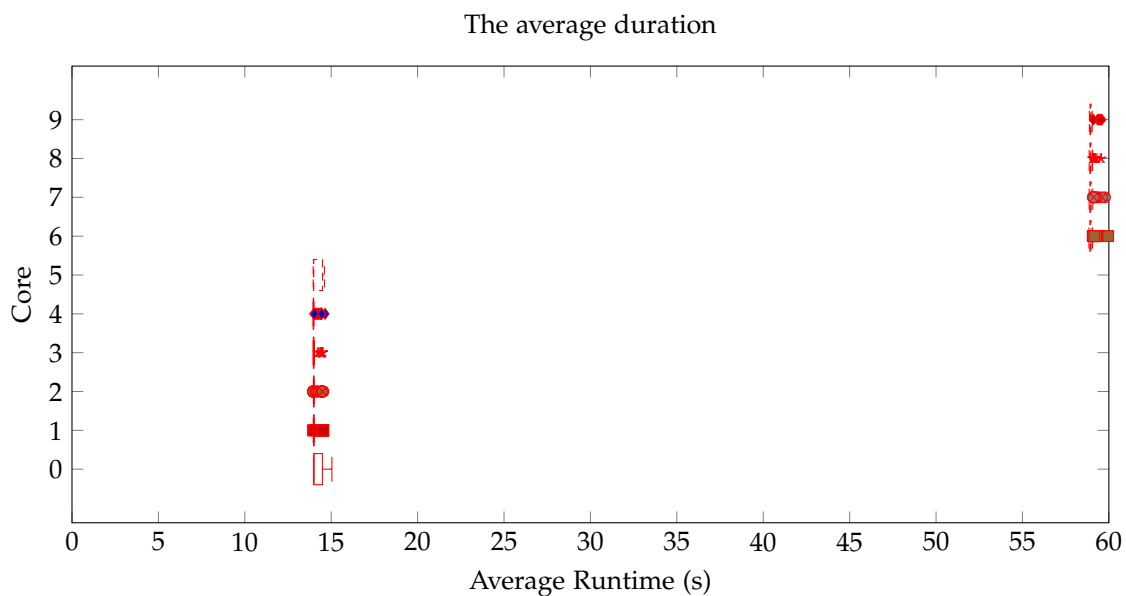**Figure 28:** CPU measurements by IPG on DUT 1 for benchmark(s) SN compiled on oneAPI

The DEC per second of the CPU

Figure 29: CPU measurements by IPG on DUT 1 for benchmark(s) SN compiled on oneAPI

The average duration

Figure 30: Runtime measurements by IPG on DUT 1 for benchmark(s) SN compiled on oneAPI

The DEC of the CPU

Figure 31: CPU measurements by IPG on DUT 2 for benchmark(s) NB compiled on oneAPI

The DEC per second of the CPU

Figure 32: CPU measurements by IPG on DUT 2 for benchmark(s) NB compiled on oneAPI

Figure 33: Runtime measurements by IPG on DUT 2 for benchmark(s) NB compiled on oneAPI

Figure 34: CPU measurements by IPG on DUT 2 for benchmark(s) SN compiled on oneAPI

The DEC per second of the CPU

Figure 35: CPU measurements by IPG on DUT 2 for benchmark(s) SN compiled on oneAPI

The average duration

Figure 36: Runtime measurements by IPG on DUT 2 for benchmark(s) SN compiled on oneAPI

I   Measurements Required in Experiment Three Cores

This section illustrates how many measurements are required from IPG when measuring the energy consumption on different cores in order to gain confidence in them, and are used in Section **5.3**.

| Initial Measurements		
Name	NBody	Spectral-Norm
Core 0	5.162	1.991
Core 1	11.771	1.999
Core 2	5.119	2.047
Core 3	4.678	2.039
Core 4	4.597	1.979
Core 5	5.005	2.082
Core 6	4.622	1.852
Core 7	4.996	1.945

Table 14: The required samples to gain confidence in the measurements made by IPG in different cores for DUT 1

| Initial Measurements		
Name	NBody	Spectral-Norm
Core 0	4	36
Core 1	7	33
Core 2	1	35
Core 3	1	28
Core 4	3	33
Core 5	2	30
Core 6	17	115
Core 7	22	99
Core 8	18	121
Core 9	39	92

Table 15: The required samples to gain confidence in the measurements made by IPG in different cores for DUT 2

J   Measurements Required in Experiment Three Macrobenchmarks

This section illustrates how many measurements are required from IPG when measuring the energy consumption of the macrobenchmarks in order to gain confidence in them, and are used in Section **5.3**.

Initial Measurements		
Name	3DM	PCM
1 Core	1207	*TBD*
2 Cores	1470	*TBD*
3 Cores	1531	*TBD*
4 Cores	1524	*TBD*
5 Cores	2054	*TBD*
6 Cores	2359	*TBD*
7 Cores	1810	*TBD*
8 Cores	1391	*TBD*

Table 16: The required samples to gain confidence in the measurements made by IPG for the macrobenchmarks for DUT 1

Initial Measurements		
Name	3DM	PCM
1 Core	22	*TBD*
2 Cores	183	*TBD*
3 Cores	135	*TBD*
4 Cores	56	*TBD*
5 Cores	79	*TBD*
6 Cores	53	*TBD*
7 Cores	25	*TBD*
8 Cores	20	*TBD*
9 Cores	42	*TBD*
10 Cores	44	*TBD*

Table 17: The required samples to gain confidence in the measurements made by IPG on for different macrobenchmarks for DUT 2

## Results for Macrobenchmarks in the Third Experiment

In this section the energy consumption for an increasing number of cores can be found, referenced in Section **5.3**.
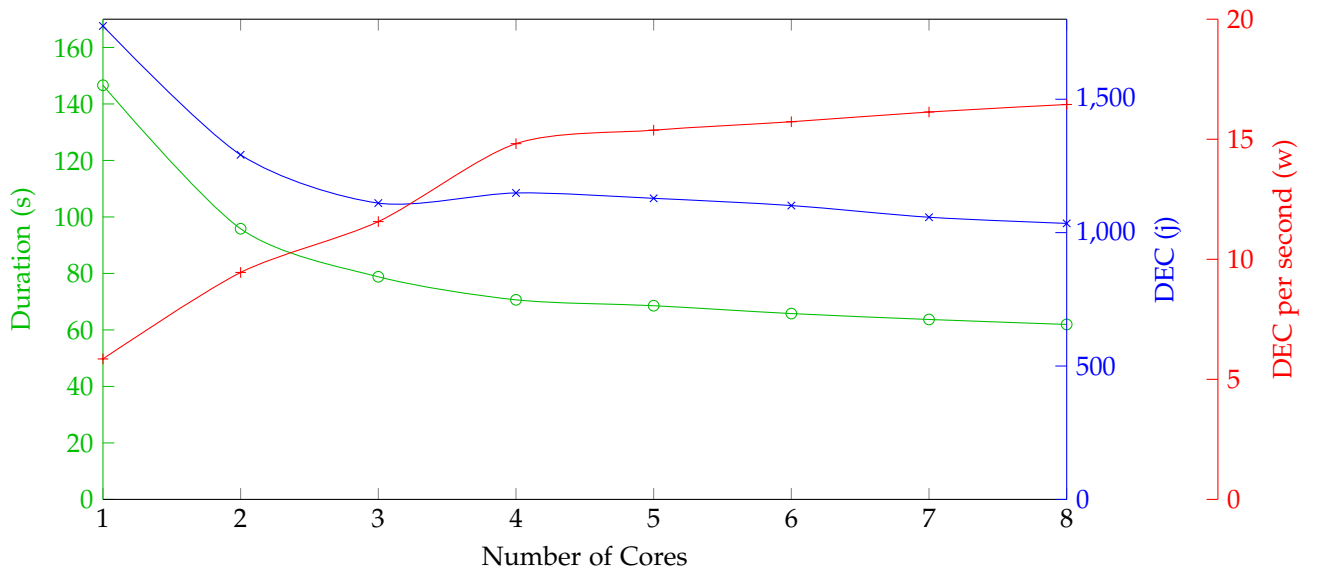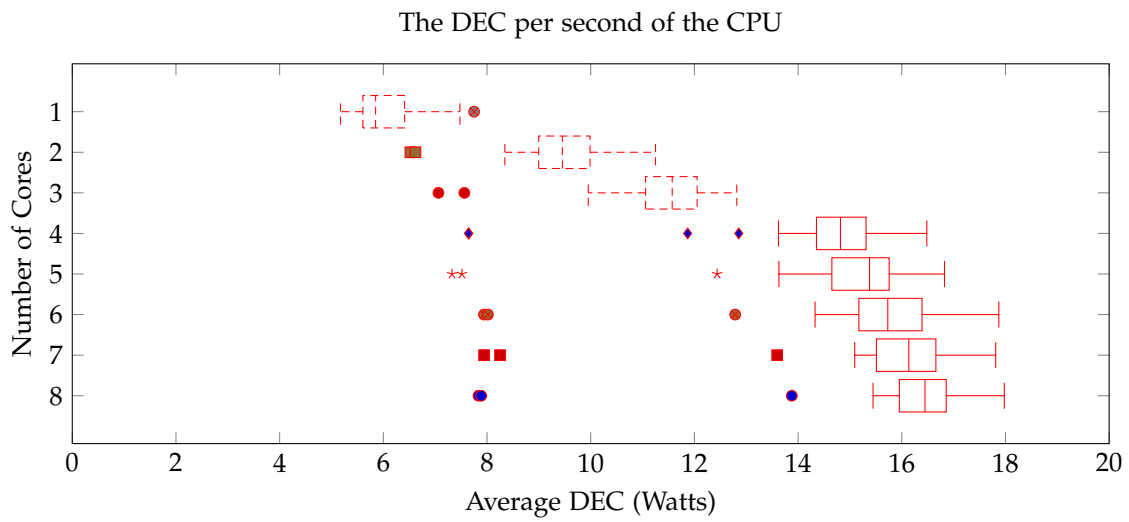
Figure 37: The evolution of the DEC (blue), DEC per second (red) and duration (green) as more cores are allocated to 3DM on DUT 1
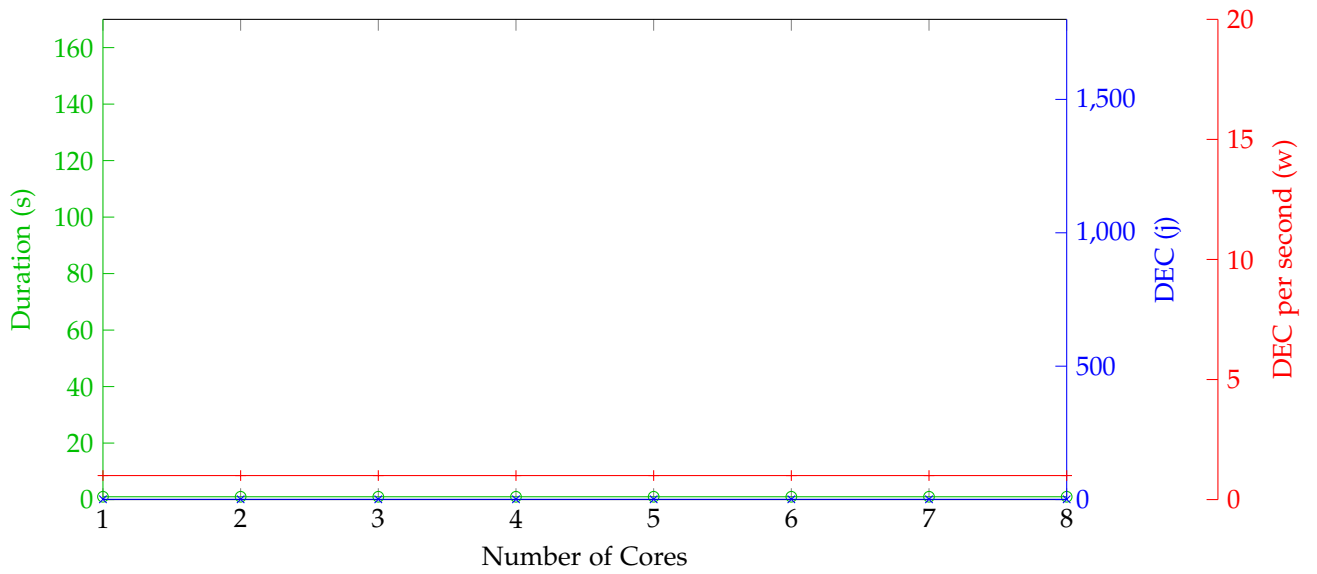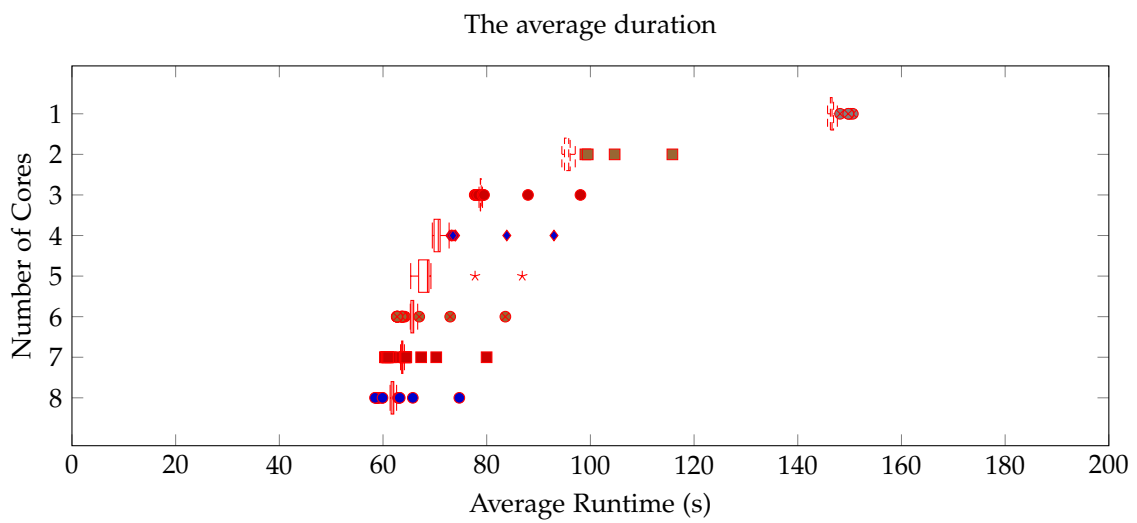

Figure 38: The evolution of the DEC (blue), DEC per second (red) and duration (green) as more cores are allocated to PCM on DUT 1
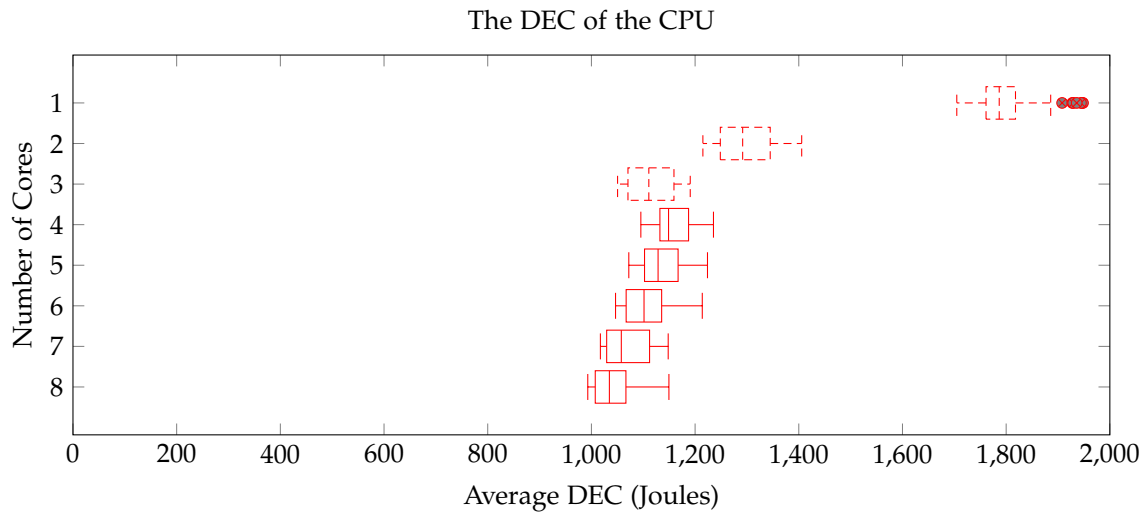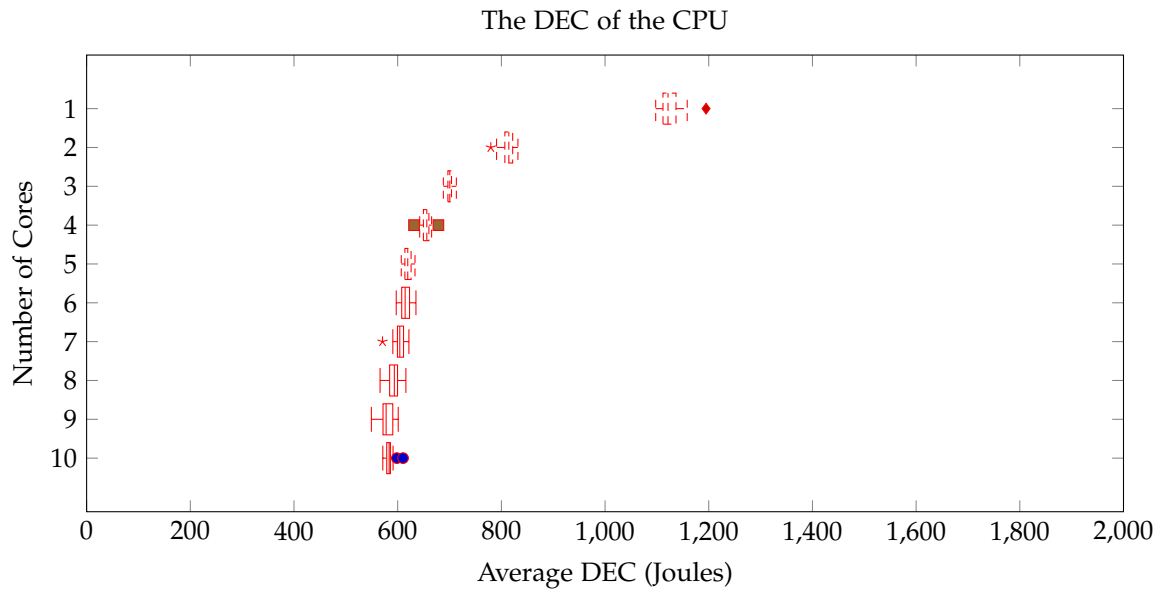
Figure 39: CPU measurements by IPG on DUT 1 for test case(s) 3DM
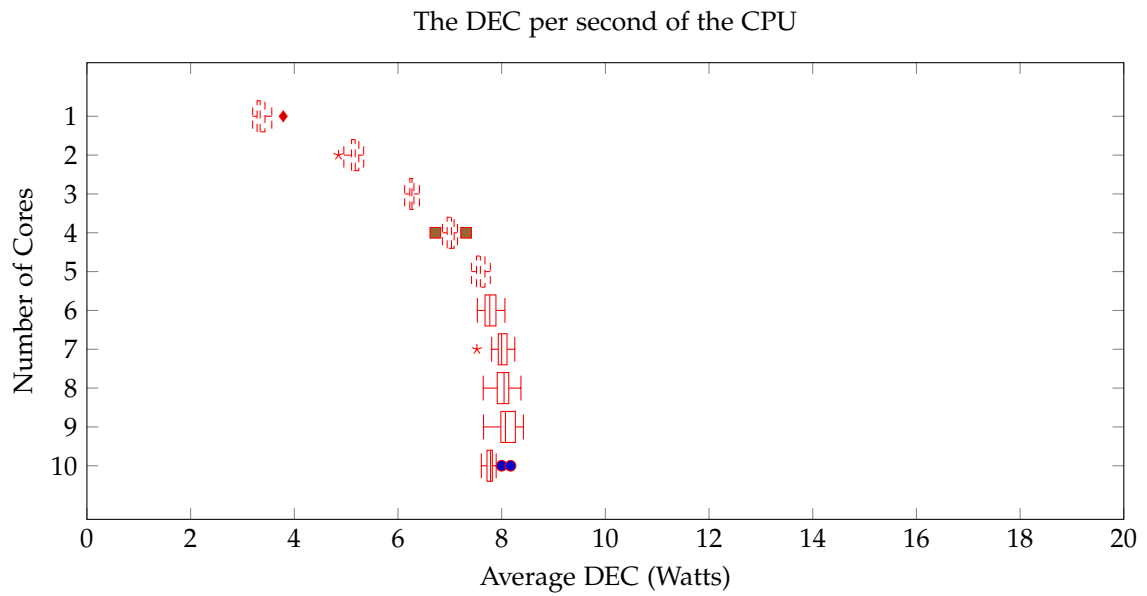

Figure 40: CPU measurements by IPG on DUT 1 for test case(s) 3DM

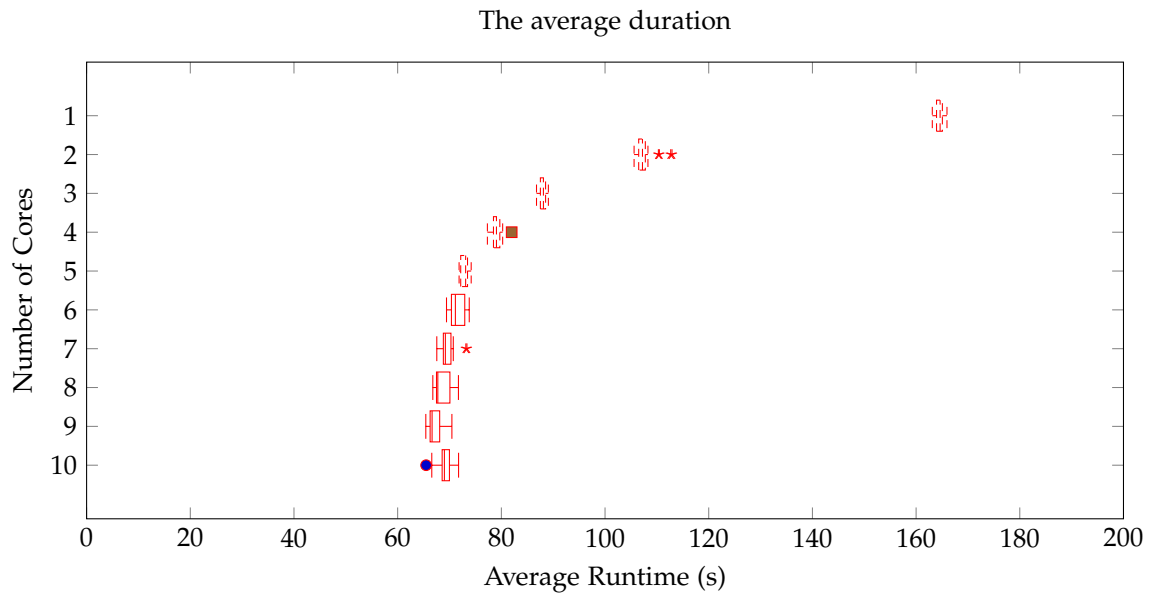**Figure 41:** Runtime measurements by IPG on DUT 1 for test case(s) 3DM

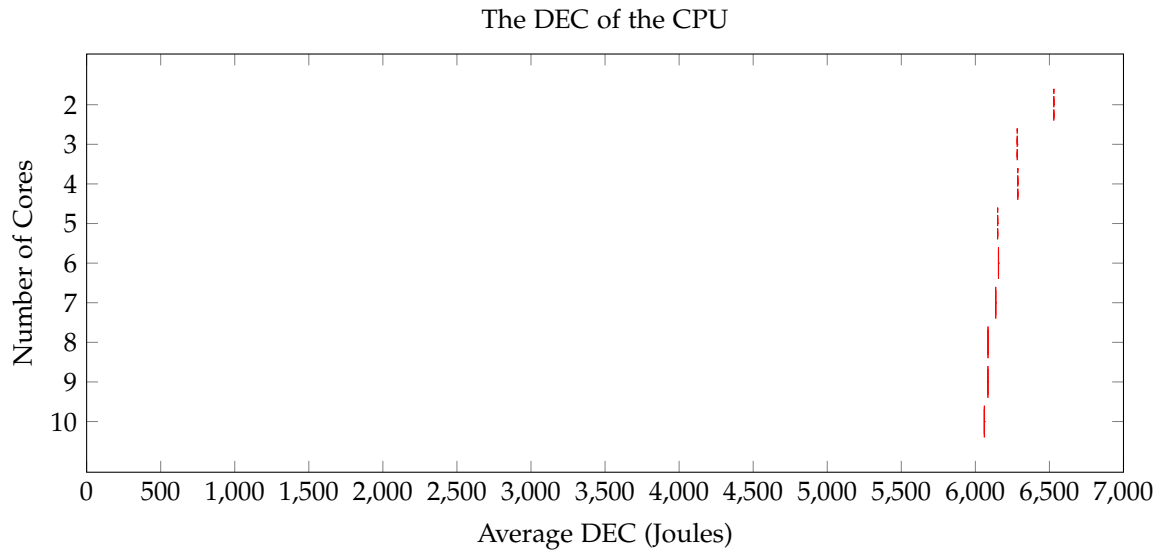**Figure 42:** CPU measurements by IPG on DUT 2 for test case(s) 3DM

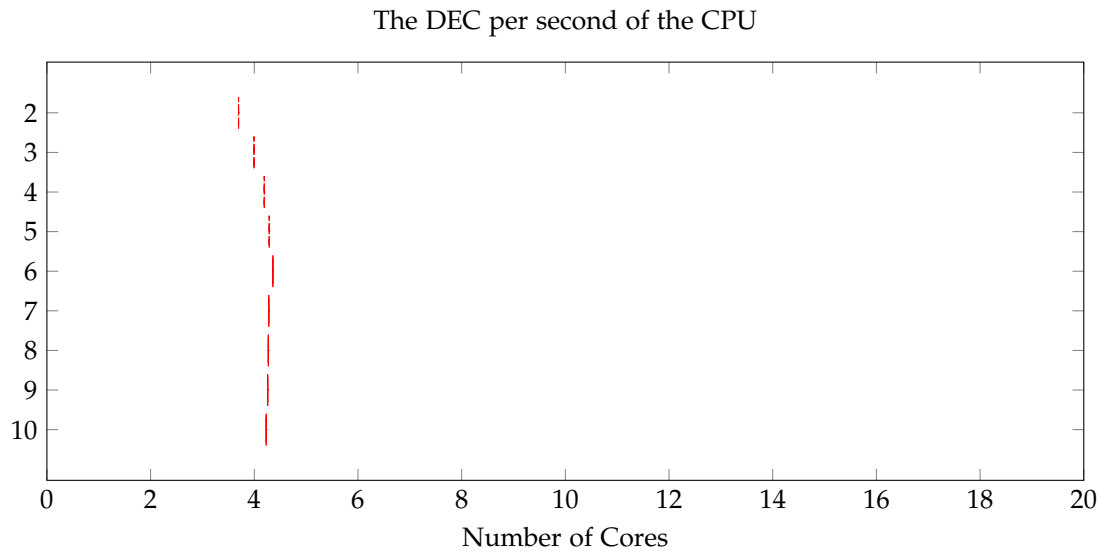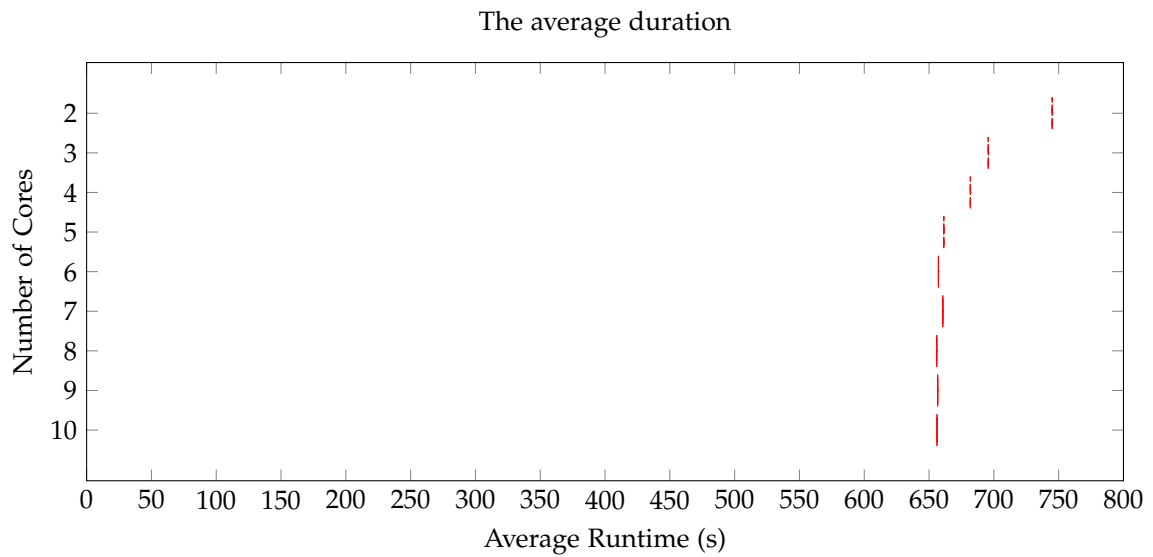**Figure 43:** CPU measurements by IPG on DUT 2 for test case(s) 3DM

Figure 44: Runtime measurements by IPG on DUT 2 for test case(s) 3DM

Figure 45: CPU measurements by IPG on DUT 2 for test case(s) PCM

The DEC per second of the CPU

Figure 46: CPU measurements by IPG on DUT 2 for test case(s) PCM

The average duration

Figure 47: Runtime measurements by IPG on DUT 2 for test case(s)

K   Experiment Three Combined Results

This section shows the results illustrated in Appendix **J** from experiment three as a table. This table is used in Section **5.3**.

| | DUT 1 | | | | DUT 2 | | | |
| | PCM | | 3DM | | PCM | | 3DM | |
Cores	Duration	DEC	Duration	DEC	Duration	DEC	Duration	DEC
					Performance Evolution			
1	*TBD*	*TBD*	146.6 s	1774.6 j	*TBD*	*TBD*	164.0 s	1111.2 j
2	*TBD*	*TBD*	−34.6%	−27.2%	*TBD*	*TBD*	−34.5%	−26.7%
3	*TBD*	*TBD*	−17.7%	−14.0%	*TBD*	*TBD*	−17.7%	−14.0%
4	*TBD*	*TBD*	−10.4%	+3.4%	*TBD*	*TBD*	−10.3%	−6.3%
5	*TBD*	*TBD*	−2.9%	−1.8%	*TBD*	*TBD*	−7.4%	−5.6%
6	*TBD*	*TBD*	−4.9%	−2.4%	*TBD*	*TBD*	−3.0%	−0.9%
7	*TBD*	*TBD*	−3.2%	−4.0%	*TBD*	*TBD*	−2.6%	−1.5%
8	*TBD*	*TBD*	−2.8%	−2.2%	*TBD*	*TBD*	−3.1%	−1.8%
9	*TBD*	*TBD*			*TBD*	*TBD*	−0.4%	−2.7%
10	*TBD*	*TBD*			*TBD*	*TBD*	+3.5	+0.7%

Table 18: The results when executing PCM and 3DM on DUT 1 and 2, where each row represents the percent difference from the previous row.