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READEX
Runtime Exploitation of Application Dynamism for Energy-efficient eXascale computing

# D5.1
# Report on Application Dynamism

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# Contents

# 1 Introduction

The energy consumption of supercomputers is one of the critical problems for the upcoming Exascale supercomputing era. The awareness of power and energy consumption is required on both software and hardware side. This report presents the evaluation of basic kernels, several more complex proxy applications from ProxyApps package and a set of full fledge applications, such as ESPRESO FEM library with FETI based solvers, molecular dynamics code MiniMD and sheet metal forming simulation software Indeed and well known open-source CFD package OpenFOAM.

Section 2 introduces crucial metrics used for detection and evaluation of the dynamic behavior of applications. These are the execution time, the computational intensity and energy consumption.

The selected tuning parameters from three different domains: (1) hardware parameters, (2) runtime system parameters and (3) application parameters are described in Section 3. The list of parameters is not final and more will be investigated in the second half of the project.

In order to evaluate the dynamic behavior of any parallel application we have developed MERIC, a tool for semi-automatic energy consumption evaluation. By semi-automatic we mean that the regions of the code that user want to evaluate must be annotated manually, but the rest of the evaluation process is automatic. In the current version the MERIC uses exhaustive parameters space search. This tool is introduced in Section 4.

Section 5 describes the RADAR report and the automatic report generator. This is used for reporting the dynamic savings in this document.

Sections 6 and 7 present the achieved energy savings for selected applications for intra-phase and inter-phase dynamism, respectively. The applications range from basic BLAS kernels to real world applications. The evaluation is using various tuning parameters including hardware, system software, and application parameters. The effect of both types of tuning: (1) static tuning (when the tuning parameter is fixed for the whole phase) and (2) dynamic tuning (when the tuning parameter changes for particular kernels of this phase) were examined.

Finally Section 8 concludes the document with an overview of the achieved savings of all applications and final discussion.

## 2 Overview of Dynamism Metrics

The READEX tool suite will tune hardware, system software and application tuning parameters as described in D4.1 [10]. In order to apply the best configurations for the tuning parameters during run-time application tuning (RAT) that are computed during design time analysis (DTA), the dynamism present in an application has to be first analysed and quantified using dynamism metrics during DTA. To achieve this, experiments are performed during which the application is run to obtain measurements for the different dynamism metrics to quantify the dynamism present in the application. Additionally, these tools also evaluate the potential savings using objective values (such as energy consumed and execution time) that indicate the result of run-time tuning.

The dynamism metrics that are presently measured and used in the READEX project are:

1. Execution time.
2. Energy consumed.
3. Computational intensity.

Among these three metrics, the semantics of execution time and energy consumed are straightforward. Variation in the execution time and energy consumed by regions in an application during its execution is an indication of different resource requirements. The execution time and energy consumed are also used in an objective function that will be measured to quantify the result or potential gain of tuning an application using the READEX tool suite. The computational intensity is a metric that is used to model the behaviour of an application based on the workload imposed by it on the CPU and the memory. Presently, computational intensity is calculated using the following formula and is analogous to the operational intensity used in the roofline model [16].

$$Computational\ Intensity \quad = \quad \frac{Total\ number\ of\ instructions\ executed}{Total\ number\ of\ L3\ cache\ misses}.$$

Computational intensity can directly dictate the tuning of two hardware parameters: CPU core frequency and CPU uncore frequency. A low computational intensity may indicate an application that is more memory intensive, which results in increased L3 cache misses. Since this would cause increased traffic between the L3 cache and the main memory, it will be desirable to increase the uncore frequency. On the other hand, a high computational intensity may indicate an application that is more computation intensive. In this case, it will be desirable to increase the frequency of the CPU cores.

In the context of the READEX project, an application is termed to exhibit the following two types of dynamism:

- Inter-phase dynamism: This is when each phase of a phase region in the application exhibits different characteristics. This results in different values for the measured objective values and thus may require different configurations to be applied for the tuning parameters.

- Intra-phase dynamism: This is when each run-time situation of the significant regions in a phase region exhibits different characteristics and thus may need different configurations to be applied for the tuning parameters.

Due to the different localities of dynamism in an application, the dynamism metrics are measured and analysed from the following three perspectives:

- For the entire run of the application.
- For all phases of the phase region in the application – this allows analysis of inter-phase dynamism that may be present in the application.
- For all run-time situtations of the significant regions in the application – this allows analysis of intra-phase dynamism that may be present in the application.

The dynamism observed in an application can be due to variation of the following factors:

- Floating point computations (for example, this may occur due to variation in the density of matrices in dense linear algebra).
- Memory read/write access patterns (for example, this may occur due to variation in the sparsity of matrices in sparse linear algebra).
- Inter-process communication patterns (for example, this may occur due to irregularity in a data structure leading to irregular exchange of messages for operations such as global reductions).
- I/O operations performed during the application's execution, see Section 2.2.
- Different inputs to regions in the application.

To address these factors, a set of tuning parameters have been identified in the READEX project as discussed in Section 3.

Presently the MERIC tool (Section 4.1) is being developed and used in the READEX project to measure the above-mentioned dynamism metrics and evaluate applications. The measurements collected by this tools for an application are logged into a READEX Application Dynamism Analysis Report (RADAR) described in Section 5.1.

To demonstrate the idea of the READEX methodology we present the evaluation of three workloads with different computational intensity, Section 2.1. It proves that different configuration of tuning parameters is optimal for different workloads. In addition we perform the detailed evaluation of parallel I/O in Section 2.2.

## 2.1 Investigation of Computational Intensity

The computational intensity (CI) is one of the key metrics to evaluate the dynamism. If an application has a low CI, the application is memory bound (such as Matrix-Vector Multiplication - GEMV) and high CPU frequency cannot be utilized as the data in caches cannot be reused. On the other hand, for high arithmetical intensity (such as Matrix-Matrix vector multiplication - GEMM) the memory traffic is significantly lower and a CPU running at high frequency can be fully utilized.

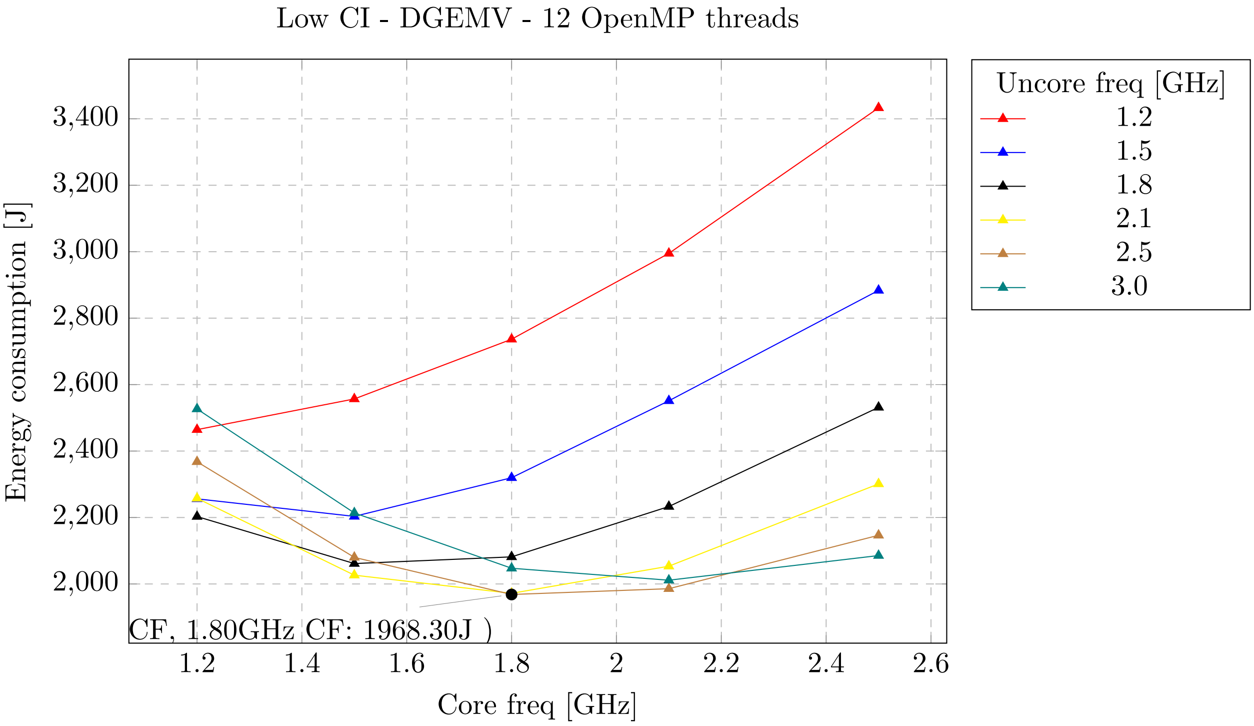
The goal of this section is to demonstrate how the energy consumption for operations with different compute intensity (DGEMV - low CI; DGEMM - higher CI; compute only kernel - very high CI) is affected by the CPU core and uncore frequencies. Please note that in this section we use two MPI processes per node and one MPI process per socket. This way we eliminate the NUMA effect. For this experiment the best configuration for all three functions is to use all cores, i.e. 12 OpenMP threads.

Table 2.1 shows that with increasing CI the effect of the uncore frequency becomes less important, see figures bellow, and the optimal setting is decreased from 2.5 GHz to 1.2 GHz. On the other hand the optimal core frequency should be high (2.5 GHz) for applications with high CI and it is decreasing with lower CI. It can be also observed that core frequency tuning is most efficient for kernels high CI.

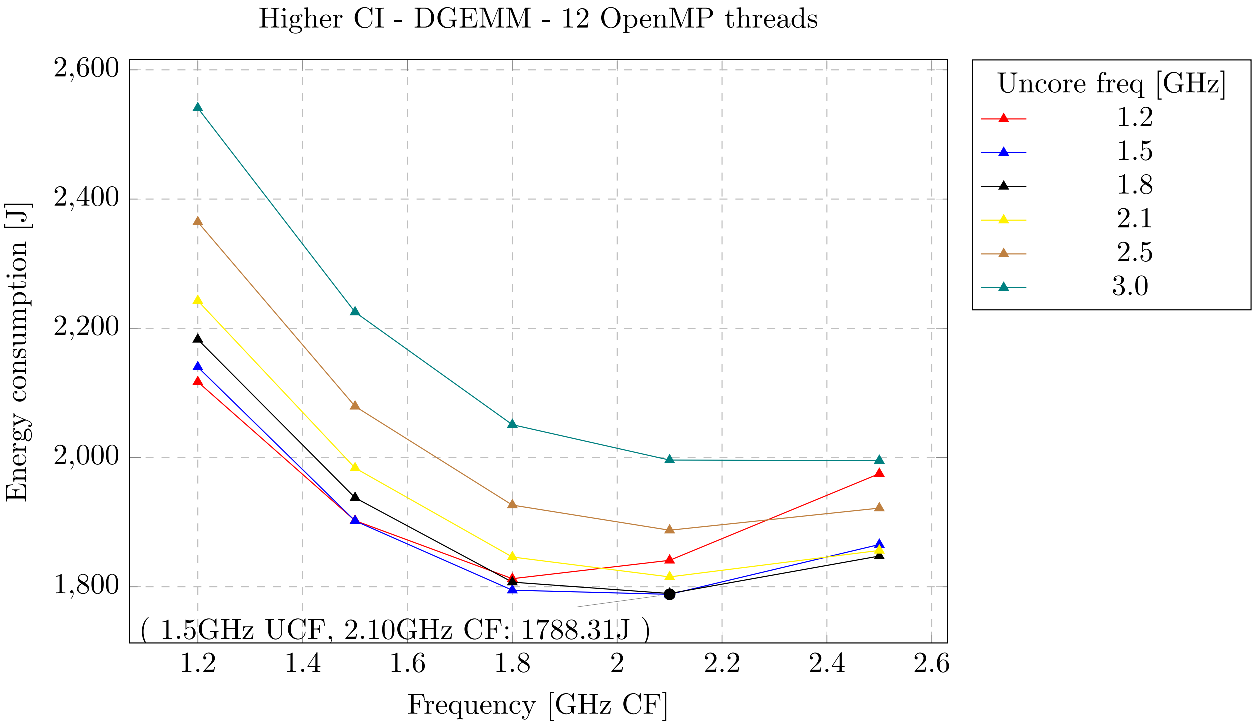
Finally we can observe, that the highest static energy savings, 12.5%, have been achieved by compute bound codes while memory bounded code achieved only 5.6%.

| | **Energy consumption evaluation** | | | |
|---|---|---|---|---|
| **Workload type** | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** |
| DGEMV | 12 threads, 3.0 GHz UCF, 2.5 GHz CF | 2085.47 J | 12 threads, 2.5 GHz UCF, 1.8 GHz CF | 117.17 J (5.62%) |
| DGEMM | 12 threads, 3.0 GHz UCF, 2.5 GHz CF | 1995.29 J | 12 threads, 1.5 GHz UCF, 2.1 GHz CF | 206.98 J (10.37%) |
| Compute only | 12 threads, 3.0 GHz UCF, 2.5 GHz CF | 1666.32 J | 12 threads, 1.2 GHz UCF, 2.5 GHz CF | 212.51 J (12.75%) |

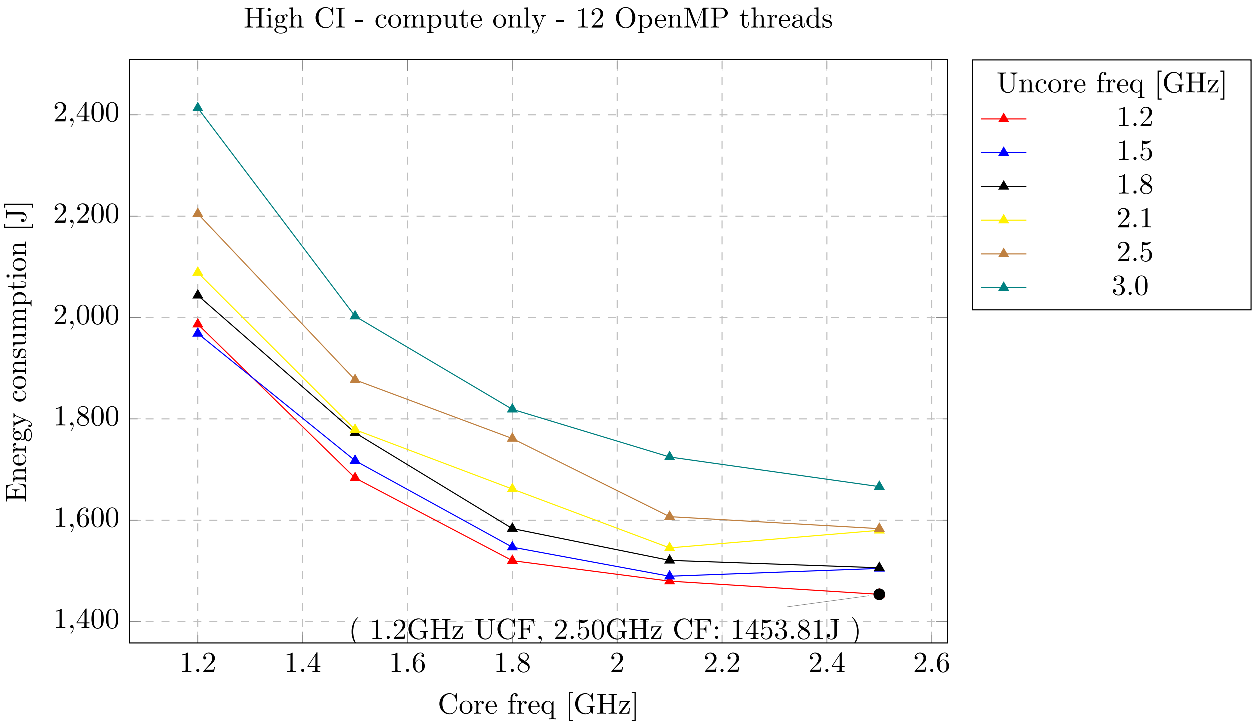
Table 1: Evaluation of the kernels with various compute intensity (DGEMV - low CI, DGEMM - higher CI, and compute only - the highest CI). Note: CF - CPU core frequency, UCF - CPU uncore frequency, threads - number of OpenMP threads.




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.5 | 1.8 | 2.1 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|
| 1.2 | 2,464.45 | 2,256.16 | 2,202.93 | 2,257.76 | 2,367.74 | 2,526.65 |
| 1.5 | 2,556.83 | 2,203.36 | 2,061.39 | 2,026.45 | 2,080.01 | 2,213.78 |
| 1.8 | 2,736.55 | 2,319.69 | 2,081.53 | 1,971.79 | 1,968.3 | 2,047.27 |
| 2.1 | 2,994.96 | 2,551.26 | 2,233.03 | 2,053.46 | 1,985.7 | 2,011.27 |
| 2.5 | 3,432.98 | 2,883.56 | 2,531.54 | 2,301.16 | 2,146.5 | 2,085.47 |




| Uncore freq [GHz UCF] / Core freq [GHz] | 1.2 | 1.5 | 1.8 | 2.1 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|
| 1.2 | 2,117.08 | 2,140.04 | 2,182.8 | 2,242.67 | 2,364.48 | 2,540.92 |
| 1.5 | 1,902.38 | 1,901.92 | 1,937.77 | 1,983.77 | 2,079.23 | 2,225.04 |
| 1.8 | 1,812.5 | 1,794.7 | 1,807.14 | 1,846.06 | 1,926.4 | 2,050.86 |
| 2.1 | 1,840.92 | 1,788.31 | 1,789.54 | 1,815.26 | 1,887.52 | 1,996.09 |
| 2.5 | 1,975.04 | 1,865.36 | 1,847.54 | 1,856.24 | 1,921.72 | 1,995.29 |



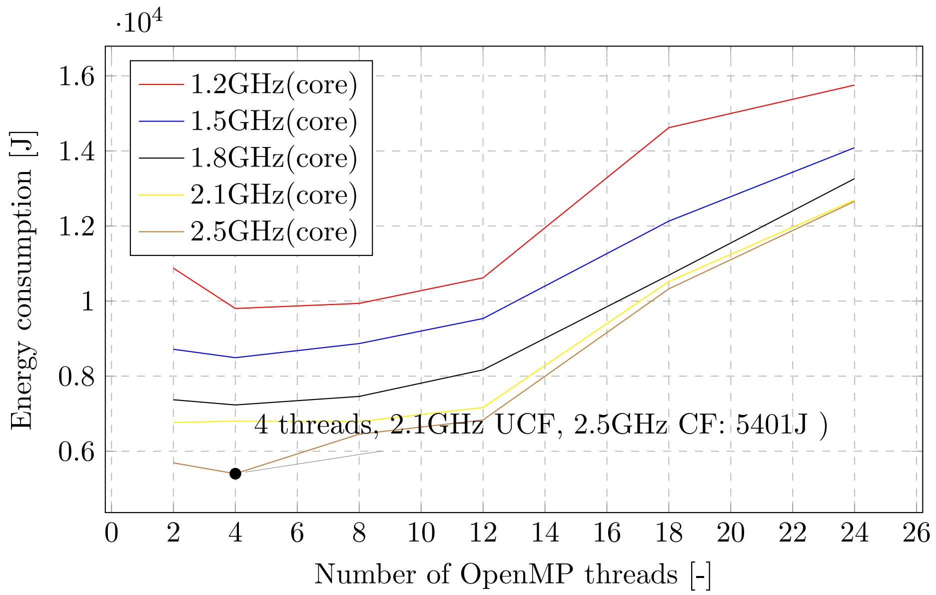

| Uncore freq [GHz UCF] / Core freq [GHz] | 1.2 | 1.5 | 1.8 | 2.1 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|
| 1.2 | 1,986.81 | 1,968.58 | 2,043.81 | 2,088.83 | 2,204.84 | 2,413.44 |
| 1.5 | 1,683.44 | 1,717.64 | 1,772.68 | 1,778.7 | 1,877.02 | 2,002.64 |
| 1.8 | 1,520.23 | 1,546.89 | 1,583.61 | 1,661.61 | 1,761.28 | 1,818.92 |
| 2.1 | 1,479.83 | 1,489.49 | 1,520.81 | 1,545.45 | 1,607.07 | 1,724.81 |
| 2.5 | 1,453.81 | 1,504.91 | 1,506.23 | 1,580.08 | 1,583.42 | 1,666.32 |

## 2.2 Investigation of Parallel I/O

To evaluate multithreaded (OpenMP) parallel I/O we have developed a benchmark which reads the sparse matrix from file. Matrices are obtained from the SuiteSparse Matrix Collection [4] and are stored in the Matrix Market format. The parallelization is done using OpenMP. The following results show the optimal setup for reading large amount of data from network file system on Taurus machine.

| Workload type | Energy consumption evaluation: Default settings | Default values | Best static configuration | Static Savings |
|---|---|---|---|---|
| Parallel I/O | 12 threads, 3.0 GHz UCF, 2.5 GHz CF | 12397 J | 4 threads, 2.1 GHz UCF, 2.5 GHz CF | 6996 J (56.43%) |

Table 2: Evaluation of the parallel I/O. Note: CF - CPU core frequency, UCF - CPU uncore frequency, threads - number of OpenMP threads.




| Threads [-] \ Core freq [GHz] | 1.2 | 1.5 | 1.8 | 2.1 | 2.5 |
|---|---|---|---|---|---|
| 2 | 10,877 | 8,717 | 7,371 | 6,767 | 5,690 |
| 4 | 9,803 | 8,492 | 7,233 | 6,802 | 5,401 |
| 8 | 9,939 | 8,869 | 7,461 | 6,791 | 6,455 |
| 12 | 10,621 | 9,536 | 8,168 | 7,165 | 6,833 |
| 18 | 14,621 | 12,130 | 10,690 | 10,521 | 10,326 |
| 24 | 15,755 | 14,087 | 13,263 | 12,693 | 12,657 |

Table 3: The heat map presenting the optimal setting for the parallel I/O benchmark. The uncore frequency for this visualization is set to 2.1GHz which is the best setting.

# 3 Overview of Tuning Parameters

In this deliverable the following tuning parameters have been used:

- hardware parameters of the CPU
  - Core Frequency (CF)
  - Uncore frequency (UCF) [1]
- system software parameters
  - number of OpenMP threads
- application-level parameters
  - depends on the specific application

In this report a set of applications is analyzed, each with a different set of tuning parameters. The list of applications and the used parameters are:

- Investigation of Computational Intensity : CPU core frequency; CPU uncore frequency, number of OpenMP threads
- Investigation of Parallel I/O : CPU core frequency; CPU uncore frequency, number of OpenMP threads
- Intel Math Kernel Library Sparse BLAS routines : CPU core frequency; CPU uncore frequency, number of OpenMP threads
- ProxyApps 1 - AMG2013 : CPU core frequency; CPU uncore frequency, number of OpenMP threads
- ProxyApps 2 - Kripke : CPU core frequency; CPU uncore frequency, number of OpenMP threads
- ProxyApps 3 - LULESH : CPU core frequency; CPU uncore frequency, number of OpenMP threads
- ProxyApps 4 - MCB : CPU core frequency; CPU uncore frequency, number of OpenMP threads
- ESPRESO : (1) Hardware parameters: CPU core frequency; CPU uncore frequency, number of OpenMP threads. (2) Application parameters: different algorithms, type of preconditioner

[1] Uncore frequency refers to frequency of subsystems in the physical processor package that are shared by multiple processor cores. E.g., L3 cache or on-chip ring interconnect.

- OpenFOAM : CPU core frequency; CPU uncore frequency (Note: MPI only application, no threading)
- Indeed : CPU core frequency; CPU uncore frequency
- MiniMD : CPU core frequency; CPU uncore frequency, number of OpenMP threads

# 4 Methodology for Dynamism Analysis

Detecting the dynamism of an application is the initial step of the READEX approach. The tuning potential of an application is determined by measuring its intra-phase and inter-phase dynamism. The tuning potential analysis is described in deliverable D2.1 [8] in more detail.

## 4.1 Manual Dynamism Evaluation with MERIC

MERIC is a C++ dynamic library that measures energy consumption and runtime of annotated regions inside a user application. It also can change the tuning parameters during the runtime. By running the code with different settings of the tuning parameters, we analyze possibilities for energy savings. Subsequently, the optimal configurations are applied by changing the tuning parameters during the application runtime. MERIC wraps a list of libraries, that provide access to different hardware knobs and registers, operating system and runtime system variables, i.e. tuning parameters, in order to read or modify their values.

The library is easy to use, all a user needs to do is to initialize the MERIC. After that it is possible to insert so called probes, that wrap potentially significant regions of the analyzed code. Besides storing the measurement results, the user should not notice any changes in application behavior.

The main motivation for the development of this tool was to simplify the evaluation of various applications which includes a large number of measurements. MERIC automates energy measurements of applications for various system parameters (frequency, number of threads, compiler, application parameters, etc.). It also allows to split the application code into parts, that may require different settings to show energy savings.

### 4.1.1 MERIC features

- **Environment settings**
  During the MERIC initialization and at each region start and end the CPU frequency, uncore frequency and number of OpenMP threads are set. To do so, MERIC uses the OpenMP runtime API and the cpufreq and x86_adapt libraries.
- **HDEEM**
  The key MERIC feature is energy measurement using HDEEM. HDEEM provides energy consumption measurement in two different ways, and in MERIC it is possible to choose which one the user wants to use by setting the MERIC_CONTINUAL parameter. In one mode, the energy consumed from the point that HDEEM was initialised is taken from the HDEEM Stats structure (a data structure used by the HDEEM library to provide measurement information to the user application). In this mode we read the structure at each region start and end. This solution is straightforward, however there is a delay of approximately 4 ms associated with every read from HDEEM API. To avoid the delay, we take advantage of the fact that during the measurement HDEEM

stores energy samples in its internal memory. In this case the MERIC only needs to record timestamps at the beginning and the end of each region instead of calling the HDEEM API. This results in a very small overhead of MERIC instrumentation during the application runtime because all samples are transferred from HDEEM memory at the end of the application runtime. The energy is subsequently calculated from the samples based on the recorded timestamps.

- **Intel Running Average Power Limit**
  Contemporary Intel processors support energy consumption measurements via the Running Average Power Limit (RAPL) interface. MERIC uses the RAPL counters to allow energy measurements on machines without the HDEEM infrastructure as well as to compare them with HDEEM measurements. RAPL counters are read by the x86_adapt library.

- **Hardware performance counters**
  To provide more information about the instrumented regions of the application, we use the perf_event and PAPI libraries, which provide access to hardware performance counters.

- **Computational intensity**
  MERIC also measures the computational intensity based on performance counters measured by the perf_event or PAPI library. This is a key metric for dynamism detection as described in Section 2.

### 4.1.2 MERIC requirements

The MERIC tool relies on the following:

- Machine instrumented with HDEEM or x86_adapt library for accessing RAPL counters
- Compiler with C++14 standard support
- PAPI and perf_event for accessing hardware counters

### 4.1.3 Workflow

1. **Identification of significant regions**
   First, the user has to analyze its application using a profiler tool (such as Allinea MAP) and find the significant regions in order to cover the most consuming functions in term of time, MPI communication or I/O.

2. **Insertion of MERIC probes**
   To use MERIC the user has to initialize the library and then insert the probes to annotate the regions. At first the functions MERIC_Init() and MERIC_Close() should

be inserted in the main function of the code. These functions should be inserted directly after MPI_Init() and before MPI_Finalize(), respectively if MPI is used. Then every significant region should be wrapped by the MERIC_MeasureStart("NAME") and MERIC_MeasureStop() functions, where NAME is a user defined name of the region. These start and stop functions are called the probes. The stop function does not have any input parameters, because it ends the region that has been started most recently.

3. **Compilation of MERIC and a user code**
MERIC is compiled using the Waf [11] compilation tool . Waf is a Python-based framework for configuring, compiling and installing applications. Because there is lack of general knowledge about Waf, the code repository contains also a Makefile, that provides several Waf compilation commands. To compile a user application, it must be linked with the MERIC library (with its MPI or non-MPI version) and with other libraries, that MERIC wraps and the user want to use.

4. **Setting MERIC parameters**
MERIC has almost no influence on the application's runtime. The instrumented application should be run as usual. MERIC is controlled using the following environmental variables:

   - MERIC_FREQUENCY
   After the MERIC initialization the CPU frequency is set to this value. The parameter should be in 0.1 GHz steps.
   - MERIC_UNCORE_FREQUENCY
   On Intel Haswell processors the frequency of the uncore (i.e., the compenents that are shared by all cores) can also be adjusted in 0.1 GHz steps.
   - MERIC_NUM_THREADS
   Number of OpenMP threads, that will be used by the application.
   - MERIC_MODE
   MERIC works in four basic modes. In the default mode the energy consumption is provided by HDEEM. Because this library is only available on Taurus in TU Dresden, it is also possible not to use HDEEM, but to work with the Intel RAPL counters instead. Another possibility is to use both, to compare the output values, or simply run the code without energy measurements.
   - MERIC_COUNTERS
   For each region it is also possible to access hardware performance counters via perf_event or PAPI library.
   - MERIC_OUTPUT_DIR
   Name of the output directory.
   - MERIC_OUTPUT_FILENAME
   Name of the output .csv file, that contains energy data.
   - MERIC_CONTINUAL
   Set MERIC to read energy consumption directly (with HDEEM internal delay) at

each region start and end (MERIC_CONTINUAL=0) or from samples stored in the HDEEM internal memory at the end of execution (MERIC_CONTINUAL=1).

- MERIC_DETAILED
  If set, energy consumption is not only measured for the whole node, but for each CPU and DRAM as well.
- MERIC_AGGREGATE
  Setting for the MPI version. If set, measurement results are gathered at one MPI process, that stores only minimum, maximum and average values over all MPI processes.
- MERIC_REGION_OPTIONS
  File with each region runtime settings.

Detailed description of all parameters can be found in the MERIC README file.

5. **Running complete energy measurement**
   Now it is possible to run a test to measure all the possible settings. To do so, in the test directory there is a template of the batch script. The batch script consists of three parts. At the beginning of the script there are settings that should be consistent for all runs of the code (e.g., MERIC output format). After that, there are loops for every parameter, setting it to one of the possible values. And in the last part, the user must set the variable MERIC_OUTPUT_FILENAME, that should be composed of each parameter value and run the code.

6. **Processing the results**
   When the MERIC regions are defined and its parameters are set, we may run the code. The results are stored in two directories. The first one contains the information how often the measurement was performed with a given setting. The second directory is filled with the measurement results, that are stored in .csv file format. These files are analyzed with the RADAR, that produces a detailed report where results are visualized in graphs and logged in tables. RADAR also gives information about the best static and dynamic settings of the measured code.

7. **Dynamic tuning**
   MERIC can enforce specific configuration for each significant region from a JSON formatted configuration file (details are described in the MERIC README file). The user may set this file using the MERIC environment variable. MERIC sets the environment during runtime for each region to its required settings and therefore performs the dynamic tuning.

### 4.1.4 MERIC repository

The MERIC repository contains not only the library, but also a small set of test applications, that already have several annotated regions. These examples show the potential user how to use MERIC and test whether everything is ready to use. The test directory also contains a script to print and/or set all MERIC environment variables and a complete energy measurement template of a batch script as mentioned in Section 4.1.3 item 5.

# 5 Metodology for Dynamism Reporting

## 5.1 RADAR

READEX Application Dynamism Analysis Report (RADAR) represents a brief measurement results of dynamism metrics of different runs of an application. The report depicts graphical representations of the energy consumption with respect to a set of tuning parameters. It also contains different sets of graphical comparisons of static and dynamic significant energy savings across the regions for different hardware tuning parameter configurations.

## 5.2 RADAR Generator for MERIC

When the significant regions are annotated with MERIC probes we run the application for all combinations of the selected tuning parameters. Subsequently, the measurement results are analyzed with the RADAR report generator tool.

The report generator is a Python based tool which visualizes the MERIC measurements in form of the Latex/PDF document. The goal is to present results in easily readable format using aggregated tables, 2D plots and heat-maps. The report generator not only visualizes the measured results, but more importantly it also evaluates the energy consumption using both HDEEM or RAPL, runtime and arithmetical intensity for each significant region. This analysis detects an optimal configuration of tuning parameters for each significant region and calculates the potential energy savings.

The energy savings are calculated for both static and dynamic tuning. In case of static tuning we evaluate the energy consumption of the entire application and find the single optimal configuration. For the dynamic tuning we evaluate each of the significant regions independently and calculate the additional savings over the static tuning. All the savings are then acumulated to report a single value for static savings and a single value for dynamic savings.

Optimal configurations for each significant region are then saved to the JSON configuration file which is used by a MERIC instrumented application for dynamic tuning.

The RADAR reports in this document always present the results for tuning for two objective functions: (1) minimal energy consumption and (2) minimal runtime. This clearly show how different are the optimal settings for these two objective functions.

### 5.2.1 Report elements

**Overall application evaluation** is the basic overview of the behavior of the entire application also called the main region. This listing contains the default configuration of tuning parameters, the optimal configuration for the entire application and static and dynamic savings. An example is given in Table 4.

**Overall application evaluation**

| | Default settings | Default values | Best static configuration | Static Savings | Dynamic Savings |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 24 MPI proc , 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 10515.1 J | 24 MPI proc , 1 thread, 1.3 GHz UCF, 1.4 GHz CF | 3355.32 J (31.91%) | 63.87 J of 7159.78 J (0.89 %) |
| Runtime of application [s] | 24 MPI proc 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 45.16 s | 24 MPI procs,, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.19 s of 45.16 s (0.42 %) |

Table 4: Example of overall application evaluation

**Intra-Phase Dynamic Tuning Evaluation** contains the optimal configuration of the tuning parameters for each significant region. All regions in this section are considered to be nested regions of the main region. Therefore as the default configuration we take the best configuration for the main region, i.e. the configuration that provides the best static savings. An example is given in Table 5.

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| LTimes | 19.82 | 24 MPI proc , 1 thread, 1.3 GHz UCF, 1.4 GHz CF | 589.78 J | 24 MPI proc , 1 thread, 1.2 GHz UCF, 1.2 GHz CF | 576.29 J | 13.49 J (2.29%) |
| Source | 19.32 | 24 MPI proc , 1 thread, 1.3 GHz UCF, 1.4 GHz CF | 574.96 J | 24 MPI proc , 1 thread, 1.2 GHz UCF, 1.2 GHz CF | 562.34 J | 12.62 J (2.20%) |
| LPlusTimes | 19.88 | 24 MPI proc , 1 thread, 1.3 GHz UCF, 1.4 GHz CF | 591.50 J | 24 MPI proc , 1 thread, 1.2 GHz UCF, 1.2 GHz CF | 582.50 J | 9.00 J (1.52%) |
| Scattering | 19.62 | 24 MPI proc , 1 thread, 1.3 GHz UCF, 1.4 GHz CF | 583.76 J | 24 MPI proc , 1 thread, 1.2 GHz UCF, 1.2 GHz CF | 570.57 J | 13.19 J (2.26%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Sweep | 21.36 | 24 MPI proc, 1 thread, 1.3 GHz UCF, 1.4 GHz CF | 635.47 J | 24 MPI proc, 1 thread, 1.4 GHz UCF, 1.3 GHz CF | 619.88 J | 15.58 J (2.45%) |
| **Total values for static tuning for significant regions** | | | 589.78 + 574.96 + 591.50 + 583.76 + 635.47 = 2975.45 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 13.49 + 12.62 + 9.00 + 13.19 + 15.58 = 63.87 J of 2975.45 J (2.15 %) | | | |
| **Dynamic savings for application runtime** | | | 63.87 J of 7159.78 J (0.89 %) | | | |

Table 5: Example of the overview table of the optimal settings for the significant regions.

| **Phase ID** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Default Energy consumption [J]** | 624.35 | 49.83 | 59.68 | 62.89 | 63.35 |
| **% per 1 phase** | 91.54 | 37.38 | 39.10 | 39.17 | 38.61 |
| **Per phase optimal settings** | 2.0 GHz UCF, 2.5 GHz CF | 2.1 GHz UCF, 1.7 GHz CF | 2.2 GHz UCF, 1.7 GHz CF | 2.1 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF |
| **Dynamic savings [J]** | 14.63 | 1.37 | 3.76 | 4.78 | 5.51 |
| **Dynamic savings [%]** | 2.34 | 2.74 | 6.30 | 7.61 | 8.70 |

Table 6: Example of the inter-phase evaluation per significant region for 5 phases

**Inter-Phase Dynamic Tuning Evaluation** contains optimal configurations and dynamic savings detected for significant regions per phase of the phase region. By default the main region is used as the phase region but this can be changed by the user to any other significant region. Please note that the phase region can be either the main region itself or another region nested in the main region. The evaluated significant regions must be nested in the phase region.

This evaluation is useful for solvers based on iterative methods (e.g. Conjugate Gradients), where we're interested mostly in profiling the steps of the iterations itself.

An example can be seen in Table 6 and results are shown in section 7.

**2D plots** are used in the report to visualize the dependence between some of the parameterss set, e.g. core frequency, number of threads and energy consumed. A simple plot can be seen in Figure 1.

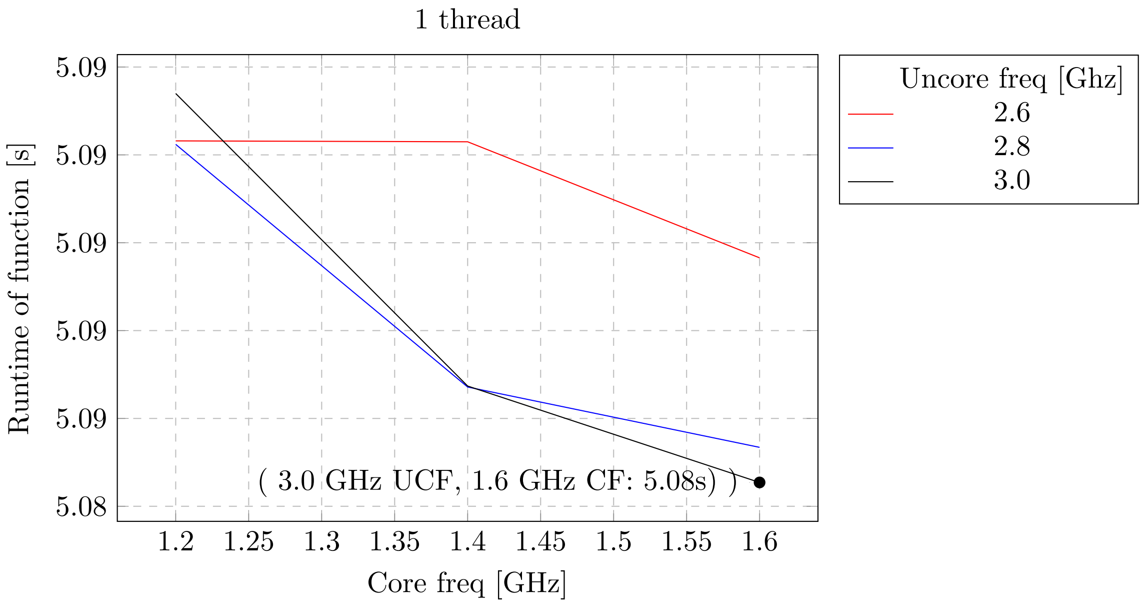



Figure 1: Example of a plot representing the behavior of an application for various of core and uncore frequencies.

**Heat-maps** have exactly the same purpose and are used in the same way as plots. They were introduced in RADAR report generator, because for some data sets the relations between quantities are easily visible this way. An example can be seen in Table 7.

| Uncore freq [GHz] / Core freq [GHz] | 2.6 | 2.8 | 3.0 |
|---|---|---|---|
| 1.2 | 5.0923 | 5.0922 | 5.0934 |
| 1.4 | 5.0923 | 5.0867 | 5.0667 |
| 1.6 | 5.0897 | 5.0653 | 5.0245 |

Table 7: Heat map example generated by the RADAR report generator

### 5.2.2 Using the RADAR report generator

All the necessary settings are done (and described in detail) in the `config.py` file. After customizing the settings, the generation of the report itself is performed by the script `printFullReport.py`. Then, the file `results.tex` is created in the folder with data (i.e. the path assigned in `config.py` to the variable `rootfolder`). The file is subsequently compiled with *pdflatex* or *lualatex*, the later one being the better choice because of its dynamically allocated memory, which prevents crashing during compilation when there are plenty of data processed.

The compilation creates many files when drawing plots named like `data*.csv`. When you compile with flag `--shell-escape`, they are removed automatically at the end of the compilation.

Finally, you can see examples of reports generated by this tool in the Results section (e.g., Section 6.2.2).

# 6 Results – Intra-Phase Dynamism

In this section we present energy savings that were achieved by both static and dynamic tuning of the selected applications. We present two types of evaluations (1) the intra-phase dynamism, see sections 6.1–6.9, and (2) the inter-phase dynamism which has been detected only for a subset of the evaluated applications, see Section 7.

## 6.1 Intel Math Kernel Library Sparse BLAS routines

This section deals with the energy consumption evaluation of selected Sparse BLAS Level 2 and 3 routines. We have investigated the following routines from the Intel Math Kernel Library (MKL) [3] version 2017.

- Sparse Matrix-Vector Multiplication in IJV/COO format,
- Sparse Matrix-Vector Multiplication in CSR format,
- Sparse Matrix-Matrix Multiplication in CSR format,
- Sparse Matrix-Matrix Addition in CSR format,

These belong to the most frequently used operations in HPC applications. For benchmarking we have used the University Florida set of matrices [1] and the MERIC library for the energy and time measurements.

The measured characteristics illustrate a different energy consumption for different BLAS routines, as some operations are more memory-bound and others are more compute-bound. We also show that some of the routines suffer significantly from the NUMA effect and should be executed on single CPU socket only.

Table 6.1 shows measurements where default number of CPU cores have been set to 24 therefore both sockets of the node have been used. We can see that most of the routines have optimal number of cores smaller than 12 and therefore using only 1 CPU socket. We can see that significant savings up to 66% can be achieved in this case. Table 6.1 shows result of the same experiment but in this case running on one CPU socket only (no NUMA effect). In this case the savings are between 2.7% – 12.3%.

The optimal uncore frequency in both tests has been between 2.1 GHz and 2.5 GHz (default value is 3.0 GHz). Matrix with higher number of non-zero values (road_central) requires also higher uncore frequency. The range of CPU core frequency is between 1.5 GHz and 2.5 GHz (default value is 2.5 GHz). The sparse matrix-vector multiplication for CSR sparse matrix format is the only routine that runs more efficiently on rather low core frequencies 1.5–1.8 GHz, while the remaining operations take advantage of higher one. We can also observe, that matrix with higher number of non-zero values becomes more memory bound (optimum is on higher uncore frequency and lower core frequency).

| Matrix name | Rows | Cols | Nonzero | Nonzero [%] | Method | Th. | CF | UCF | Savings [%] |
|---|---|---|---|---|---|---|---|---|---|
| road_central | 14,081,816 | 14,081,816 | 33,866,826 | 1.71E-07 | SpMV CSR | 12 | 1.5 | 2.1 | 41.42 |
| | | | | | SpMV COO | 24 | 2.5 | 2.5 | 4.21 |
| | | | | | SpMM CSR | 12 | 2.1 | 2.5 | 18.5 |
| | | | | | Sp Mat Add CSR | 8 | 1.8 | 2.5 | 21.17 |
| sls | 1,748,122 | 62,729 | 6,804,304 | 6.21E-05 | SpMV CSR | 18 | 1.5 | 2.1 | 45.22 |
| | | | | | SpMV COO | 8 | 2.5 | 2.1 | 7.35 |
| | | | | | SpMM CSR | 6 | 2.5 | 2.1 | 22.83 |
| | | | | | Sp Mat Add CSR | 6 | 2.5 | 2.1 | 29.30 |
| TSOPF_RS_b2052_c1 | 25,626 | 25,626 | 6,761,100 | 1.03E-02 | SpMV CSR | 12 | 1.8 | 2.1 | 66.19 |
| | | | | | SpMV COO | 6 | 2.5 | 2.1 | 7.24 |
| | | | | | SpMM CSR | 24 | 2.1 | 1.8 | 7.83 |
| | | | | | Sp Mat Add CSR | 8 | 2.5 | 2.1 | 31.66 |

Table 8: The MKL sparse routines evaluation with NUMA effect (running on 2 CPU sockets) using 3 representative matrices (1 node, 6–24 threads, savings compared to 3 GHz core, 2.5 GHz uncore, 24 threads). Note: Th. – threads; CF – CPU core frequency in GHz; UCF – CPU uncore frequency in GHz.

| Matrix name | Rows | Cols | Nonzero | Nonzero [%] | Method | Th. | CF | UCF | Savings [%] |
|---|---|---|---|---|---|---|---|---|---|
| road_central | 14,081,816 | 14,081,816 | 33,866,826 | 1.71E-07 | SpMV CSR | 12 | 1.5 | 2.1 | 12.29 |
| | | | | | SpMV COO | 6 | 2.5 | 2.5 | 4.21 |
| | | | | | SpMM CSR | 12 | 2.1 | 2.5 | 3.12 |
| | | | | | Sp Mat Add CSR | 8 | 1.8 | 2.5 | 6.41 |
| sls | 1,748,122 | 62,729 | 6,804,304 | 6.21E-05 | SpMV CSR | 12 | 1.8 | 2.1 | 11.44 |
| | | | | | SpMV COO | 8 | 2.5 | 2.1 | 6.10 |
| | | | | | SpMM CSR | 6 | 2.5 | 2.1 | 2.72 |
| | | | | | Sp Mat Add CSR | 6 | 2.5 | 2.1 | 9.94 |
| TSOPF_RS_b2052_c1 | 25,626 | 25,626 | 6,761,100 | 1.03E-02 | SpMV CSR | 12 | 1.8 | 2.1 | 5.21 |
| | | | | | SpMV COO | 6 | 2.5 | 2.1 | 7.39 |
| | | | | | SpMM CSR | 12 | 2.5 | 1.5 | 9.75 |
| | | | | | Sp Mat Add CSR | 8 | 2.5 | 2.1 | 5.56 |

Table 9: The MKL sparse routines evaluation without NUMA effect (running on 1 CPU socket) using 3 representative matrices (1 node, 6–24 threads, savings compared to 3 GHz core, 2.5 GHz uncore, 12 threads). Note: Th. – threads; CF – CPU core frequency in GHz; UCF – CPU uncore frequency in GHz.

## 6.2 ESPRESO

For many years, the Finite Element Tearing and Interconnecting method (FETI) [6], [7] has been successfully used in the engineering community for solving very large problems arising from the discretization of partial differential equations. In such an approach the original structure is decomposed into several non-overlapping subdomains. Mutual continuity of primal variables between neighboring subdomains is enforced afterwards by dual variables, i.e., Lagrange multipliers (LM). They are usually obtained iteratively by one of the Krylov subspace methods, then the primal solution is evaluated locally for each subdomain.

In 2006 Dostál et al. [5] introduced a new variant of an algorithm called Total FETI (or TFETI) in which Dirichlet boundary condition is enforced also by LM.

The HTFETI method is a variant of hybrid FETI methods introduced by Klawonn and Rheinbach [9] for FETI and FETI-DP. In the original approach a number of subdomains is gathered into clusters. This can be seen as a three-level domain decomposition approach. Each cluster consists of a number of subdomains and for these, a FETI-DP system is set up. The clusters are then solved by a traditional FETI approach using projections to treat the non trivial kernels. In contrast, in HTFETI, a TFETI approach is used for the subdomains in each cluster and the FETI approach with projections is used for clusters.

The main advantage of HTFETI is its ability to solve problems decomposed into a very large number of subdomains [14]. We have ran tests with over 21 million subdomains organized into 17,576 clusters. This means two things: (i) an extremely large problem can be solved (over 120 billion DOF); (ii) moderate size problems (up to few billion DOF) can be decomposed into very small subdomains which improves memory, computational and numerical efficiency.

### 6.2.1 ESPRESO Library

The ESPRESO library is a combination of Finite Element (FEM) and Boundary Element (BEM) tools and TFETI/HTFETI solvers. It supports FEM and BEM (uses BEM4I library) discretization for Advection-diffusion equation, Stokes flow and Structural mechanics. Real engineering problems are imported from Ansys Workbench or OpenFOAM. A C API allows ESPRESO to be used as a solver library for third party applications. For large scale tests library also contains a multiblock benchmark generator. The postprocessing and vizualization is based on the VTK library and Paraview including Paraview Catalyst for inSitu vizualization.

The ESPRESO solver is a parallel linear solver, which includes a highly efficient MPI communication layer [12] designed for massively parallel machines with thousands of compute nodes. The parallelization inside a node is done using OpenMP. Three versions of the solver are being developed: (i) *ESPRESO CPU* uses sparse matrices and sparse direct solvers to process the system matrices; (ii) *ESPRESO MIC* is an Intel Xeon Phi accelerated version, which works with both sparse and dense representation of system matrices; and (iii) *ESPRESO GPU* is a GPU accelerated version, which supports dense structures only [13]. Support for sparse structures using cuSolver is under development.

All versions can solve both symmetric (conjugate gradient (CG) solver) and nonsymmetric systems (GMRES and BiCGStab).

**Hardware Tuning Parameters:** The dynamism of the ESPRESO library has been evaluated using the following hardware parameters:

- CPU Core frequency
- Number of OpenMP threads
- CPU Uncore frequency

### 6.2.2 Application Tuning Parameters

**Preconditioners:** The ESPRESO solver supports several preconditioners, that can be dynamically switched during the runtime of the iterative solver. The list of preconditioners that are evaluated are:

- Lumped preconditioner - uses *sparse* BLAS2 - matrix-vector multiplication,
- Dirichlet preconditioner - uses *dense* BLAS2 - matrix-vector multiplication.

The order of the list is based on the numerical efficiency (from the worst to the best) which also corresponds to their computational demand (from low to high). From the nature of the FETI method the (ii) weight function and (iii) the lumped preconditioners are always available and we do not need to calculate them at additional cost. However the (iv) Dirichlet preconditioner needs to be calculated if required, which potentially increases the preprocessing time and the energy consumption.

**Stiffness Matrix Processing:** In FETI a stiffness matrix is a sparse matrix which in a general approach is processed by a SParse Direct Solver (SPDS). In particular each stiffness matrix is factorized once during the preprocessing and then in each iteration a forward and backward substitutions (the solve routine of the SPDS) are called.

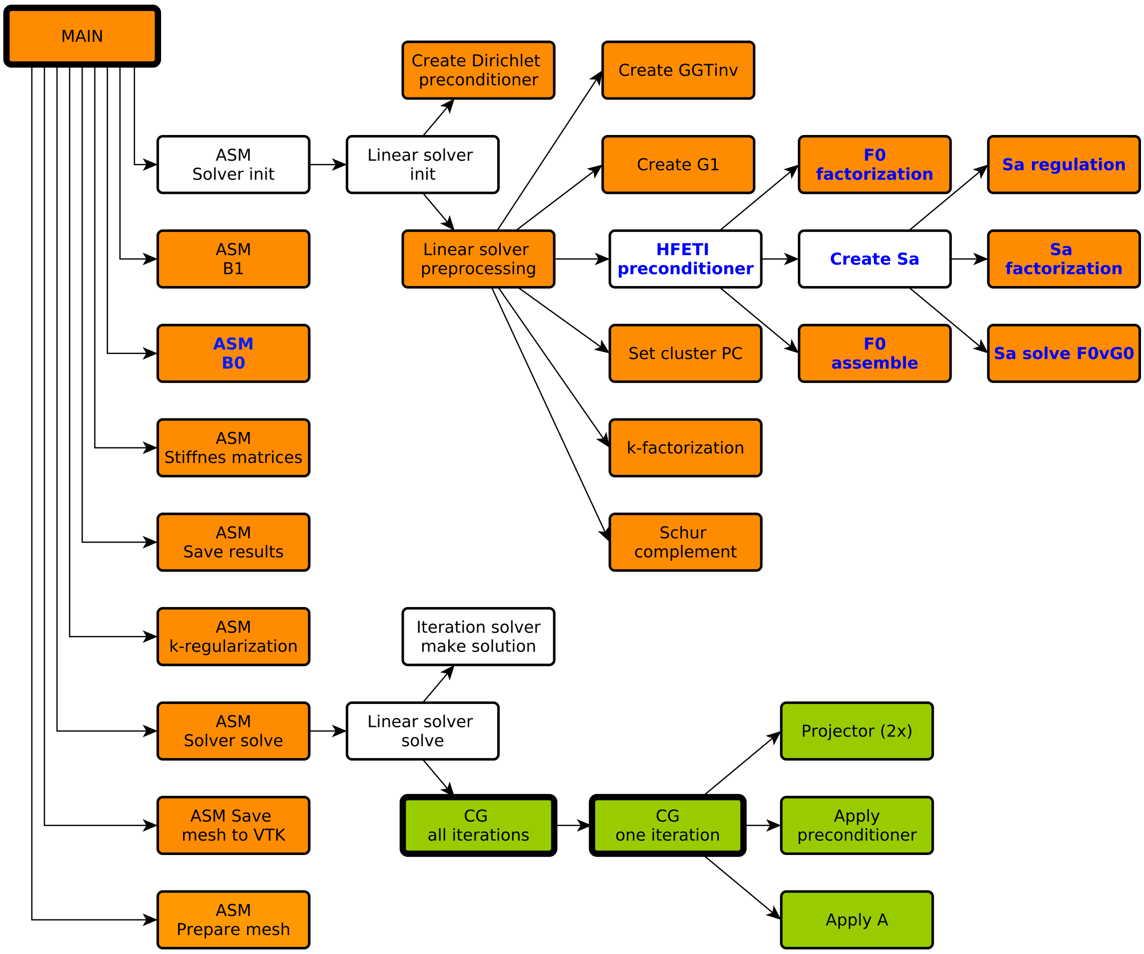



Figure 2: Diagram of the significant regions in the ESPRESO library as used for the dynamic savings evaluation in this section. The orange regions are called just once per iteration and therefore are used only for intra-phase dynamism evaluation. White regions are ignored because there are other significant regions nested in them. The green regions denotes the iterative solver (conjugate gradient (CG)) and provides an opportunity for inter-phase dynamism. The regions with names highlighted in bold are called only if Hybrid Total FETI is used.

ESPRESO contains an alternative method based on the Local Schur Complement method (LSC) for stiffness matrix processing originally developed for GPGPU and Intel Xeon Phi accelerators, see [13]. In this method the preprocessing is more expensive as we have to calculate the LSC for each subdomain using SPDS. However the iterative FETI solver than uses dense matrix-vector multiplication using LSCs instead of more expensive solve routine of the SPDS. So the following methods will be evaluated:

- Sparse Direct Solver (SPDS) - is using the solve routine (in this case the Intel MKL PARDISO solver is used),
- Local Schur Complement (LSC) - is using the dense BLAS 2 matrix-vector multiplication.

We can calculate both (i) factorization of the stiffness matrices and (ii) the local Schur complements during the preprocessing stage and than ESPRESO can dynamically switch between these two methods during the runtime.

**FETI Method:** The ESPRESO solver contains two FETI methods: Total FETI (two level method - better numerical behavioral, but limited parallel scalability) and Hybrid Total FETI (three level method with worse numerical behavior, but very good parallel scalability). As of now the dynamic switching between these two methods in not implemented, however with certain effort this can be implemented into ESPRESO. So the dynamism for the following FETI methods can be evaluated:

- Total FETI method
- Hybrid Total FETI method

#### 6.2.3 RADAR Reports for ESPRESO

In this section we present a series of experiments, that have been executed with the ESPRESO library. For all runs the significant regions shown in Figure 2 have been used for measurements.

##### 6.2.3.1 Configuration 0: 1 node with 1 MPI process; 2 to 24 OpenMP threads

- Method: Hybrid Total FETI
- Preconditioner: Dirichlet (dense)
- Stiffness matrix processing: PARDISO Sparse Direct Solver (sparse)
- Decomposition: 1x1x1 cluster; 8x8x8 subdomains per cluster; 11x11x11 elements per subdomain

**Overall application evaluation**

| | Default settings | Default values | Best static configuration | Static Savings | Dynamic Savings |
|---|---|---|---|---|---|
| Energy consumption [J] , Blade summary | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 10678.9 J | 20 threads, 2.0 Ghz, 2.4 Ghz | 597.00 J (5.59%) | 880.75 J (8.74%) |
| Runtime of function [s] | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 29.73 s | 20 threads, 3.0 Ghz, 2.5 Ghz | 0.00 s (0.00%) | 0.7 s (1.52%) |

#### 6.2.3.2 Configuration 2: 1 node with 1 MPI process; 2 to 24 OpenMP threads

- Method: Hybrid Total FETI
- Preconditioner: Dirichlet (dense)
- Stiffness matrix processing: Local Schur Complement method (Dense)
- Decomposition: 1x1x1 cluster; 8x8x8 subdomains per cluster; 11x11x11 elements per subdomain

**Overall application evaluation**

| | Default settings | Default values | Best static configuration | Static Savings | Dynamic Savings |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 23176.1 J | 24 threads, 1.8 Ghz, 2.0 Ghz | 1815.00 J (7.83%) | 994.91 J (4.66%) |
| Runtime of function [s] | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 86.38 s | 24 threads, 3.0 Ghz, 2.5 Ghz | 0.00 s (0.00%) | 0.56 s (0.64%) |

#### 6.2.3.3 Configuration 3: 1 node with 1 MPI process; 2 to 24 OpenMP threads

- Method: Hybrid Total FETI
- Preconditioner: Lumped (sparse)
- Stiffness matrix processing: Local Schur Complement method (Dense)
- Decomposition: 1x1x1 cluster; 8x8x8 subdomains per cluster; 11x11x11 elements per subdomain

**Overall application evaluation**

| | Default settings | Default values | Best static configuration | Static Savings | Dynamic Savings |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 20508.9 J | 24 threads, 2.0 Ghz, 2.2 Ghz | 1589.70 J (7.75%) | 1017.92 J (5.38%) |
| Runtime of function [s] | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 86.38 s | 24 threads, 3.0 Ghz, 2.5 Ghz | 0.00 s (0.00%) | 0.54 s (0.74%) |

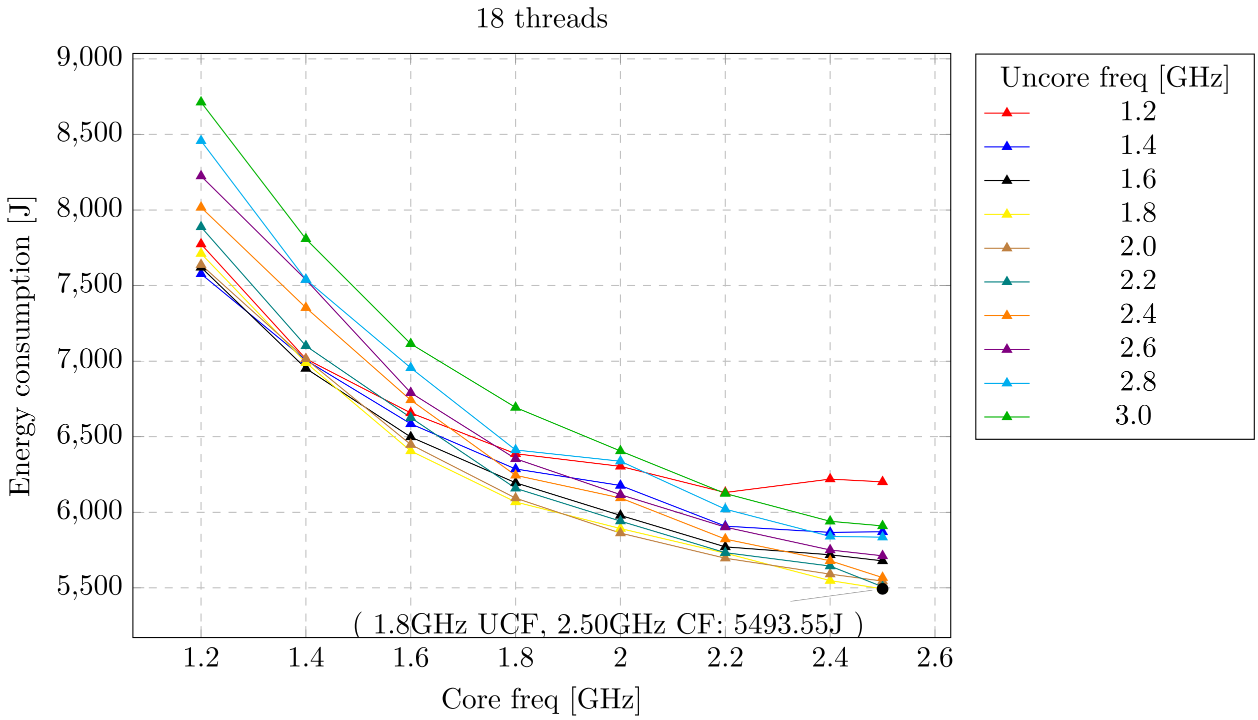
#### 6.2.3.4 Configuration 1: 1 node with 1 MPI process; 2 to 24 OpenMP threads

For this experiment we provide more detailed report as it has achieved the most significant static and dynamic savings.

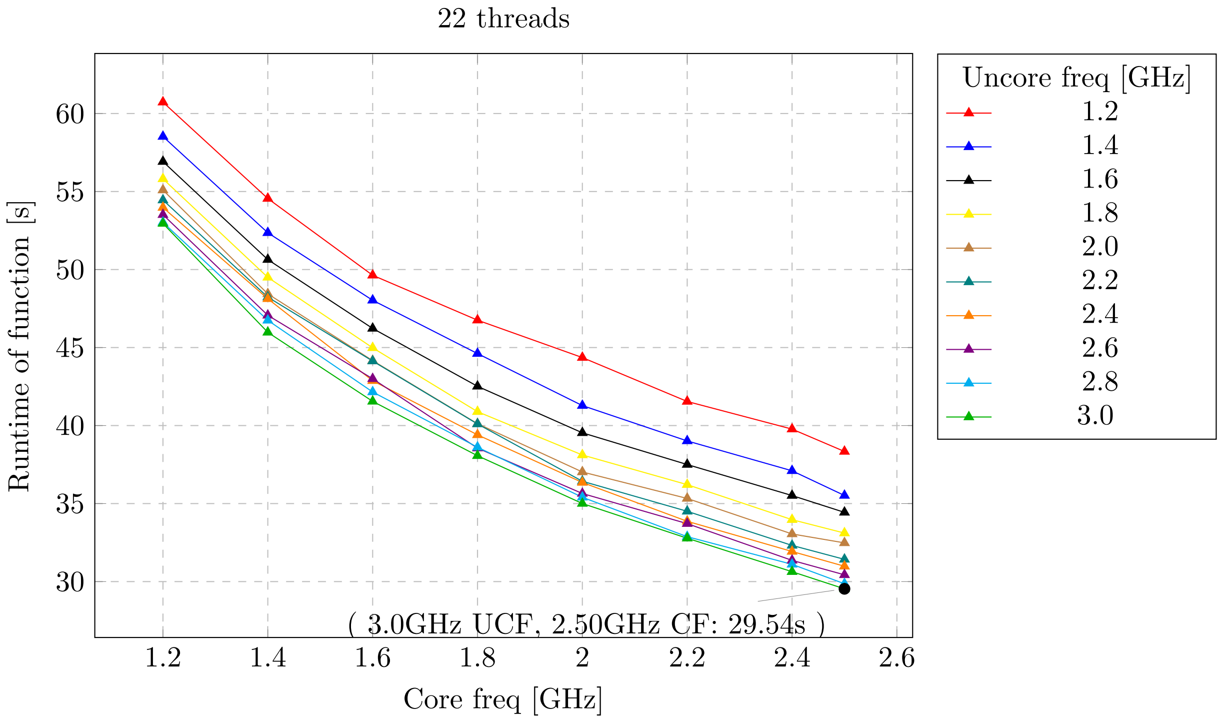
- Method: Hybrid Total FETI
- Preconditioner: Lumped (sparse)
- Stiffness matrix processing: PARDISO Sparse Direct Solver (sparse)
- Decomposition: 1x1x1 cluster; 8x8x8 subdomains per cluster; 11x11x11 elements per subdomain

**Overall application evaluation**

| | Default settings | Default values | Best static configuration | Static Savings | Dynamic Savings |
|---|---|---|---|---|---|
| Energy consumption [J] , Blade summary | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 6265.18 J | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 771.63 J (12.32%) | 499.2 J of 5493.6 J (9.09 %) |
| Runtime of function [s], Job info - hdeem | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 29.55 s | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.01 s (0.04%) | 0.82 s of 29.54 s (2.76 %) |




| Uncore freq [GHz UCF] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 7,774.33 | 7,577.13 | 7,620.86 | 7,712.41 | 7,638.19 | 7,887.51 | 8,017.52 | 8,224.55 | 8,457.63 | 8,713.34 |
| 1.4 | 7,014.96 | 7,006.61 | 6,951.7 | 6,989.9 | 7,013.88 | 7,100.78 | 7,353.77 | 7,538.7 | 7,540.17 | 7,808.45 |
| 1.6 | 6,657.43 | 6,585.3 | 6,497.84 | 6,405.66 | 6,448.15 | 6,626.3 | 6,742.37 | 6,790.9 | 6,955.32 | 7,114.6 |
| 1.8 | 6,387.41 | 6,286.4 | 6,195.08 | 6,068.22 | 6,093.49 | 6,158.65 | 6,244.49 | 6,354.23 | 6,412.18 | 6,693.56 |
| 2 | 6,303.9 | 6,177.23 | 5,979.14 | 5,892.41 | 5,862.35 | 5,941.4 | 6,094.83 | 6,116.72 | 6,337.78 | 6,405.45 |
| 2.2 | 6,130.89 | 5,908.28 | 5,771.2 | 5,729.32 | 5,695.97 | 5,732.87 | 5,822.58 | 5,901.66 | 6,020.53 | 6,124.2 |
| 2.4 | 6,219.49 | 5,866.82 | 5,718.77 | 5,548.09 | 5,590.74 | 5,644.12 | 5,679.25 | 5,750.53 | 5,840.8 | 5,940.3 |
| 2.5 | 6,201.34 | 5,870.99 | 5,678.56 | 5,493.55 | 5,544.76 | 5,507.07 | 5,567.86 | 5,711.89 | 5,834.93 | 5,909.88 |




| Uncore freq [GHz UCF] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 60.727 | 58.527 | 56.92 | 55.813 | 55.095 | 54.454 | 53.975 | 53.517 | 53.023 | 52.953 |
| 1.4 | 54.553 | 52.357 | 50.638 | 49.499 | 48.44 | 48.232 | 48.128 | 47.066 | 46.746 | 45.975 |
| 1.6 | 49.634 | 48.031 | 46.226 | 44.984 | 44.163 | 44.134 | 42.875 | 42.999 | 42.153 | 41.551 |
| 1.8 | 46.755 | 44.614 | 42.516 | 40.89 | 40.118 | 40.101 | 39.405 | 38.555 | 38.611 | 38.067 |
| 2 | 44.359 | 41.281 | 39.536 | 38.114 | 37.025 | 36.431 | 36.352 | 35.646 | 35.404 | 35.005 |
| 2.2 | 41.544 | 39.015 | 37.503 | 36.214 | 35.329 | 34.505 | 33.865 | 33.714 | 32.878 | 32.779 |
| 2.4 | 39.773 | 37.102 | 35.515 | 33.968 | 33.053 | 32.318 | 31.931 | 31.36 | 31.106 | 30.634 |
| 2.5 | 38.339 | 35.518 | 34.437 | 33.109 | 32.481 | 31.425 | 30.983 | 30.433 | 29.862 | 29.536 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| Assembler–AssembleStiffMat | 14.32 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 733.73 J | 20 threads, 2.0 GHz UCF, 2.5 GHz CF | 731.22 J | 2.51 J (0.34%) |
| Assembler–Assemble-B1 | 2.23 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 114.30 J | 2 threads, 2.2 GHz UCF, 2.5 GHz CF | 94.15 J | 20.15 J (17.63%) |
| Cluster–CreateF0-FactF0 | 0.17 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 8.71 J | 6 threads, 1.6 GHz UCF, 2.5 GHz CF | 6.90 J | 1.80 J (20.73%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Assembler–SaveResults | 3.10 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 158.81 J | 2 threads, 1.2 GHz UCF, 2.5 GHz CF | 147.66 J | 11.16 J (7.03%) |
| Assembler-K_Regular-ization | 5.43 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 278.39 J | 2 threads, 1.8 GHz UCF, 2.5 GHz CF | 231.38 J | 47.01 J (16.89%) |
| Cluster–CreateSa-SolveF0vG0 | 2.22 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 113.87 J | 6 threads, 2.0 GHz UCF, 2.5 GHz CF | 97.46 J | 16.41 J (14.41%) |
| Create_-GGT_Inv | 0.28 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 14.23 J | 2 threads, 1.2 GHz UCF, 2.5 GHz CF | 8.92 J | 5.31 J (37.34%) |
| Cluster–Kfactorization | 12.84 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 658.07 J | 24 threads, 2.0 GHz UCF, 2.4 GHz CF | 629.62 J | 28.45 J (4.32%) |
| Assembler–SaveMeshtoVTK | 6.36 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 325.69 J | 2 threads, 1.2 GHz UCF, 2.5 GHz CF | 296.66 J | 29.03 J (8.91%) |
| Cluster–CreateSa-SaFactorization | 1.95 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 99.93 J | 4 threads, 2.2 GHz UCF, 2.5 GHz CF | 80.85 J | 19.08 J (19.09%) |
| Cluster–SetClusterPC | 1.46 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 74.70 J | 20 threads, 2.0 GHz UCF, 2.5 GHz CF | 74.54 J | 0.16 J (0.22%) |
| Assembler–PrepareMesh | 12.53 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 641.88 J | 22 threads, 1.8 GHz UCF, 2.5 GHz CF | 639.39 J | 2.49 J (0.39%) |
| Assembler–SolverSolve | 30.79 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 1578.06 J | 10 threads, 2.2 GHz UCF, 2.5 GHz CF | 1289.85 J | 288.21 J (18.26%) |
| Assembler–Assemble-B0 | 0.26 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 13.28 J | 24 threads, 2.0 GHz UCF, 2.5 GHz CF | 12.51 J | 0.77 J (5.81%) |
| Cluster–CreateG1-perCluster | 0.47 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 24.20 J | 14 threads, 2.2 GHz UCF, 2.5 GHz CF | 22.32 J | 1.88 J (7.76%) |
| Cluster–CreateF0-AssembleF0 | 5.43 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 278.22 J | 24 threads, 2.2 GHz UCF, 2.2 GHz CF | 254.98 J | 23.24 J (8.35%) |
| Cluster–CreateSa-SaReg | 0.17 | 18 threads, 1.8 GHz UCF, 2.5 GHz CF | 8.59 J | 8 threads, 2.0 GHz UCF, 2.5 GHz CF | 7.03 J | 1.56 J (18.15%) |

| | |
|---|---|
| **Total value for static tuning for significant regions** | 733.73 + 114.30 + 8.71 + 158.81 + 278.39 + 113.87 + 14.23 + 658.07 + 325.69 + 99.93 + 74.70 + 641.88 + 1578.06 + 13.28 + 24.20 + 278.22 + 8.59 = 5124.66 J |
| **Total savings for dynamic tuning for significant regions** | 2.51 + 20.15 + 1.80 + 11.16 + 47.01 + 16.41 + 5.31 + 28.45 + 29.03 + 19.08 + 0.16 + 2.49 + 288.21 + 0.77 + 1.88 + 23.24 + 1.56 = 499.22 J of 5124.66 J (9.74 %) |
| **Dynamic savings for application runtime** | 499.22 J of 5493.55 J (9.09 %) |
| **Total value after savings** | 4994.33 J (79.72 % of 6265.18 J) |

**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| Assembler–AssembleStiffMat | 11.91 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 3.25 s | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 3.21 s | 0.04 s (1.23%) |
| Assembler–Assemble-B1 | 2.60 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.71 s | 16 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.70 s | 0.01 s (1.63%) |
| Cluster–CreateF0-FactF0 | 0.16 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.04 s | 22 threads, 2.8 GHz UCF, 2.5 GHz CF | 0.04 s | 0.00 s (2.03%) |
| Assembler–SaveResults | 5.10 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.39 s | 12 threads, 2.4 GHz UCF, 2.5 GHz CF | 1.38 s | 0.01 s (0.75%) |
| Assembler-K_Regularization | 8.12 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.21 s | 2 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.82 s | 0.39 s (17.53%) |
| Cluster–CreateSa-SolveF0vG0 | 2.20 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.60 s | 18 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.60 s | 0.00 s (0.13%) |
| Create_-GGT_Inv | 0.29 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.08 s | 6 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.08 s | 0.00 s (0.39%) |
| Cluster–Kfactorization | 9.40 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.56 s | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.39 s | 0.18 s (6.84%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Assembler–SaveMeshtoVTK | 9.75 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.66 s | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.66 s | 0.00 s (0.00%) |
| Cluster–CreateSa-SaFactorization | 1.84 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.50 s | 12 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.49 s | 0.01 s (1.06%) |
| Cluster–SetClusterPC | 1.35 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.37 s | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.36 s | 0.01 s (1.48%) |
| Assembler–PrepareMesh | 19.61 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 5.34 s | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 5.29 s | 0.06 s (1.03%) |
| Assembler–SolverSolve | 23.27 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 6.34 s | 12 threads, 3.0 GHz UCF, 2.4 GHz CF | 6.26 s | 0.08 s (1.20%) |
| Assembler–Assemble-B0 | 0.28 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.08 s | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.07 s | 0.00 s (2.70%) |
| Cluster–CreateG1-perCluster | 0.37 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.10 s | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.10 s | 0.00 s (3.99%) |
| Cluster–CreateF0-AssembleF0 | 3.60 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.98 s | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.94 s | 0.04 s (4.26%) |
| Cluster–CreateSa-SaReg | 0.15 | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.04 s | 22 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.04 s | 0.00 s (0.00%) |
| **Total value for static tuning for significant regions** | | | 3.25 + 0.71 + 0.04 + 1.39 + 2.21 + 0.60 + 0.08 + 2.56 + 2.66 + 0.50 + 0.37 + 5.34 + 6.34 + 0.08 + 0.10 + 0.98 + 0.04 = 27.24 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.04 + 0.01 + 0.00 + 0.01 + 0.39 + 0.00 + 0.00 + 0.18 + 0.00 + 0.01 + 0.01 + 0.06 + 0.08 + 0.00 + 0.00 + 0.04 + 0.00 = 0.82 s of 27.24 s (3.00 %) | | | |
| **Dynamic savings for application runtime** | | | 0.82 s of 29.54 s (2.76 %) | | | |
| **Total value after savings** | | | 28.72 s (97.19 % of 29.55 s) | | | |

### 6.3 Indeed

Indeed is a commercial finite element software package that has been especially designed for the simulation of sheet metal forming processes. The REDAEX consortium member GNS is the owner of this product and is responsible for its development, maintenance and marketing. Most of Indeed's users are based in the automotive industry or its suppliers.

In contrast to most of its competitors, Indeed makes use of an implicit time integration method. As a result, its computational cost is relatively high, but on the other hand it can provide a very high degree of accuracy of the numerical solutions. Indeed is available in two versions, a shared memory version based on an OpenMP parallelization and a distributed memory version based on a hybrid OpenMP and MPI approach.

The READEX-related analysis of Indeed has been performed jointly by GNS and TU München. The work has so far concentrated on the OpenMP version because it is more important from the perspective of the users.

Following a detection of the significant regions, Indeed has been instrumented with the MERIC system and numerous measurements have been started. At the time of writing this document, not all of these experiments were finished, but nevertheless a number of results can already be reported.

Specifically, we have started with an investigation of the potential energy savings with static tuning measures based on changes in the number of OpenMP threads, the core frequency and the uncore frequency.

From those plots and the underlying figures, it is evident that it is always advisable to choose the highest possible core frequency. The optimal choice of uncore frequency and number of threads depends on the objective function with respect to which the user attempts to optimize the program run's environment settings. For example, using a large number of threads is sensible when optimizing for runtime, but not when optimizing (purely) with respect to the energy requirements. Similarly, a high uncore frequency is usually advantageous from the runtime point of view but not from the energy perspective. In practice, one is frequently interested in a compromise between these two objective functions; a suitable approach to achieve this goal is provided by the energy delay product EDP1, i.e. the product of run time and required energy. When using this objective function, it turns out that it makes sense to use many threads but only a medium high uncore frequency. A quantitative assessment of the tuning potential that can be realized in this manner is given in Table 12.

The analysis of Indeed's dynamic tuning potential is currently in progress and not finished yet. The results will be reported later.

The future steps in this connection will also include similar investigations based on other types of input data sets that might exhibit a different behaviour.

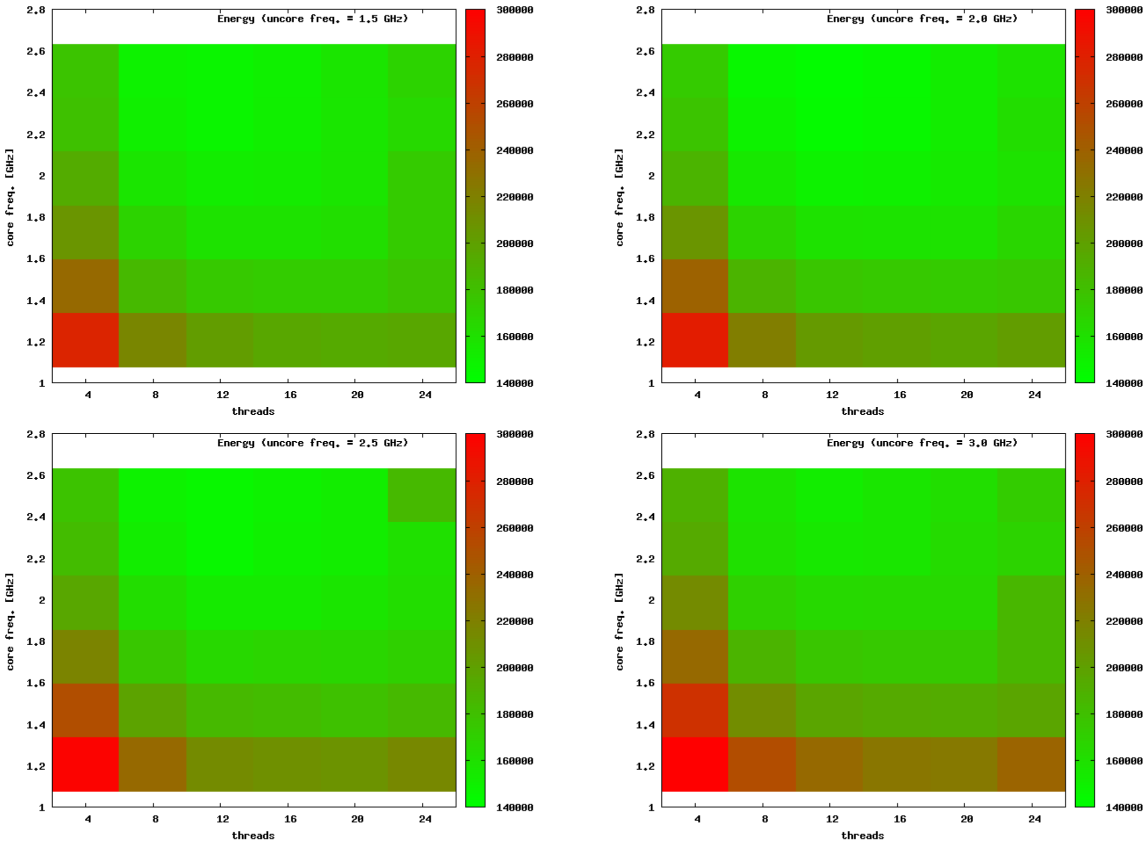



Figure 3: Energy requirements of example Indeed run for various choices of core frequency and number of threads. The plots indicate the results for an uncore frequency of 1.5 GHz (top left), 2.0 GHz (top right), 2.5 GHz (bottom left) and 3.0 GHz (bottom right).

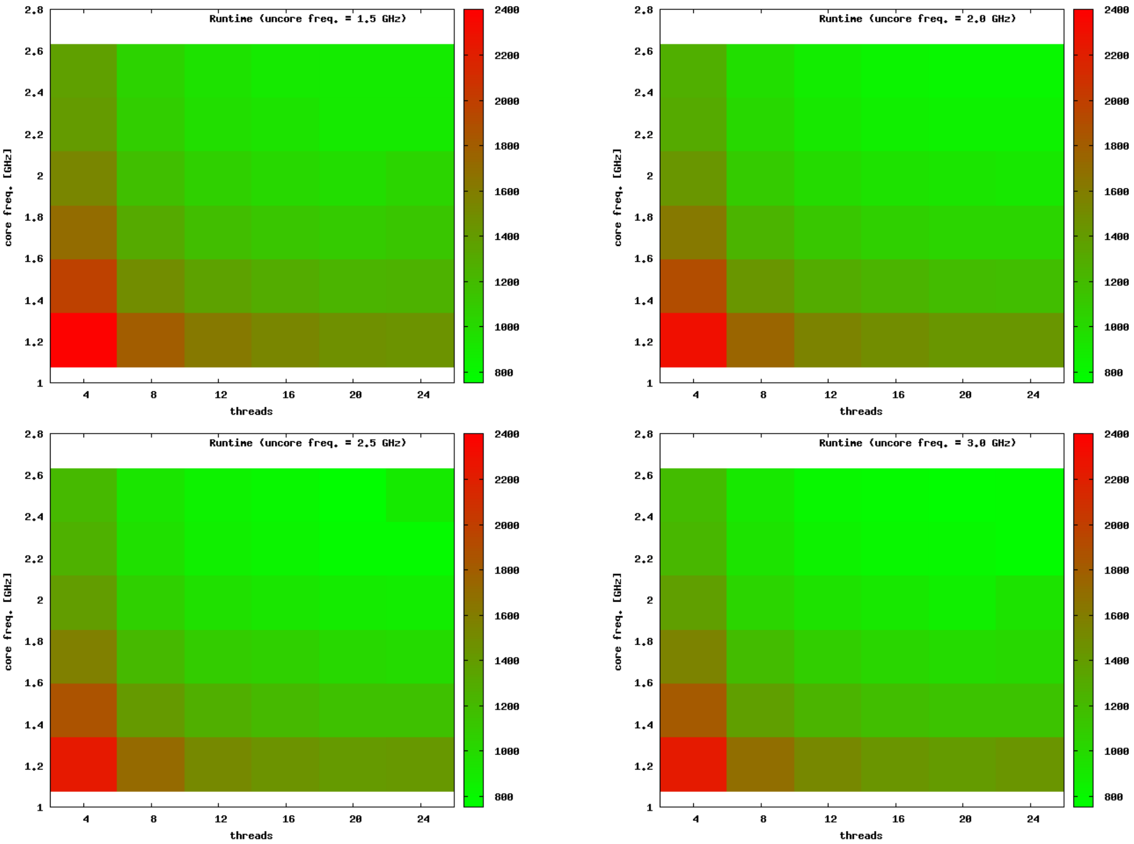



Figure 4: Run time requirements of example Indeed run for various choices of core frequency and number of threads. The plots indicate the results for an uncore frequency of 1.5 GHz (top left), 2.0 GHz (top right), 2.5 GHz (bottom left) and 3.0 GHz (bottom right).

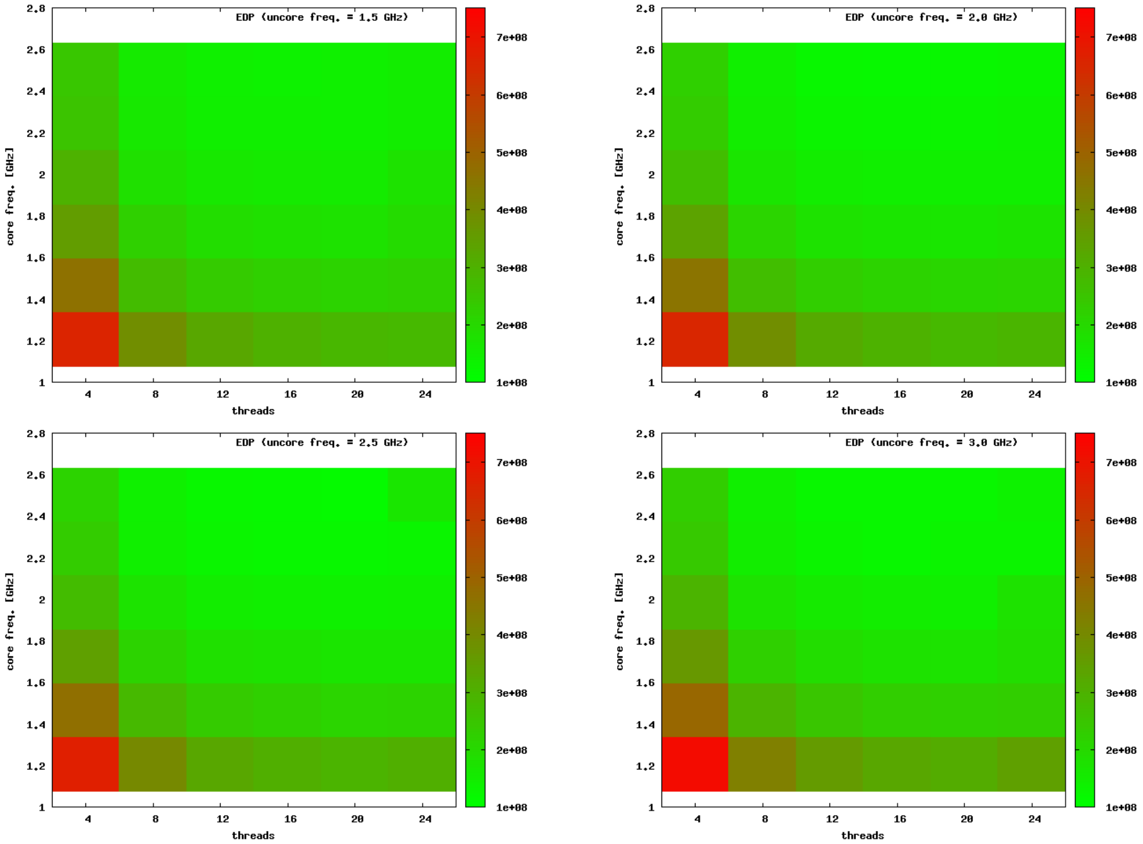



Figure 5: Energy delay product (EDP1) requirements of example Indeed run for various choices of core frequency and number of threads. The plots indicate the results for an uncore frequency of 1.5 GHz (top left), 2.0 GHz (top right), 2.5 GHz (bottom left) and 3.0 GHz (bottom right).

| Tuning objective | Optimal settings | Energy [J] (improvement) | Runtime [s] (improvement) | EDP1 [MJs] (improvement) |
|---|---|---|---|---|
| None (Default Parameters) | 24 Threads<br>2.5 GHz core freq.<br>3.0 GHz uncore freq. | 171967 | 772 | 132 |
| Energy | 12 Threads<br>2.5 GHz core freq.<br>2.0 GHz uncore freq. | 141751<br>(17.6%) | 871<br>(−12.8%) | 123<br>(6.8%) |
| Runtime | 20 Threads<br>2.5 GHz core freq.<br>3.0 GHz uncore freq. | 160538<br>(6.6%) | 762<br>(1.3%) | 122<br>(7.6%) |
| EDP1 | 20 Threads<br>2.5 GHz core freq.<br>2.5 GHz uncore freq. | 151200<br>(12.1%) | 764<br>(1.0%) | 115<br>(12.9%) |

Table 12: Static tuning potential for Indeed.

## 6.4 MiniMD

MiniMD is a parallel molecular dynamics (MD) simulation package written in C++ and is based on many of the same algorithm concepts of LAMMPS parallel MD code, but is much simpler. The self-contained application performs parallel molecular dynamics simulation of a Lennard-Jones or a EAM system and gives timing information.

MiniMD consists of less than 5,000 lines of code and uses spatial decomposition MD, where individual processors in a cluster own subsets of the simulation box. The application uses neighbour lists for the force calculation. The input to miniMD, which is provided as a file, includes a problem size, atom density, temperature in the box, timestep size for the simulation, number of timesteps to perform, and particle interation cut-off distance.

### 6.4.1 Instrumentation with MERIC

To instrument the miniMD application with MERIC, we identified the phase region to be the for-loop in the `Integrate::run()` function in `integrate.cpp`. The for-loop iterates for the number of timesteps provided as input to the application. Within this for-loop, the three regions that we instrumented are the calls to functions `borders()`, `build()` and `compute()`. Thus for analysis, we instrumented the for-loop as phase region with MERIC, while the three regions were instrumented as significant regions.

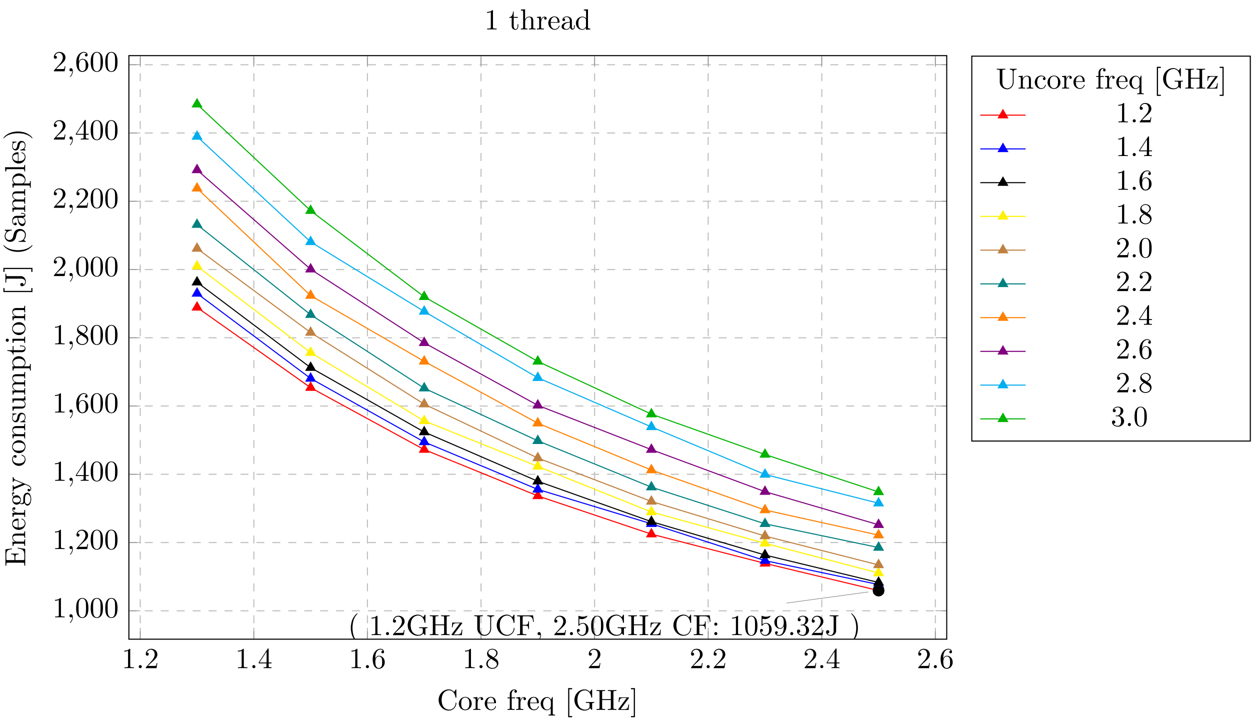
### 6.4.2 Results

We conducted the two experiments, one with the Lennard-Jones and another with EAM systems, by varying the processor core and uncore frequencies. The results from using the Lennard-Jones system are summarised in Section 6.4.2.1, while those from using the EAM system are presented in Section 6.4.2.2. The inter-phase dynamism observed and the associated results of tuning are reported in Section 7.2. Further, we observe from these experiments that the significant regions that contribute to the energy consumption and execution time are `build()` and `compute` functions.

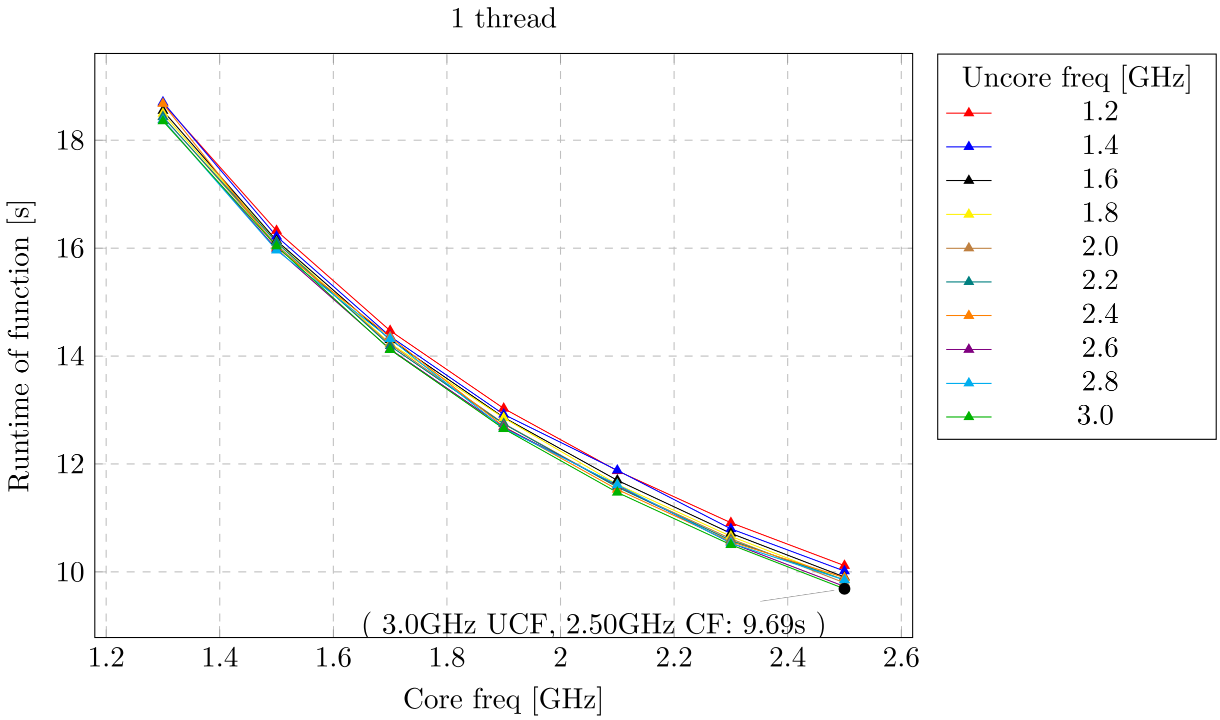
**6.4.2.1 Experiment 1** This experiment was conducted using the Lennard-Jones system configuration of miniMD with the input file `in.lj.miniMD` that is available in the application folder with the application run for 100 iterations and reneighbouring of atoms performed once every 20 iterations. The core and uncore frequencies were varied in steps of 0.2 GHz. We observe that while static tuning results in saving around 21% of energy, there are no dynamic savings reported for the energy consumption and execution time.

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J] (Samples), Blade summary | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 1348.27 J | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 288.95 J (21.43%) | 0.00 J of 1059.32 J (0.00 %) |
| Runtime of function [s], Job info - hdeem | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 9.69 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.00 s of 9.69 s (0.00 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 1,888.99 | 1,929.84 | 1,962.73 | 2,009.72 | 2,061.49 | 2,131.48 | 2,237.87 | 2,291.71 | 2,389.63 | 2,484.21 |
| 1.5 | 1,653.81 | 1,680.75 | 1,712.4 | 1,756.5 | 1,815.37 | 1,867.59 | 1,923.6 | 2,000.78 | 2,080.96 | 2,172.35 |
| 1.7 | 1,472.38 | 1,494.71 | 1,523.82 | 1,556.46 | 1,605.55 | 1,652.25 | 1,730.88 | 1,785.18 | 1,877.01 | 1,920.05 |
| 1.9 | 1,336.63 | 1,355.74 | 1,379.6 | 1,423.11 | 1,447.66 | 1,498.09 | 1,549.65 | 1,602.05 | 1,682.81 | 1,730.74 |
| 2.1 | 1,224.64 | 1,255.05 | 1,261.31 | 1,289.55 | 1,320.5 | 1,362.35 | 1,412.43 | 1,472.32 | 1,538.84 | 1,576.28 |
| 2.3 | 1,139.03 | 1,147.07 | 1,163.44 | 1,197.83 | 1,219.15 | 1,254.94 | 1,295.33 | 1,349.15 | 1,399.41 | 1,458.06 |
| 2.5 | 1,059.32 | 1,076.93 | 1,083.04 | 1,110.74 | 1,134.39 | 1,185.37 | 1,221.75 | 1,252.1 | 1,315.25 | 1,348.27 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 18.685 | 18.703 | 18.546 | 18.494 | 18.44 | 18.429 | 18.675 | 18.376 | 18.374 | 18.353 |
| 1.5 | 16.322 | 16.219 | 16.139 | 16.112 | 16.059 | 16.107 | 16.012 | 15.981 | 15.96 | 16.036 |
| 1.7 | 14.47 | 14.365 | 14.304 | 14.235 | 14.22 | 14.186 | 14.353 | 14.128 | 14.318 | 14.118 |
| 1.9 | 13.03 | 12.919 | 12.864 | 12.854 | 12.751 | 12.742 | 12.694 | 12.682 | 12.66 | 12.653 |
| 2.1 | 11.874 | 11.883 | 11.698 | 11.621 | 11.58 | 11.571 | 11.529 | 11.606 | 11.615 | 11.473 |
| 2.3 | 10.911 | 10.799 | 10.715 | 10.66 | 10.615 | 10.584 | 10.561 | 10.536 | 10.534 | 10.504 |
| 2.5 | 10.117 | 10.016 | 9.906 | 9.85 | 9.798 | 9.853 | 9.894 | 9.731 | 9.85 | 9.688 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| Build | 13.57 | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 1.34 J | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 1.34 J | 0.00 J (0.00%) |
| Borders | 0.18 | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 0.02 J | 1 th, 2.2 GHz UCF, 2.5 GHz CF | 0.01 J | 0.00 J (18.83%) |
| Compute | 86.25 | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 8.54 J | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 8.54 J | 0.00 J (0.00%) |

| | |
|---|---|
| **Total value for static tuning for significant regions** | 1.34 + 0.02 + 8.54 = 9.91 J |
| **Total savings for dynamic tuning for significant regions** | 0.00 + 0.00 + 0.00 = 0.00 J of 9.91 J (0.03 %) |
| **Dynamic savings for application runtime** | 0.00 J of 1059.32 J (0.00 %) |
| **Total value after savings** | 1059.32 J (78.57 % of 1348.27 J) |

**Intra-Phase Dynamism Evaluation**
**Job info - hdeem, Runtime of function [s]**

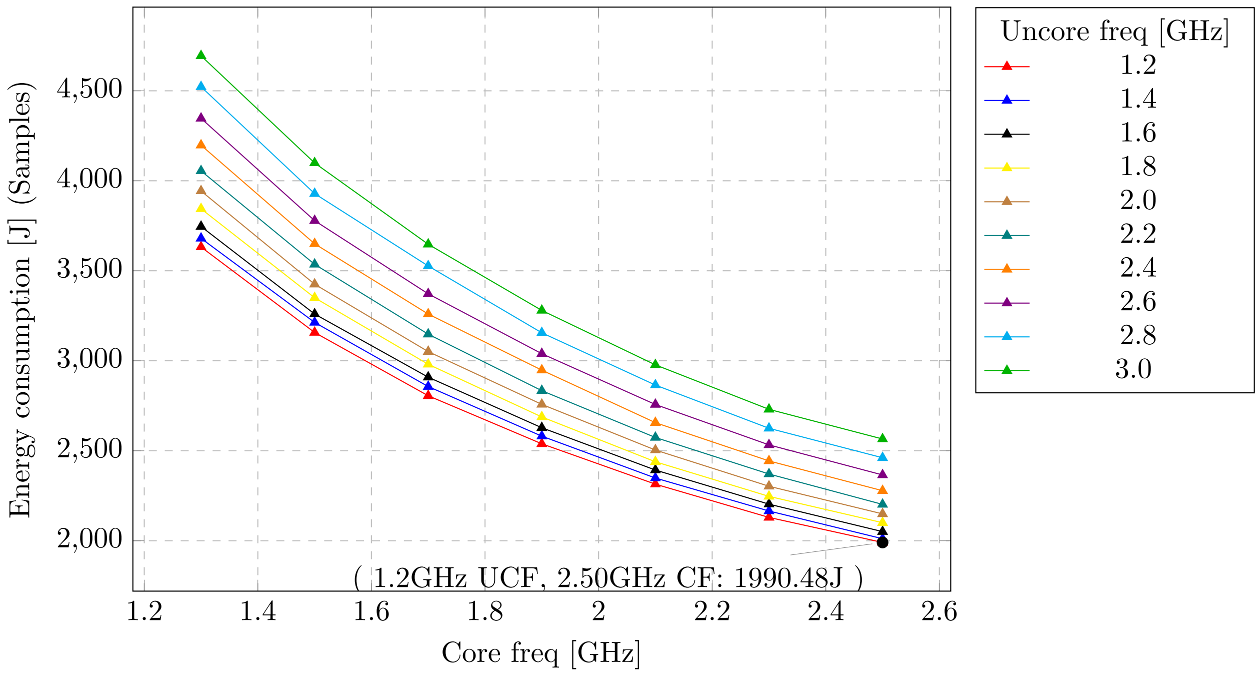
| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| Build | 13.89 | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.01 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.01 s | 0.00 s (0.00%) |
| Borders | 0.12 | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s | 0.00 s (0.00%) |
| Compute | 85.99 | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.08 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.08 s | 0.00 s (0.00%) |
| **Total value for static tuning for significant regions** | | | 0.01 + 0.00 + 0.08 = 0.09 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.00 + 0.00 + 0.00 = 0.00 s of 0.09 s (0.00 %) | | | |
| **Dynamic savings for application runtime** | | | 0.00 s of 9.69 s (0.00 %) | | | |
| **Total value after savings** | | | 9.69 s (100.00 % of 9.69 s) | | | |

**6.4.2.2 Experiment 2** This experiment was conducted using the EAM system configuration of miniMD with the input file `in.eam.miniMD` that is available in the application folder with the application run for 100 iterations and reneighbouring of atoms performed once every 20 iterations. The core and uncore frequencies were varied in steps of 0.2 GHz. We observe that while static tuning results in saving around 22% of energy, there are no dynamic savings reported for the energy consumption and execution time.

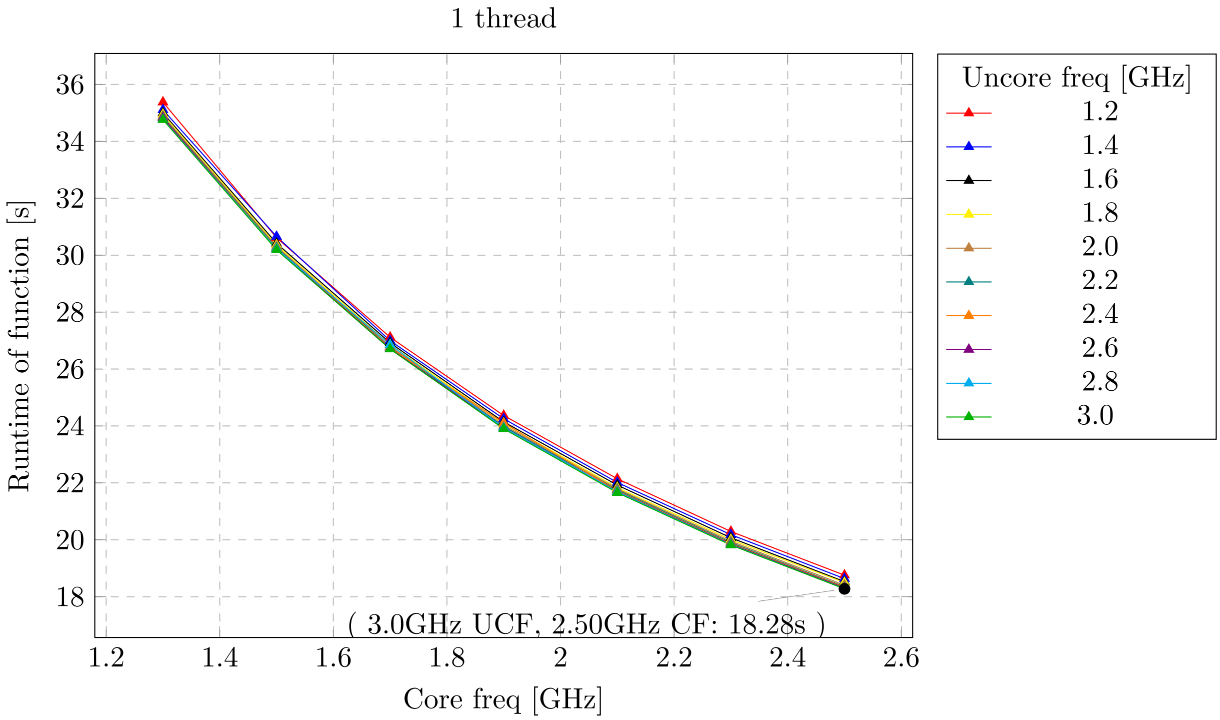
**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J] (Samples), Blade summary | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 2565.29 J | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 574.81 J (22.41%) | 0.00 J of 1990.48 J (0.00 %) |
| Runtime of function [s], Job info - hdeem | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 18.28 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.00 s of 18.28 s (0.00 %) |

1 thread




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 3,632.17 | 3,680.32 | 3,746.07 | 3,844.45 | 3,943.41 | 4,055.09 | 4,197.78 | 4,346.98 | 4,522.45 | 4,694.48 |
| 1.5 | 3,157.15 | 3,213.13 | 3,259.76 | 3,350.18 | 3,425.36 | 3,535.88 | 3,650.1 | 3,778.52 | 3,928.76 | 4,099.13 |
| 1.7 | 2,805.57 | 2,856.72 | 2,908.73 | 2,980.48 | 3,050.93 | 3,147.65 | 3,259.53 | 3,371.93 | 3,526.74 | 3,647.38 |
| 1.9 | 2,538.64 | 2,581.08 | 2,627.83 | 2,687.8 | 2,757.72 | 2,833.8 | 2,947.94 | 3,039.34 | 3,155.44 | 3,279.84 |
| 2.1 | 2,314.35 | 2,348.43 | 2,392.8 | 2,438.77 | 2,504.02 | 2,573.81 | 2,656.13 | 2,757.06 | 2,864.99 | 2,977.3 |
| 2.3 | 2,129.61 | 2,165.26 | 2,203.31 | 2,246.53 | 2,302.75 | 2,370.86 | 2,443.55 | 2,532.71 | 2,624.84 | 2,730.2 |
| 2.5 | 1,990.48 | 2,011.18 | 2,050.7 | 2,100.27 | 2,149.23 | 2,201.92 | 2,277.96 | 2,365.57 | 2,461.13 | 2,565.29 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 35.377 | 35.11 | 34.998 | 34.949 | 34.891 | 34.863 | 34.842 | 34.824 | 34.772 | 34.759 |
| 1.5 | 30.615 | 30.657 | 30.418 | 30.359 | 30.31 | 30.265 | 30.236 | 30.211 | 30.221 | 30.188 |
| 1.7 | 27.117 | 26.994 | 26.919 | 26.857 | 26.791 | 26.757 | 26.74 | 26.714 | 26.856 | 26.7 |
| 1.9 | 24.368 | 24.252 | 24.143 | 24.081 | 24.028 | 23.982 | 24.106 | 23.94 | 23.934 | 23.9 |
| 2.1 | 22.145 | 22.014 | 21.921 | 21.833 | 21.791 | 21.755 | 21.723 | 21.699 | 21.69 | 21.656 |
| 2.3 | 20.292 | 20.18 | 20.071 | 20.006 | 19.95 | 19.902 | 19.871 | 19.847 | 19.827 | 19.815 |
| 2.5 | 18.757 | 18.636 | 18.53 | 18.498 | 18.406 | 18.355 | 18.336 | 18.309 | 18.281 | 18.277 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| Borders | 0.09 | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 0.02 J | 1 th, 2.4 GHz UCF, 2.5 GHz CF | 0.01 J | 0.00 J (19.90%) |
| Build | 11.07 | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 2.13 J | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 2.13 J | 0.00 J (0.00%) |
| Compute | 88.83 | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 17.13 J | 1 th, 1.2 GHz UCF, 2.5 GHz CF | 17.13 J | 0.00 J (0.00%) |

| | |
|---|---|
| **Total value for static tuning for significant regions** | 0.02 + 2.13 + 17.13 = 19.28 J |
| **Total savings for dynamic tuning for significant regions** | 0.00 + 0.00 + 0.00 = 0.00 J of 19.28 J (0.02 %) |
| **Dynamic savings for application runtime** | 0.00 J of 1990.48 J (0.00 %) |
| **Total value after savings** | 1990.48 J (77.59 % of 2565.29 J) |

**Intra-Phase Dynamism Evaluation**
**Job info - hdeem, Runtime of function [s]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| Borders | 0.06 | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s | 0.00 s (0.00%) |
| Build | 11.18 | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.02 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.02 s | 0.00 s (0.00%) |
| Compute | 88.76 | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.16 s | 1 th, 3.0 GHz UCF, 2.5 GHz CF | 0.16 s | 0.00 s (0.00%) |
| **Total value for static tuning for significant regions** | | | 0.00 + 0.02 + 0.16 = 0.18 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.00 + 0.00 + 0.00 = 0.00 s of 0.18 s (0.00 %) | | | |
| **Dynamic savings for application runtime** | | | 0.00 s of 18.28 s (0.00 %) | | | |
| **Total value after savings** | | | 18.28 s (100.00 % of 18.28 s) | | | |

## 6.5 OpenFOAM

OpenFOAM is an abbreviation for Open source Field Operation And Manipulation. It is an open source C++ toolbox for computational fluid dynamics (CFD). OpenFOAM does not have a generic solver applicable to all cases, but there is a long list of solvers each for specific class of problems. Solvers are categorized into several categories, e.g. compressible and incompressible flow, multiphase flow, combustion, particle-tracking flows heat transfer and many more. Besides the solvers, OpenFOAM has a set of pre-/post-processing features in meshing, physical modeling or numerical methods. More information about the OpenFOAM software can be found at www.openfoam.com.

### 6.5.1 Instrumentation with MERIC

For the OpenFOAM investigation we have selected the simpleFoam application, the steady-state solver for incompressible flows with turbulence modeling.

The application was split into following parts: the initialization, iterative solver for pressure, velocity and turbulence problems and the part for saving the results to the output file. The initialization part was split into more fine grained regions according to division in the simpleFoam source code.

### 6.5.2 Results

We ran a test with the OpenFOAM application simpleFoam on the test example motorBike, that is part of the OpenFOAM repository. The experiment were done on one single node with 24 MPI processes, that were used to decompose the domain using the simple decomposition method for decomposition into $6 \times 2 \times 2$ blocks of $48 \times 20 \times 20$ elements.

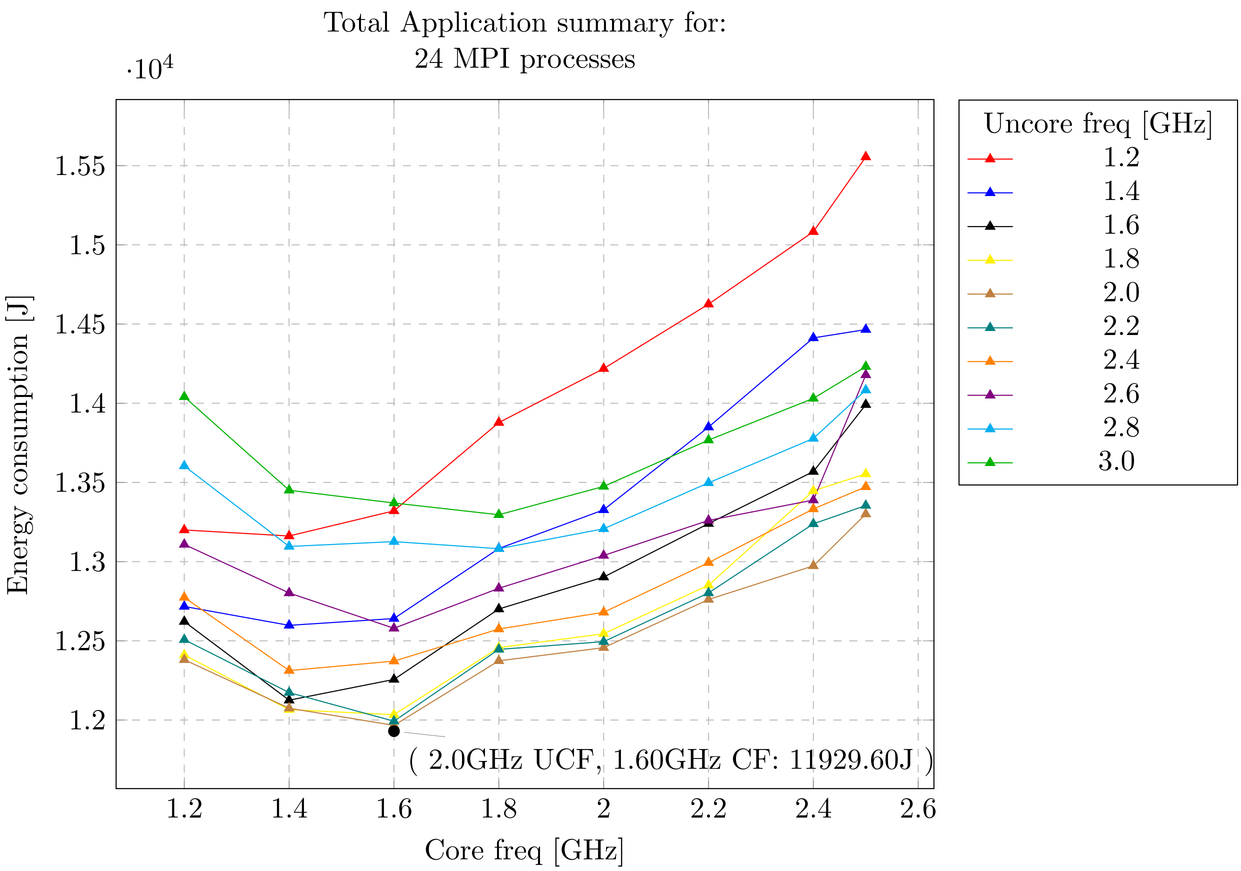
The simpleFoam application were set to use GAMG solver for pEqn region and PBiCG solver for UEqn, transport and turbulence regions. The results were written twice during the runtime into binary uncompressed format.

The core and uncore frequencies ranged between 1.2 - 2.5 GHz and 1.2 - 3.0 GHz, respectively, with the step size of 0.2 GHz. The test were ran five times to reduce measurement oscillations mainly due to network traffic. RADAR reports an average values across these measurements.

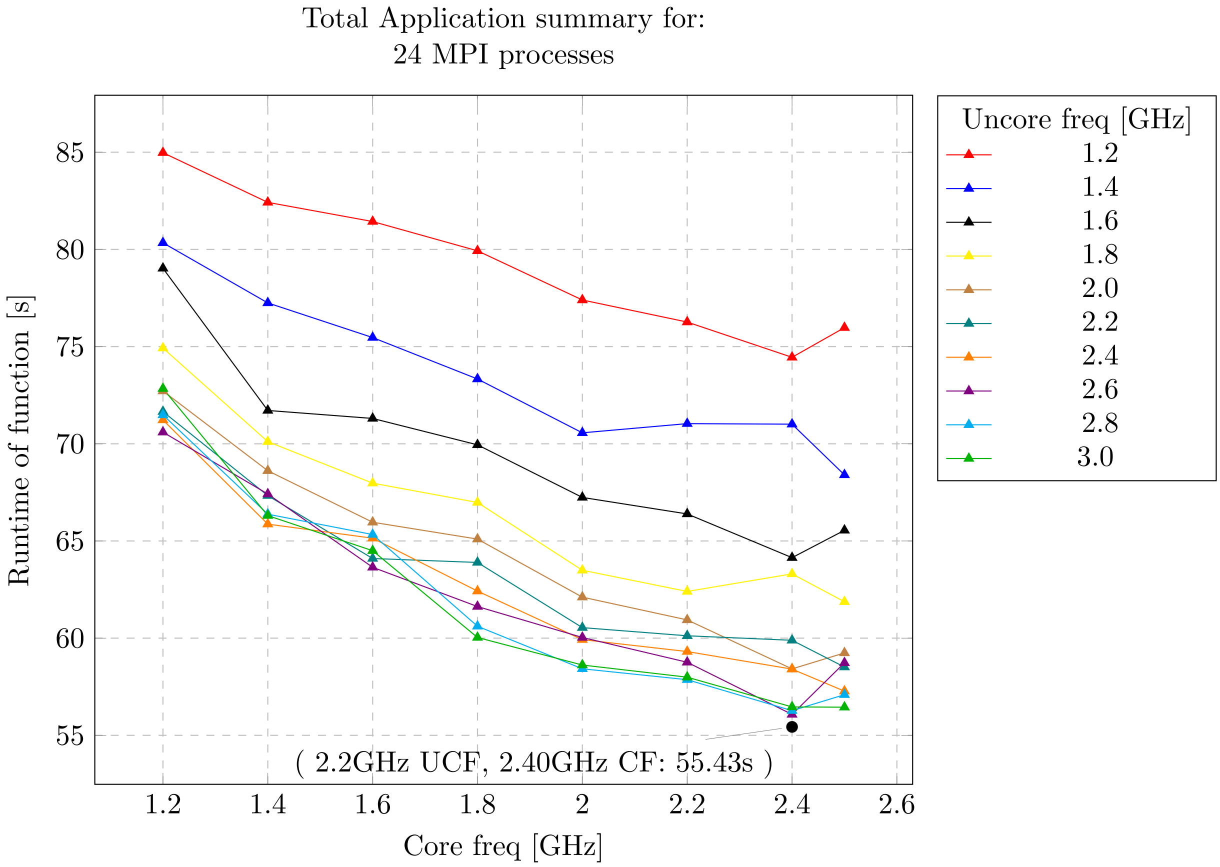
Since the most time consuming regions, the GAMG and PBiCG solvers, perform similar sparse BLAS operations the optimal configuration is either identical or very similar. Due to this reason the most of the saving can be achieved by static tuning, 15.9%, while only the remaining regions provide some potential for dynamic savings. Since the runtime of remaining regions is only $\tilde{1}4.5\%$ the overall dynamic savings are only 1.7%.

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 3.0 GHz UCF, 2.5 GHz CF | 14231.30 J | 2.0 GHz UCF, 1.6 GHz CF | 2264.94 J (15.92%) | 207.54 J of 11966.36 J (1.73 %) |
| Runtime of function [s], Job info - hdeem | 3.0 GHz UCF, 2.5 GHz CF | 56.45 s | 2.6 GHz UCF, 2.4 GHz CF | 0.37 s (0.66%) | 2.36 s of 56.08 s (4.20 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 13,200.02 | 12,717.1 | 12,621.78 | 12,410.62 | 12,380.68 | 12,507.38 | 12,774.16 | 13,108.6 | 13,604.2 | 14,040.8 |
| 1.4 | 13,161.9 | 12,597.78 | 12,125.18 | 12,065.52 | 12,074.54 | 12,173.36 | 12,312.24 | 12,802.26 | 13,095.84 | 13,450.8 |
| 1.6 | 13,320.66 | 12,640.76 | 12,256.22 | 12,033.62 | 11,966.36 | 11,992.7 | 12,372.04 | 12,579.22 | 13,126.44 | 13,370.24 |
| 1.8 | 13,878.04 | 13,082.66 | 12,700.92 | 12,457.08 | 12,373.86 | 12,445.98 | 12,574.6 | 12,831.82 | 13,081.62 | 13,296.04 |
| 2 | 14,218.58 | 13,327.12 | 12,902.62 | 12,544.82 | 12,456.82 | 12,494.8 | 12,680.32 | 13,038.86 | 13,207.38 | 13,474.8 |
| 2.2 | 14,625.62 | 13,849.58 | 13,240.14 | 12,851 | 12,760.98 | 12,802.24 | 12,993.44 | 13,260.38 | 13,497.6 | 13,767.62 |
| 2.4 | 15,083.2 | 14,412.62 | 13,568.68 | 13,447.18 | 12,973.38 | 13,238.6 | 13,332.7 | 13,388.7 | 13,777.68 | 14,030.66 |
| 2.5 | 15,554.96 | 14,465.2 | 13,991 | 13,553.84 | 13,300.24 | 13,354.46 | 13,472.36 | 14,179.16 | 14,083.06 | 14,231.3 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 84.976 | 80.339 | 79.028 | 74.925 | 72.716 | 71.654 | 71.226 | 70.598 | 71.485 | 72.839 |
| 1.4 | 82.421 | 77.248 | 71.714 | 70.108 | 68.613 | 67.333 | 65.866 | 67.414 | 66.378 | 66.305 |
| 1.6 | 81.434 | 75.465 | 71.304 | 67.975 | 65.964 | 64.097 | 65.142 | 63.646 | 65.33 | 64.499 |
| 1.8 | 79.927 | 73.333 | 69.946 | 66.98 | 65.096 | 63.895 | 62.421 | 61.626 | 60.613 | 60.035 |
| 2 | 77.398 | 70.564 | 67.241 | 63.494 | 62.111 | 60.541 | 59.925 | 60.035 | 58.424 | 58.617 |
| 2.2 | 76.263 | 71.037 | 66.391 | 62.403 | 60.939 | 60.121 | 59.311 | 58.759 | 57.863 | 57.992 |
| 2.4 | 74.449 | 71.009 | 64.141 | 63.308 | 58.418 | 59.89 | 58.406 | 56.076 | 56.27 | 56.461 |
| 2.5 | 75.975 | 68.4 | 65.549 | 61.872 | 59.241 | 58.514 | 57.273 | 58.729 | 57.091 | 56.447 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| init-createTime | 0.03 | 2.0 GHz UCF, 1.6 GHz CF | 3.35 J | 1.4 GHz UCF, 1.4 GHz CF | 2.64 J | 0.71 J (21.06%) |
| init-createFields | 4.28 | 2.0 GHz UCF, 1.6 GHz CF | 506.91 J | 2.4 GHz UCF, 2.0 GHz CF | 474.80 J | 32.11 J (6.33%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| init-createMesh | 2.26 | 2.0 GHz UCF, 1.6 GHz CF | 267.33 J | 1.4 GHz UCF, 1.4 GHz CF | 194.38 J | 72.96 J (27.29%) |
| UEqn | 40.71 | 2.0 GHz UCF, 1.6 GHz CF | 4820.82 J | 2.2 GHz UCF, 1.6 GHz CF | 4810.03 J | 10.80 J (0.22%) |
| pEqn | 19.15 | 2.0 GHz UCF, 1.6 GHz CF | 2268.19 J | 2.0 GHz UCF, 1.6 GHz CF | 2268.19 J | 0.00 J (0.00%) |
| trans-portAnd-Turbulence | 25.70 | 2.0 GHz UCF, 1.6 GHz CF | 3042.91 J | 2.0 GHz UCF, 1.6 GHz CF | 3042.91 J | 0.00 J (0.00%) |
| write | 7.88 | 2.0 GHz UCF, 1.6 GHz CF | 932.59 J | 1.2 GHz UCF, 1.4 GHz CF | 841.62 J | 90.97 J (9.75%) |
| **Total value for static tuning for significant regions** | | | 3.35 + 506.91 + 267.33 + 4820.82 + 2268.19 + 3042.91 + 932.59 = 11842.12 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.71 + 32.11 + 72.96 + 10.80 + 0.00 + 0.00 + 90.97 = 207.54 J of 11842.12 J (1.75 %) | | | |
| **Dynamic savings for application runtime** | | | 207.54 J of 11966.36 J (1.73 %) | | | |
| **Total value after savings** | | | 11758.82 J (82.63 % of 14231.30 J) | | | |

**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| init-createTime | 0.05 | 2.6 GHz UCF, 2.4 GHz CF | 0.03 s | 1.4 GHz UCF, 1.4 GHz CF | 0.02 s | 0.01 s (29.14%) |
| init-createFields | 5.22 | 2.6 GHz UCF, 2.4 GHz CF | 2.88 s | 2.4 GHz UCF, 2.0 GHz CF | 2.77 s | 0.10 s (3.54%) |
| init-createMesh | 3.61 | 2.6 GHz UCF, 2.4 GHz CF | 1.99 s | 1.4 GHz UCF, 1.4 GHz CF | 1.66 s | 0.33 s (16.49%) |
| UEqn | 36.85 | 2.6 GHz UCF, 2.4 GHz CF | 20.31 s | 3.0 GHz UCF, 2.5 GHz CF | 19.71 s | 0.60 s (2.97%) |
| pEqn | 16.52 | 2.6 GHz UCF, 2.4 GHz CF | 9.11 s | 3.0 GHz UCF, 2.5 GHz CF | 8.84 s | 0.27 s (2.94%) |
| trans-portAnd-Turbulence | 22.95 | 2.6 GHz UCF, 2.4 GHz CF | 12.65 s | 3.0 GHz UCF, 2.5 GHz CF | 12.28 s | 0.37 s (2.92%) |
| write | 14.80 | 2.6 GHz UCF, 2.4 GHz CF | 8.16 s | 2.0 GHz UCF, 2.4 GHz CF | 7.48 s | 0.68 s (8.33%) |

| | |
|---|---|
| **Total value for static tuning for significant regions** | 0.03 + 2.88 + 1.99 + 20.31 + 9.11 + 12.65 + 8.16 = 55.11 s |
| **Total savings for dynamic tuning for significant regions** | 0.01 + 0.10 + 0.33 + 0.60 + 0.27 + 0.37 + 0.68 = 2.36 s of 55.11 s (4.28 %) |
| **Dynamic savings for application runtime** | 2.36 s of 56.08 s (4.20 %) |
| **Total value after savings** | 53.72 s (95.17 % of 56.45 s) |

## 6.6 ProxyApps 1 - AMG2013

AMG2013 is a parallel algebraic multigrid solver for linear systems arising from problems on unstructured grids. It has been derived directly from the BoomerAMG solver in the hypre library, a large linear solver library that is being developed in the Center for Applied Scientific Computing (CASC) at LLNL. The driver provided in the benchmark can build various test problems. The default problem is a Laplace type problem on an unstructured domain with various jumps and an anisotropy in one part. Further, the application allows to solve a Laplace type problem on a structured grid by a finite difference scheme with either a 7-point or 27-point stencil, or a problem with jumping coefficients.

AMG2013 is written in ISO-C. It is an SPMD code which uses MPI as well as OpenMP. Parallelism is achieved by data decomposition. The driver provided with AMG2013 achieves this decomposition by simply subdividing the grid into logical P x Q x R (in 3D) chunks of equal size. The benchmark was designed to test parallel weak scaling efficiency.

AMG2013 is a highly synchronous code. The communications and computations patterns exhibit the surface-to-volume relationship common to many parallel scientific codes. Hence, parallel efficiency is largely determined by the size of the data 'chunks' mentioned above, and the speed of communications and computations on the machine. AMG2013 is also memory-access bound, doing only about 1-2 computations per memory access, so memory-access speeds will also have a large impact on performance.

For more information on the package and download links we refer the reader to https://codesign.llnl.gov/amg2013.php.

### 6.6.1 Instrumentation with MERIC

For the testing purposes we concentrated on the default problem solved by AMG2013, namely the Laplace type problem on an unstructured grid solved by a conjugate gradient scheme preconditioned by the algebraic multigrid approach.

To instrument the code with MERIC we first profiled the application in Allinea Map. There are three significant regions suitable for MERIC. Firstly, we insert the probes around the preparatory phase including the set up of the system matrices and the creation of data decomposition and communication patterns. The preconditioned conjugate gradient (PCG) method is set up in the method `HYPRE_PCGSetup`. The PCG itself is called in `HYPRE_PCGSolve` which contains individual iterations. This region can thus be evaluated on the per-iteration basis by RADAR.

To keep the runtime of the MERIC evaluation reasonable, the size of the problem was chosen such that the single simulation took tens of seconds on a single Taurus node. Specifically, we call the program by

```
srun -n $MPI_PROCS ./amg2013.exe -P PX PY PZ -r RX RY RZ
```

with `MPI_PROCS` denoting the number of MPI processes distributed in each direction by the parameters `PX`, `PY`, `PZ` with

$$\texttt{MPI\_PROCS} = \texttt{PX} \cdot \texttt{PY} \cdot \texttt{PZ}.$$

The remaining parameters define the size of the problem. Specifically for the default Laplace problem, the parameters `RX`, `RY`, `RZ` define the number of refinements of the initial grid comprising of 384 degrees of freedom.

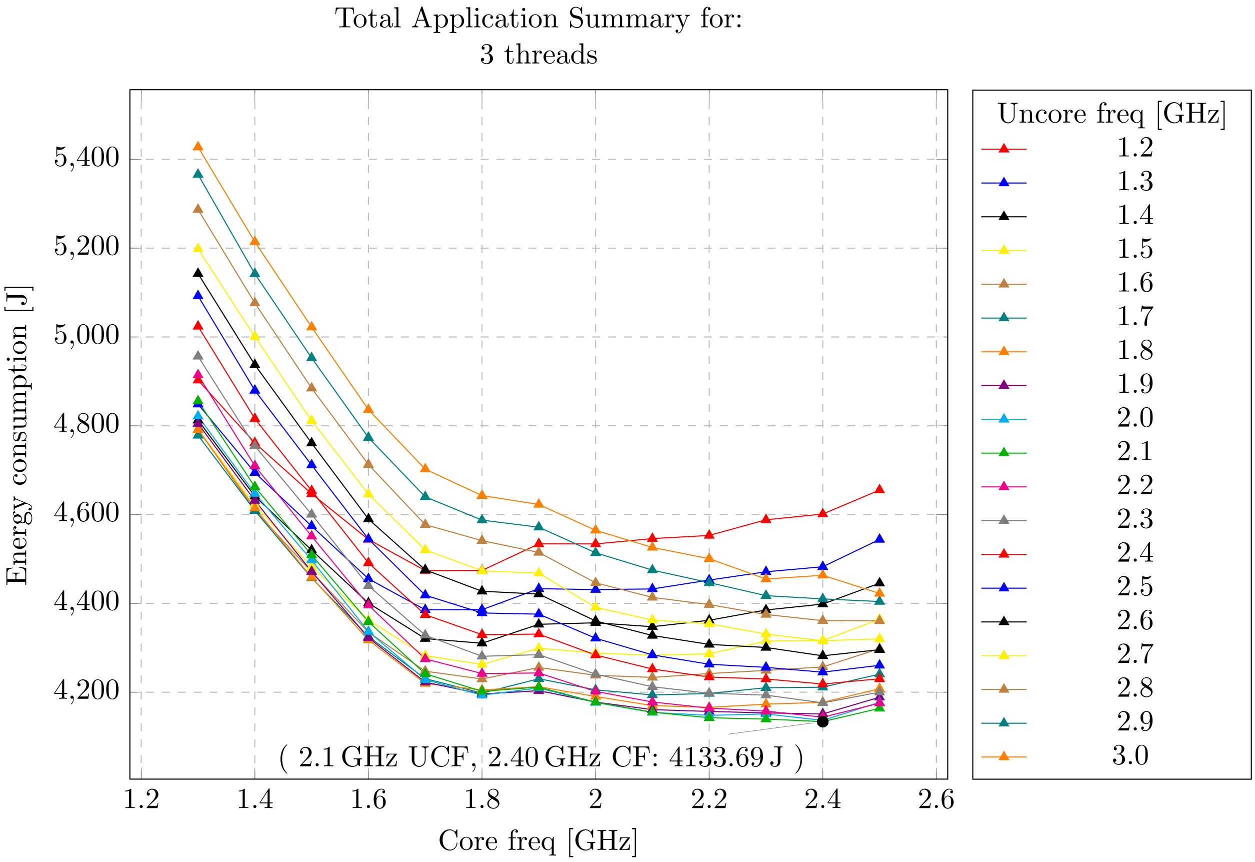
### 6.6.2 Results

For the reports we used two configurations of AMG2013. Firstly, we instrumented a symmetric decomposition of the computational domain with `PX=PY=PZ=2` and thus `MPI_PROCS=8`. The number of OpenMP threads ranged between 1–3 per process and were bound to the master thread by `OMP_PROC_BIND=close` to avoid NUMA effects. The core and uncore frequencies ranged between 1.3–2.5 GHz and 1.2–3.0 GHz, respectively, with the step size of 0.1 GHz. Secondly, since we only run on a single node, we ran the program with a single MPI process and the number of OpenMP threads ranging from 2 to 24 with the step size equal to 2 (again with close binding to the master thread). Due to a large number of runs, in this case the core and uncore frequencies ranged between the same extremal values, but with the step size of 0.2 GHz. All configurations were ran five times, RADAR reports represent an average run, i.e., both energy and time measurements are averaged across the five instances to remedy possible oscillations.

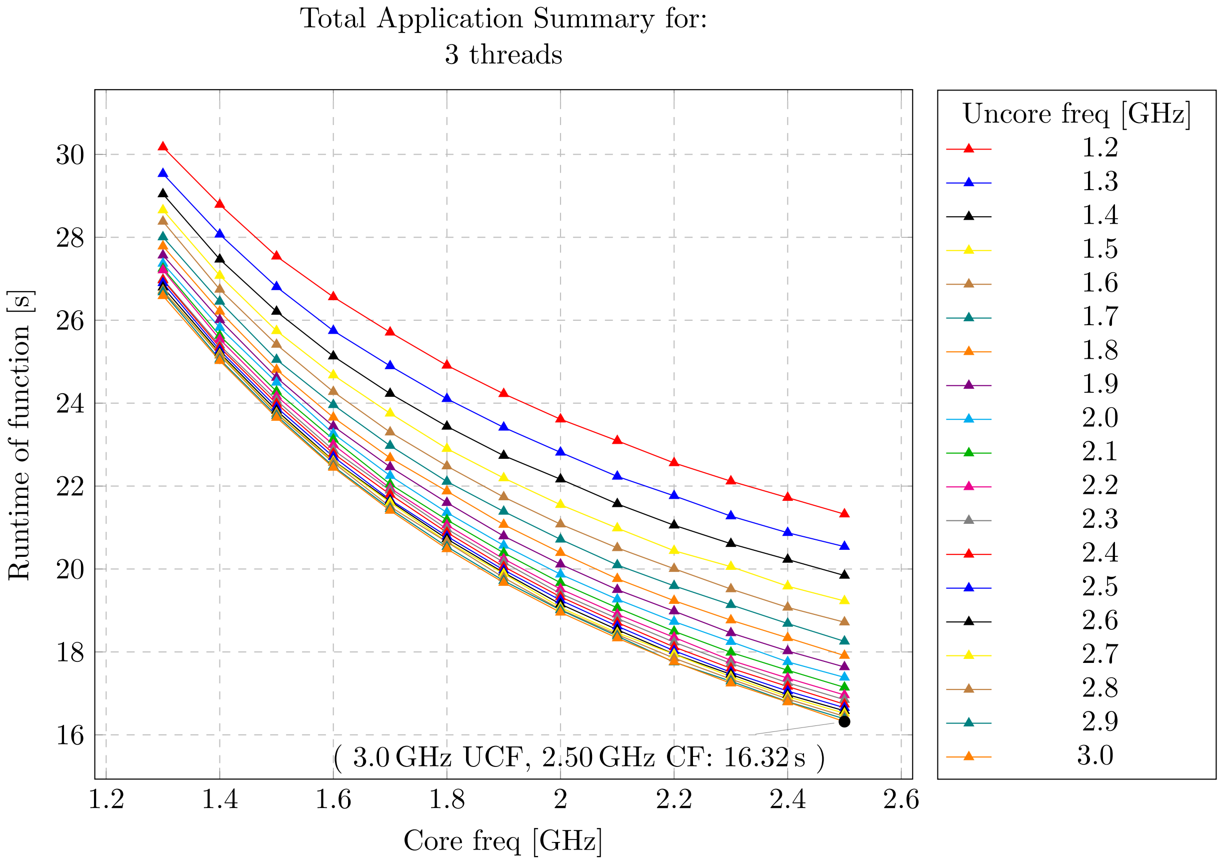
#### 6.6.2.1 `MPI_PROCS=8`, `PX=PY=PZ=2`, `RX=RY=RZ=20`

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 4422.48 J | 3 threads, 2.1 GHz UCF, 2.4 GHz CF | 288.79 J (6.53%) | 119.28 J of 4133.69 J (2.89 %) |
| Runtime of function [s], Job info - hdeem | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 16.32 s | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.00 s of 16.32 s (0.01 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 4,903 | 4,849 | 4,812 | 4,792 | 4,792 | 4,778 | 4,791 | 4,805 | 4,822 | 4,856 | 4,914 | 4,956 | 5,024 | 5,092 | 5,143 | 5,198 | 5,287 | 5,366 | 5,428 |
| 1.4 | 4,761 | 4,695 | 4,641 | 4,622 | 4,610 | 4,609 | 4,615 | 4,632 | 4,647 | 4,663 | 4,710 | 4,755 | 4,816 | 4,880 | 4,937 | 5,001 | 5,076 | 5,142 | 5,214 |
| 1.5 | 4,647 | 4,574 | 4,520 | 4,483 | 4,471 | 4,457 | 4,459 | 4,472 | 4,497 | 4,509 | 4,551 | 4,600 | 4,654 | 4,711 | 4,761 | 4,811 | 4,885 | 4,953 | 5,022 |
| 1.6 | 4,544 | 4,455 | 4,401 | 4,362 | 4,335 | 4,325 | 4,318 | 4,323 | 4,337 | 4,359 | 4,396 | 4,440 | 4,491 | 4,545 | 4,590 | 4,646 | 4,713 | 4,773 | 4,836 |
| 1.7 | 4,474 | 4,386 | 4,321 | 4,282 | 4,247 | 4,231 | 4,220 | 4,223 | 4,228 | 4,241 | 4,275 | 4,328 | 4,375 | 4,418 | 4,476 | 4,521 | 4,577 | 4,640 | 4,702 |
| 1.8 | 4,474 | 4,386 | 4,310 | 4,263 | 4,230 | 4,198 | 4,205 | 4,196 | 4,193 | 4,202 | 4,242 | 4,281 | 4,330 | 4,378 | 4,427 | 4,473 | 4,541 | 4,588 | 4,643 |
| 1.9 | 4,534 | 4,433 | 4,353 | 4,299 | 4,256 | 4,230 | 4,212 | 4,203 | 4,210 | 4,211 | 4,243 | 4,285 | 4,331 | 4,376 | 4,421 | 4,468 | 4,515 | 4,572 | 4,623 |
| 2 | 4,534 | 4,431 | 4,356 | 4,288 | 4,238 | 4,205 | 4,190 | 4,178 | 4,177 | 4,177 | 4,202 | 4,241 | 4,284 | 4,322 | 4,360 | 4,391 | 4,446 | 4,514 | 4,565 |
| 2.1 | 4,546 | 4,433 | 4,347 | 4,283 | 4,233 | 4,194 | 4,170 | 4,161 | 4,154 | 4,155 | 4,178 | 4,212 | 4,252 | 4,284 | 4,328 | 4,363 | 4,414 | 4,475 | 4,526 |
| 2.2 | 4,553 | 4,453 | 4,362 | 4,287 | 4,242 | 4,197 | 4,166 | 4,157 | 4,148 | 4,142 | 4,164 | 4,198 | 4,234 | 4,263 | 4,308 | 4,354 | 4,397 | 4,447 | 4,501 |
| 2.3 | 4,588 | 4,471 | 4,385 | 4,315 | 4,249 | 4,210 | 4,173 | 4,153 | 4,151 | 4,140 | 4,157 | 4,193 | 4,230 | 4,256 | 4,301 | 4,331 | 4,375 | 4,417 | 4,455 |
| 2.4 | 4,601 | 4,483 | 4,399 | 4,316 | 4,257 | 4,211 | 4,177 | 4,151 | 4,137 | 4,134 | 4,144 | 4,176 | 4,218 | 4,245 | 4,282 | 4,316 | 4,361 | 4,410 | 4,463 |
| 2.5 | 4,655 | 4,544 | 4,445 | 4,364 | 4,298 | 4,241 | 4,208 | 4,189 | 4,177 | 4,164 | 4,175 | 4,200 | 4,230 | 4,261 | 4,296 | 4,320 | 4,361 | 4,404 | 4,422 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 30.2 | 29.5 | 29 | 28.7 | 28.4 | 28 | 27.8 | 27.6 | 27.4 | 27.2 | 27.2 | 27 | 27 | 26.9 | 26.8 | 26.7 | 26.7 | 26.7 | 26.6 |
| 1.4 | 28.8 | 28.1 | 27.5 | 27.1 | 26.7 | 26.5 | 26.2 | 26 | 25.8 | 25.6 | 25.5 | 25.4 | 25.3 | 25.3 | 25.2 | 25.2 | 25.2 | 25.1 | 25 |
| 1.5 | 27.5 | 26.8 | 26.2 | 25.7 | 25.4 | 25 | 24.8 | 24.6 | 24.5 | 24.3 | 24.2 | 24.1 | 24 | 23.9 | 23.8 | 23.8 | 23.7 | 23.7 | 23.7 |
| 1.6 | 26.6 | 25.7 | 25.1 | 24.7 | 24.3 | 24 | 23.7 | 23.4 | 23.3 | 23.1 | 23 | 22.9 | 22.8 | 22.7 | 22.6 | 22.6 | 22.6 | 22.5 | 22.4 |
| 1.7 | 25.7 | 24.9 | 24.2 | 23.8 | 23.3 | 23 | 22.7 | 22.5 | 22.2 | 22 | 21.9 | 21.9 | 21.8 | 21.7 | 21.6 | 21.6 | 21.5 | 21.5 | 21.4 |
| 1.8 | 24.9 | 24.1 | 23.4 | 22.9 | 22.5 | 22.1 | 21.9 | 21.6 | 21.4 | 21.2 | 21.1 | 21 | 20.9 | 20.8 | 20.7 | 20.7 | 20.6 | 20.5 | 20.5 |
| 1.9 | 24.2 | 23.4 | 22.7 | 22.2 | 21.7 | 21.4 | 21.1 | 20.8 | 20.6 | 20.4 | 20.2 | 20.2 | 20.1 | 20 | 19.9 | 19.9 | 19.8 | 19.7 | 19.7 |
| 2 | 23.6 | 22.8 | 22.2 | 21.6 | 21.1 | 20.7 | 20.4 | 20.1 | 19.9 | 19.7 | 19.5 | 19.4 | 19.3 | 19.2 | 19.2 | 19.1 | 19 | 19 | 19 |
| 2.1 | 23.1 | 22.2 | 21.6 | 21 | 20.5 | 20.1 | 19.8 | 19.5 | 19.3 | 19.1 | 18.9 | 18.8 | 18.7 | 18.6 | 18.5 | 18.5 | 18.4 | 18.4 | 18.3 |
| 2.2 | 22.6 | 21.8 | 21.1 | 20.4 | 20 | 19.6 | 19.2 | 19 | 18.7 | 18.5 | 18.4 | 18.2 | 18.1 | 18 | 17.9 | 17.9 | 17.8 | 17.8 | 17.8 |
| 2.3 | 22.1 | 21.3 | 20.6 | 20.1 | 19.5 | 19.1 | 18.8 | 18.5 | 18.2 | 18 | 17.8 | 17.7 | 17.6 | 17.5 | 17.5 | 17.4 | 17.3 | 17.3 | 17.2 |
| 2.4 | 21.7 | 20.9 | 20.2 | 19.6 | 19.1 | 18.7 | 18.3 | 18 | 17.8 | 17.6 | 17.4 | 17.3 | 17.2 | 17.1 | 17 | 16.9 | 16.9 | 16.8 | 16.8 |
| 2.5 | 21.3 | 20.5 | 19.8 | 19.2 | 18.7 | 18.3 | 17.9 | 17.6 | 17.4 | 17.1 | 17 | 16.8 | 16.7 | 16.7 | 16.6 | 16.5 | 16.4 | 16.4 | 16.3 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| HYPRE_-PCGSetup | 57.21 | 3 threads, 2.1 GHz UCF, 2.4 GHz CF | 2252.82 J | 3 threads, 1.7 GHz UCF, 2.5 GHz CF | 2237.68 J | 15.14 J (0.67%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| set_up_matrix | 8.96 | 3 threads, 2.1 GHz UCF, 2.4 GHz CF | 352.99 J | 1 threads, 2.1 GHz UCF, 2.4 GHz CF | 349.29 J | 3.70 J (1.05%) |
| hypre_PCG-Solve_iter | 33.83 | 3 threads, 2.1 GHz UCF, 2.4 GHz CF | 1332.25 J | 3 threads, 2.1 GHz UCF, 1.7 GHz CF | 1231.81 J | 100.44 J (7.54%) |
| **Total value for static tuning for significant regions** | | | 2252.82 + 352.99 + 1332.25 = 3938.06 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 15.14 + 3.70 + 100.44 = 119.28 J of 3938.06 J (3.03 %) | | | |
| **Dynamic savings for application runtime** | | | 119.28 J of 4133.69 J (2.89 %) | | | |

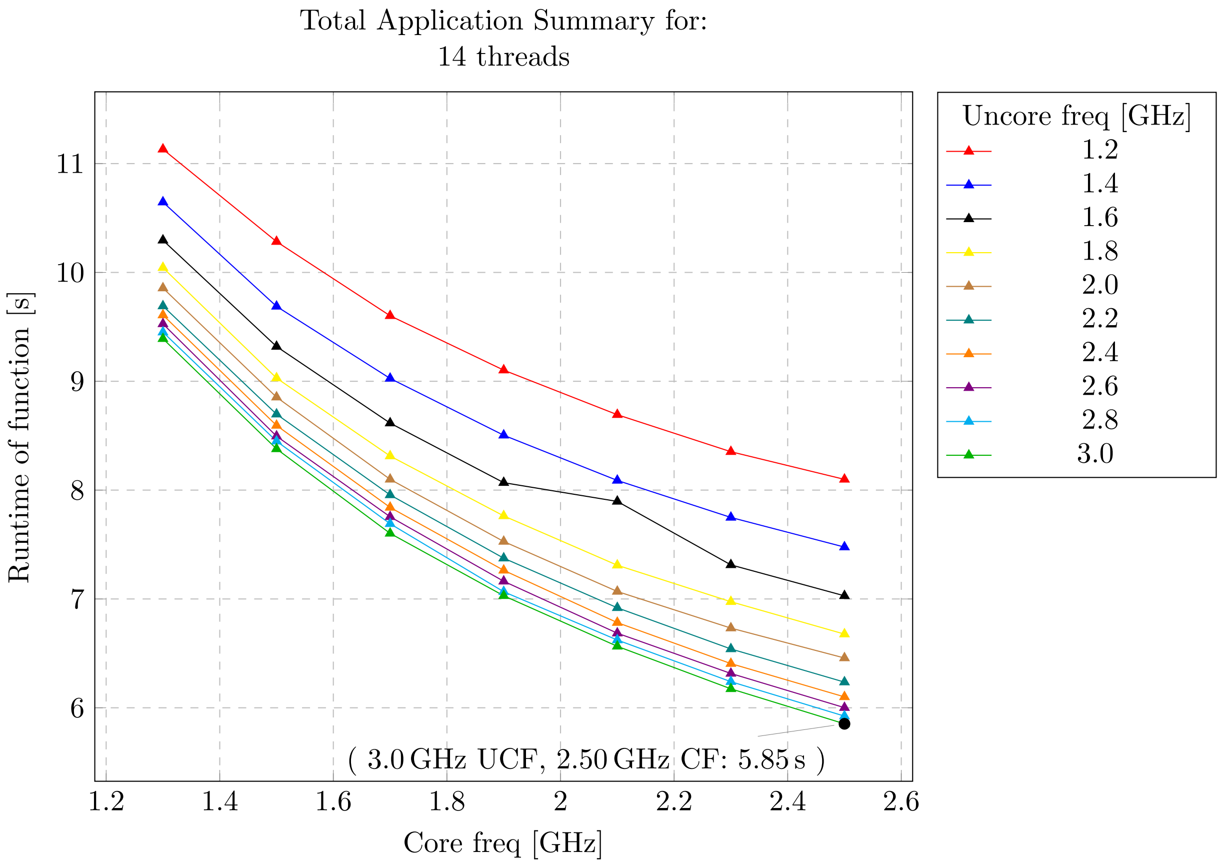
**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| HYPRE_-PCGSetup | 61.47 | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 9.60 s | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 9.60 s | 0.00 s (0.00%) |
| set_up_matrix | 11.01 | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.72 s | 1 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.72 s | 0.00 s (0.09%) |
| hypre_PCG-Solve_iter | 27.52 | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 4.30 s | 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 4.30 s | 0.00 s (0.00%) |
| **Total value for static tuning for significant regions** | | | 9.60 + 1.72 + 4.30 = 15.62 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.00 + 0.00 + 0.00 = 0.00 s of 15.62 s (0.01 %) | | | |
| **Dynamic savings for application runtime** | | | 0.00 s of 16.32 s (0.01 %) | | | |

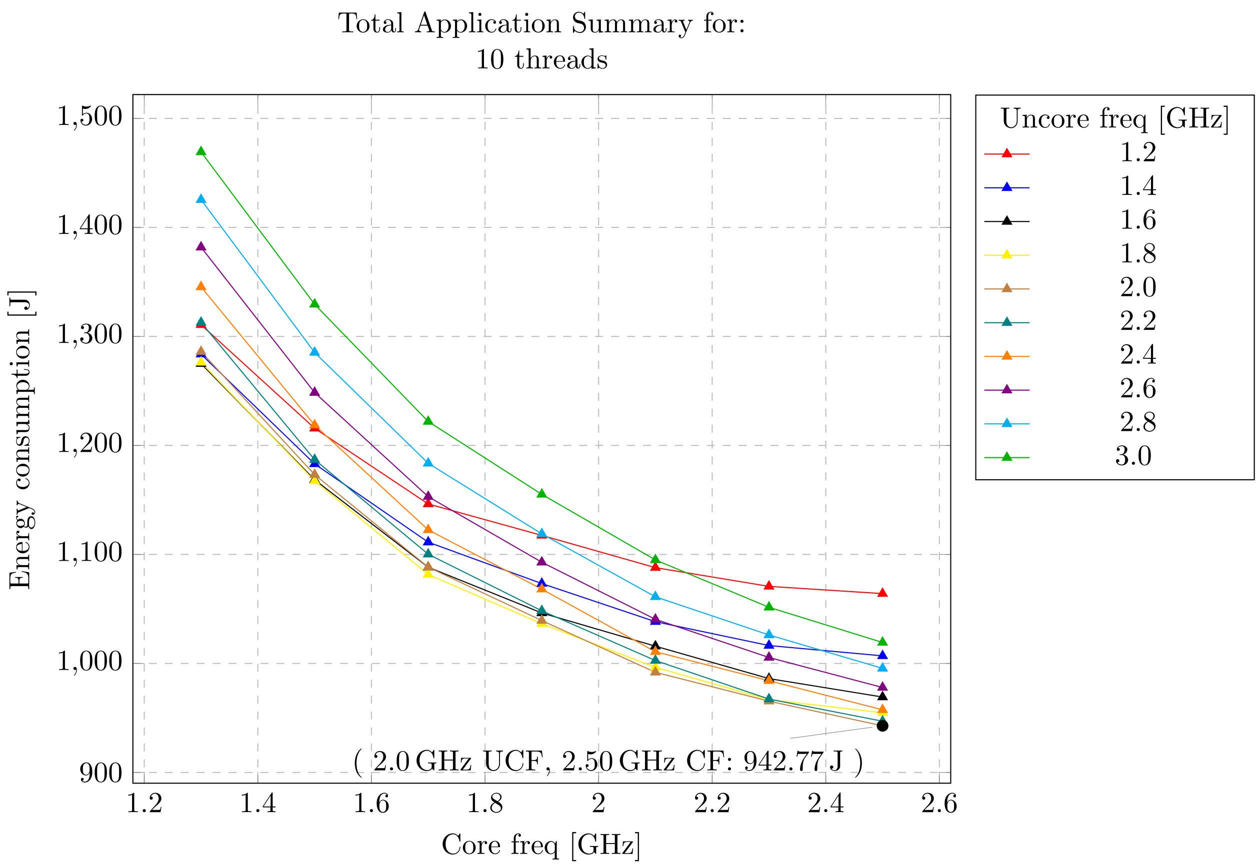
#### 6.6.2.2 `MPI_PROCS=1`, `PX=PY=PZ=1`, `RX=RY=RZ=20`

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Runtime of function [s], Job info - hdeem | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 6.50 s | 14 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.65 s (9.99%) | 0.01 s of 5.85 s (0.09 %) |
| Energy consumption [J], Blade summary | 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 1268.24 J | 10 threads, 2.0 GHz UCF, 2.5 GHz CF | 325.46 J (25.66%) | 26.41 J of 942.77 J (2.80 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 11.132 | 10.646 | 10.296 | 10.044 | 9.856 | 9.691 | 9.608 | 9.527 | 9.451 | 9.391 |
| 1.5 | 10.283 | 9.688 | 9.319 | 9.029 | 8.854 | 8.697 | 8.594 | 8.495 | 8.449 | 8.378 |
| 1.7 | 9.602 | 9.026 | 8.616 | 8.313 | 8.099 | 7.956 | 7.841 | 7.755 | 7.691 | 7.602 |
| 1.9 | 9.102 | 8.504 | 8.068 | 7.763 | 7.528 | 7.375 | 7.263 | 7.162 | 7.066 | 7.029 |
| 2.1 | 8.693 | 8.089 | 7.896 | 7.31 | 7.069 | 6.919 | 6.783 | 6.685 | 6.623 | 6.565 |
| 2.3 | 8.353 | 7.749 | 7.313 | 6.975 | 6.732 | 6.541 | 6.406 | 6.315 | 6.24 | 6.174 |
| 2.5 | 8.099 | 7.477 | 7.029 | 6.677 | 6.457 | 6.236 | 6.1 | 6.001 | 5.923 | 5.853 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 1,310.7 | 1,283.7 | 1,275.1 | 1,276.2 | 1,286 | 1,312.8 | 1,345.4 | 1,381.9 | 1,425.5 | 1,469.3 |
| 1.5 | 1,215.8 | 1,183.1 | 1,168.5 | 1,167.5 | 1,173.2 | 1,187 | 1,218.6 | 1,248.5 | 1,285.3 | 1,329.5 |
| 1.7 | 1,146.3 | 1,111.3 | 1,088.3 | 1,081.6 | 1,088.3 | 1,100.2 | 1,122.5 | 1,153 | 1,183.6 | 1,221.9 |
| 1.9 | 1,117.5 | 1,073.3 | 1,046.3 | 1,036.4 | 1,039.4 | 1,048.3 | 1,068.2 | 1,092.8 | 1,118.9 | 1,155.1 |
| 2.1 | 1,087.9 | 1,038.3 | 1,015.8 | 996.5 | 991.9 | 1,002.7 | 1,010.8 | 1,040.5 | 1,061.1 | 1,095 |
| 2.3 | 1,070.7 | 1,016.4 | 986.1 | 966.7 | 965.4 | 967.3 | 984.1 | 1,005.5 | 1,026.1 | 1,051.5 |
| 2.5 | 1,064.1 | 1,007 | 969.2 | 954.8 | 942.8 | 947 | 957.5 | 977.9 | 995.5 | 1,019.2 |

**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| set_up_matrix | 26.40 | 14 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.47 s | 12 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.46 s | 0.01 s (0.37%) |
| HYPRE_-PCGSetup | 52.96 | 14 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.94 s | 14 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.94 s | 0.00 s (0.00%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| hypre_PCG-Solve_iter | 20.63 | 14 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.15 s | 14 threads, 3.0 GHz UCF, 2.5 GHz CF | 1.15 s | 0.00 s (0.00%) |
| **Total value for static tuning for significant regions** | | | 1.47 + 2.94 + 1.15 = 5.56 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.01 + 0.00 + 0.00 = 0.01 s of 5.56 s (0.10 %) | | | |
| **Dynamic savings for application runtime** | | | 0.01 s of 5.85 s (0.09 %) | | | |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| set_up_matrix | 21.38 | 10 threads, 2.0 GHz UCF, 2.5 GHz CF | 191.13 J | 6 threads, 2.2 GHz UCF, 2.5 GHz CF | 188.31 J | 2.82 J (1.48%) |
| HYPRE_-PCGSetup | 50.35 | 10 threads, 2.0 GHz UCF, 2.5 GHz CF | 450.19 J | 10 threads, 2.0 GHz UCF, 2.5 GHz CF | 450.19 J | 0.00 J (0.00%) |
| hypre_PCG-Solve_iter | 28.27 | 10 threads, 2.0 GHz UCF, 2.5 GHz CF | 252.78 J | 16 threads, 2.0 GHz UCF, 1.7 GHz CF | 229.20 J | 23.59 J (9.33%) |
| **Total value for static tuning for significant regions** | | | 191.13 + 450.19 + 252.78 = 894.11 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 2.82 + 0.00 + 23.59 = 26.41 J of 894.11 J (2.95 %) | | | |
| **Dynamic savings for application runtime** | | | 26.41 J of 942.77 J (2.80 %) | | | |

## 6.7 ProxyApps 2 - Kripke

Kripke is a simple, scalable, 3D Sn deterministic particle transport code. Its primary purpose is to research how data layout, programming paradigms and architectures effect the implementation and performance of Sn transport. A main goal of Kripke is investigating how different data-layouts affects instruction, thread and task level parallelism, and what the implications are on overall solver performance.

Kripkie supports storage of angular fluxes (Psi) using all six striding orders (or nestings) of Directions (D), Groups (G), and Zones (Z), and provides computational kernels specifically written for each of these nestings. Most Sn transport codes are designed around one of these nestings, which is an inflexibility that leads to software engineering compromises when porting to new architectures and programming paradigms. Early research has found that the problem dimensions and the scaling (number of threads and MPI tasks) can make a profound difference in the performance of each of these nestings. To our knowledge this is a capability unique to Kripke, and should provide key insight into how data-layout effects Sn performance. An asynchronous MPI-based parallel sweep algorithm is provided, which employs the concepts of Group Sets (GS) and Zone Sets (ZS), Direction Sets (DS), borrowed from the Texas A&M code PDT.

For more information on the package and download links we refer the reader to https://codesign.llnl.gov/kripke.php.

### 6.7.1 Instrumentation with MERIC

We used Allinea Map to identify the most runtime significant parts of the code. Allinea revealed 5 main kernels, each taking 5–30 % of the runtime, see the RADAR reports below for details. Each of these kernels was wrapped by a single MERIC region. Since they are called quite infrequently, the overhead caused by MERIC is negligible.

Kripke achieves its parallelism by MPI, OpenMP, or their combination. Both the number of MPI processes and OpenMP threads are arbitrary. The OpenMP implementation (both in the pure and hybrid code) seems to be inefficient and is roughly ten times slower than the pure MPI implementation. This is mainly caused by (i) the `#pragma omp parallel for` pragmas used in the innermost `for` loops, thus increasing the threading overhead, and (ii) also by big chunks of sequential code in between the OpenMP parallel regions (Amdahl's law). From the energy scaling point of view, the OpenMP implementation was also poor, saving only a few percent of energy at best. Therefore, only the MPI parallelization with 24 processes per node, which performed and scaled very well on a single node, was tested.

In particular, the Kripke benchmark was called as:

```
mpirun -np 24 -bind-to core -map-by core ./kripke
--procs PX PY PZ --niter I --nest NEST --zones ZX ZY ZZ
[--groups G] [--legendre L] [--dset D].
```

In the above example, the parameters PX, PY, PZ denote the number of MPI processes in each direction with the restriction

$$\mathtt{PX} \cdot \mathtt{PY} \cdot \mathtt{PZ} = 24.$$

During our experiments we found out that for the best performance all these arguments should be even. The number I denotes the number of iterations, NEST stands for the chosen nesting sequence as described at the beginning of Section 6.7. The greatest energy savings were achieved for the GZD variant. The parameters ZX, ZY, ZZ further define the number of zones in each direction. It was found out that biggest static savings can be achieved with a lower number of zones, while more significant dynamic savings are possible with higher values. The numeric value G denotes the number of energy groups. Again, lower value seems to lead to better static savings. For the second instrumented run we dropped the `--groups` argument and chose additional ones. Firstly, the value L denotes the Legendre expansion order. Secondly, the parameter D, which has to be a multiple of 8, defines the number of direction sets. Higher values lead to higher dynamic savings.

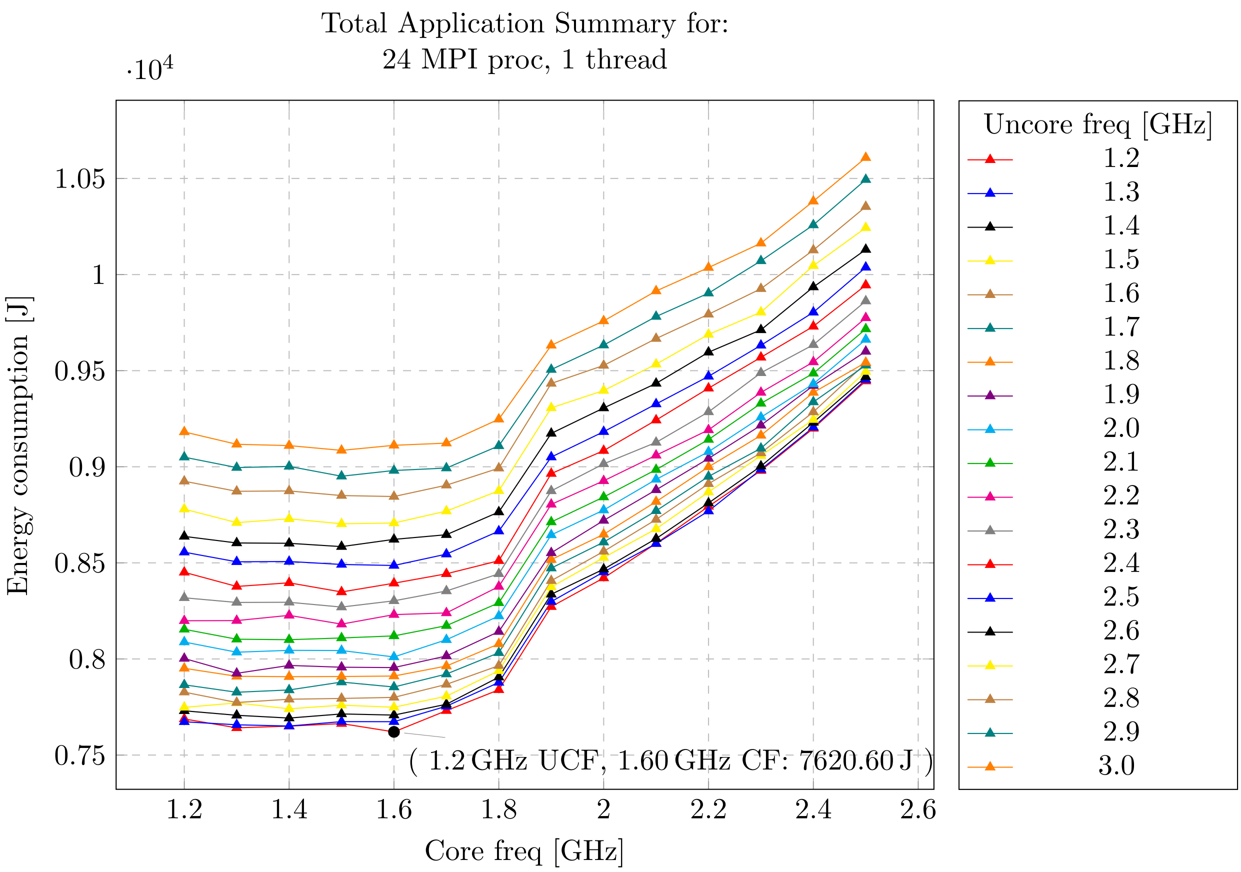
### 6.7.2 Results

For the reports we defined two sets or application arguments, as seen in Sections 6.7.2.1 and 6.7.2.2. The parameters were chosen such that they lead to significant static and dynamic energy savings, respectively. All configurations were ran five times, where the RADAR reports represent an average run.

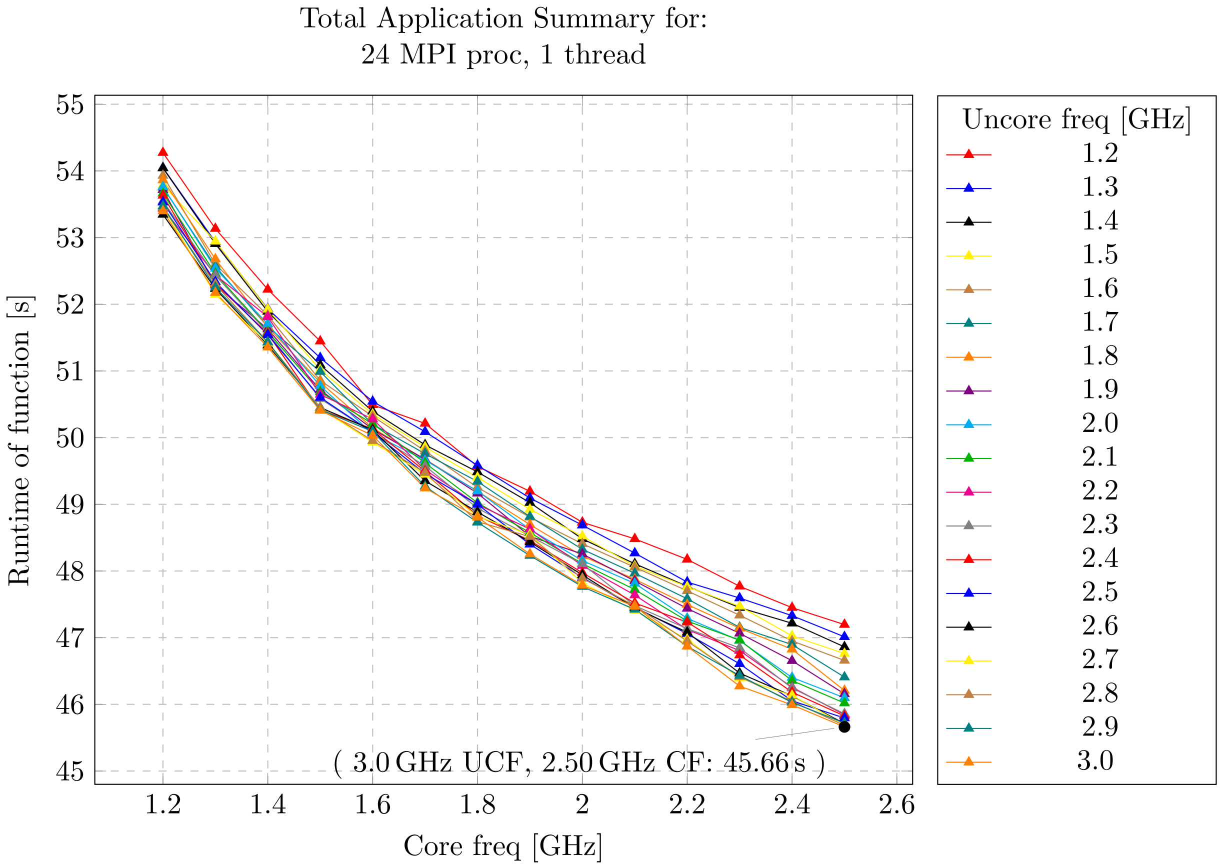
#### 6.7.2.1 PX=PY=2, PZ=6, I=1000, NEST=GZD, ZX=ZY=ZZ=4, G=8

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J] (Stats structure), Blade summary | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 10608.08 J | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.6 GHz CF | 2987.48 J (28.16%) | 118.74 J of 7620.60 J (1.56 %) |
| Runtime of function [s], Job info - hdeem | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 45.66 s | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.22 s of 45.66 s (0.47 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 7,688 | 7,673 | 7,730 | 7,748 | 7,827 | 7,866 | 7,951 | 8,002 | 8,088 | 8,154 | 8,199 | 8,318 | 8,451 | 8,556 | 8,638 | 8,780 | 8,925 | 9,050 | 9,181 |
| 1.3 | 7,642 | 7,658 | 7,707 | 7,771 | 7,773 | 7,827 | 7,910 | 7,925 | 8,035 | 8,103 | 8,200 | 8,294 | 8,377 | 8,506 | 8,604 | 8,709 | 8,872 | 8,996 | 9,117 |
| 1.4 | 7,651 | 7,651 | 7,693 | 7,741 | 7,791 | 7,839 | 7,908 | 7,966 | 8,045 | 8,100 | 8,227 | 8,295 | 8,396 | 8,507 | 8,602 | 8,729 | 8,874 | 9,002 | 9,110 |
| 1.5 | 7,664 | 7,674 | 7,714 | 7,760 | 7,795 | 7,880 | 7,909 | 7,957 | 8,044 | 8,109 | 8,181 | 8,270 | 8,349 | 8,492 | 8,585 | 8,703 | 8,850 | 8,951 | 9,085 |
| 1.6 | 7,621 | 7,674 | 7,708 | 7,749 | 7,800 | 7,854 | 7,911 | 7,955 | 8,011 | 8,120 | 8,231 | 8,303 | 8,394 | 8,486 | 8,622 | 8,707 | 8,845 | 8,981 | 9,112 |
| 1.7 | 7,731 | 7,754 | 7,764 | 7,806 | 7,868 | 7,922 | 7,963 | 8,016 | 8,100 | 8,173 | 8,240 | 8,354 | 8,443 | 8,545 | 8,646 | 8,769 | 8,904 | 8,993 | 9,123 |
| 1.8 | 7,840 | 7,878 | 7,905 | 7,939 | 7,965 | 8,032 | 8,078 | 8,142 | 8,223 | 8,292 | 8,377 | 8,443 | 8,511 | 8,665 | 8,765 | 8,875 | 8,993 | 9,109 | 9,247 |
| 1.9 | 8,272 | 8,298 | 8,337 | 8,374 | 8,407 | 8,473 | 8,517 | 8,552 | 8,645 | 8,713 | 8,804 | 8,874 | 8,965 | 9,050 | 9,174 | 9,306 | 9,434 | 9,506 | 9,632 |
| 2 | 8,421 | 8,453 | 8,467 | 8,527 | 8,560 | 8,608 | 8,648 | 8,721 | 8,775 | 8,843 | 8,927 | 9,015 | 9,084 | 9,182 | 9,306 | 9,397 | 9,527 | 9,633 | 9,759 |
| 2.1 | 8,601 | 8,600 | 8,626 | 8,677 | 8,726 | 8,771 | 8,819 | 8,880 | 8,934 | 8,985 | 9,060 | 9,127 | 9,243 | 9,327 | 9,434 | 9,534 | 9,667 | 9,782 | 9,915 |
| 2.2 | 8,794 | 8,770 | 8,811 | 8,868 | 8,912 | 8,949 | 8,999 | 9,043 | 9,078 | 9,142 | 9,192 | 9,285 | 9,409 | 9,470 | 9,596 | 9,689 | 9,793 | 9,903 | 10,036 |
| 2.3 | 8,980 | 8,986 | 9,003 | 9,058 | 9,072 | 9,096 | 9,163 | 9,216 | 9,258 | 9,330 | 9,387 | 9,489 | 9,569 | 9,632 | 9,712 | 9,804 | 9,926 | 10,071 | 10,163 |
| 2.4 | 9,200 | 9,205 | 9,231 | 9,245 | 9,285 | 9,337 | 9,386 | 9,422 | 9,431 | 9,486 | 9,545 | 9,635 | 9,731 | 9,804 | 9,935 | 10,046 | 10,127 | 10,258 | 10,382 |
| 2.5 | 9,446 | 9,453 | 9,468 | 9,495 | 9,539 | 9,528 | 9,542 | 9,600 | 9,662 | 9,717 | 9,775 | 9,862 | 9,945 | 10,038 | 10,130 | 10,244 | 10,353 | 10,494 | 10,608 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 54.27 | 54.05 | 54.04 | 53.79 | 53.93 | 53.75 | 53.86 | 53.72 | 53.76 | 53.66 | 53.44 | 53.55 | 53.63 | 53.53 | 53.35 | 53.45 | 53.45 | 53.47 | 53.4 |
| 1.3 | 53.13 | 52.93 | 52.91 | 52.94 | 52.6 | 52.57 | 52.68 | 52.29 | 52.54 | 52.46 | 52.44 | 52.43 | 52.31 | 52.34 | 52.23 | 52.15 | 52.3 | 52.25 | 52.17 |
| 1.4 | 52.22 | 51.93 | 51.89 | 51.92 | 51.83 | 51.66 | 51.66 | 51.63 | 51.7 | 51.59 | 51.81 | 51.57 | 51.56 | 51.54 | 51.39 | 51.42 | 51.43 | 51.43 | 51.36 |
| 1.5 | 51.45 | 51.2 | 51.09 | 51.02 | 50.86 | 50.99 | 50.83 | 50.71 | 50.78 | 50.68 | 50.65 | 50.58 | 50.42 | 50.6 | 50.45 | 50.44 | 50.45 | 50.42 | 50.41 |
| 1.6 | 50.49 | 50.54 | 50.39 | 50.35 | 50.32 | 50.2 | 50.14 | 50.13 | 50.06 | 50.21 | 50.28 | 50.07 | 50.13 | 50.08 | 50.12 | 49.93 | 49.95 | 50.09 | 50.03 |
| 1.7 | 50.21 | 50.09 | 49.89 | 49.86 | 49.8 | 49.76 | 49.67 | 49.67 | 49.66 | 49.62 | 49.52 | 49.57 | 49.5 | 49.46 | 49.35 | 49.45 | 49.47 | 49.27 | 49.24 |
| 1.8 | 49.57 | 49.58 | 49.49 | 49.4 | 49.25 | 49.34 | 49.2 | 49.17 | 49.2 | 49.02 | 49 | 48.94 | 48.83 | 49 | 48.88 | 48.82 | 48.74 | 48.73 | 48.81 |
| 1.9 | 49.19 | 49.09 | 49.03 | 48.92 | 48.81 | 48.82 | 48.69 | 48.52 | 48.62 | 48.58 | 48.63 | 48.52 | 48.46 | 48.4 | 48.44 | 48.55 | 48.51 | 48.23 | 48.25 |
| 2 | 48.73 | 48.69 | 48.48 | 48.52 | 48.41 | 48.32 | 48.23 | 48.25 | 48.16 | 48.11 | 48.08 | 48.11 | 47.97 | 47.9 | 47.94 | 47.82 | 47.89 | 47.77 | 47.78 |
| 2.1 | 48.48 | 48.27 | 48.11 | 48.07 | 48.06 | 47.97 | 47.88 | 47.85 | 47.81 | 47.72 | 47.64 | 47.48 | 47.52 | 47.46 | 47.45 | 47.41 | 47.48 | 47.42 | 47.47 |
| 2.2 | 48.17 | 47.83 | 47.77 | 47.77 | 47.7 | 47.58 | 47.5 | 47.44 | 47.29 | 47.25 | 47.12 | 47.14 | 47.23 | 47.06 | 47.08 | 46.97 | 46.95 | 46.87 | 46.87 |
| 2.3 | 47.77 | 47.59 | 47.45 | 47.47 | 47.34 | 47.15 | 47.14 | 47.07 | 46.96 | 46.96 | 46.81 | 46.85 | 46.74 | 46.61 | 46.47 | 46.39 | 46.41 | 46.43 | 46.27 |
| 2.4 | 47.45 | 47.33 | 47.22 | 47.03 | 46.95 | 46.9 | 46.83 | 46.65 | 46.4 | 46.36 | 46.26 | 46.24 | 46.18 | 46.05 | 46.13 | 46.13 | 46.04 | 46.03 | 45.99 |
| 2.5 | 47.2 | 47.01 | 46.86 | 46.76 | 46.66 | 46.41 | 46.21 | 46.16 | 46.1 | 46.02 | 45.84 | 45.86 | 45.83 | 45.79 | 45.71 | 45.69 | 45.68 | 45.72 | 45.66 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| LPlusTimes | 19.95 | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.6 GHz CF | 639.79 J | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.2 GHz CF | 614.22 J | 25.57 J (4.00%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| LTimes | 19.79 | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.6 GHz CF | 634.59 J | 24 MPI proc, 1 thread, 1.3 GHz UCF, 1.2 GHz CF | 612.41 J | 22.18 J (3.50%) |
| Source | 19.36 | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.6 GHz CF | 621.00 J | 24 MPI proc, 1 thread, 1.3 GHz UCF, 1.2 GHz CF | 597.48 J | 23.52 J (3.79%) |
| Scattering | 19.56 | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.6 GHz CF | 627.43 J | 24 MPI proc, 1 thread, 1.3 GHz UCF, 1.2 GHz CF | 603.15 J | 24.28 J (3.87%) |
| Sweep | 21.34 | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.6 GHz CF | 684.46 J | 24 MPI proc, 1 thread, 1.3 GHz UCF, 1.2 GHz CF | 661.26 J | 23.20 J (3.39%) |
| **Total value for static tuning for significant regions** | | | 639.79 + 634.59 + 621.00 + 627.43 + 684.46 = 3207.25 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 25.57 + 22.18 + 23.52 + 24.28 + 23.20 = 118.74 J of 3207.25 J (3.70 %) | | | |
| **Dynamic savings for application runtime** | | | 118.74 J of 7620.60 J (1.56 %) | | | |

**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

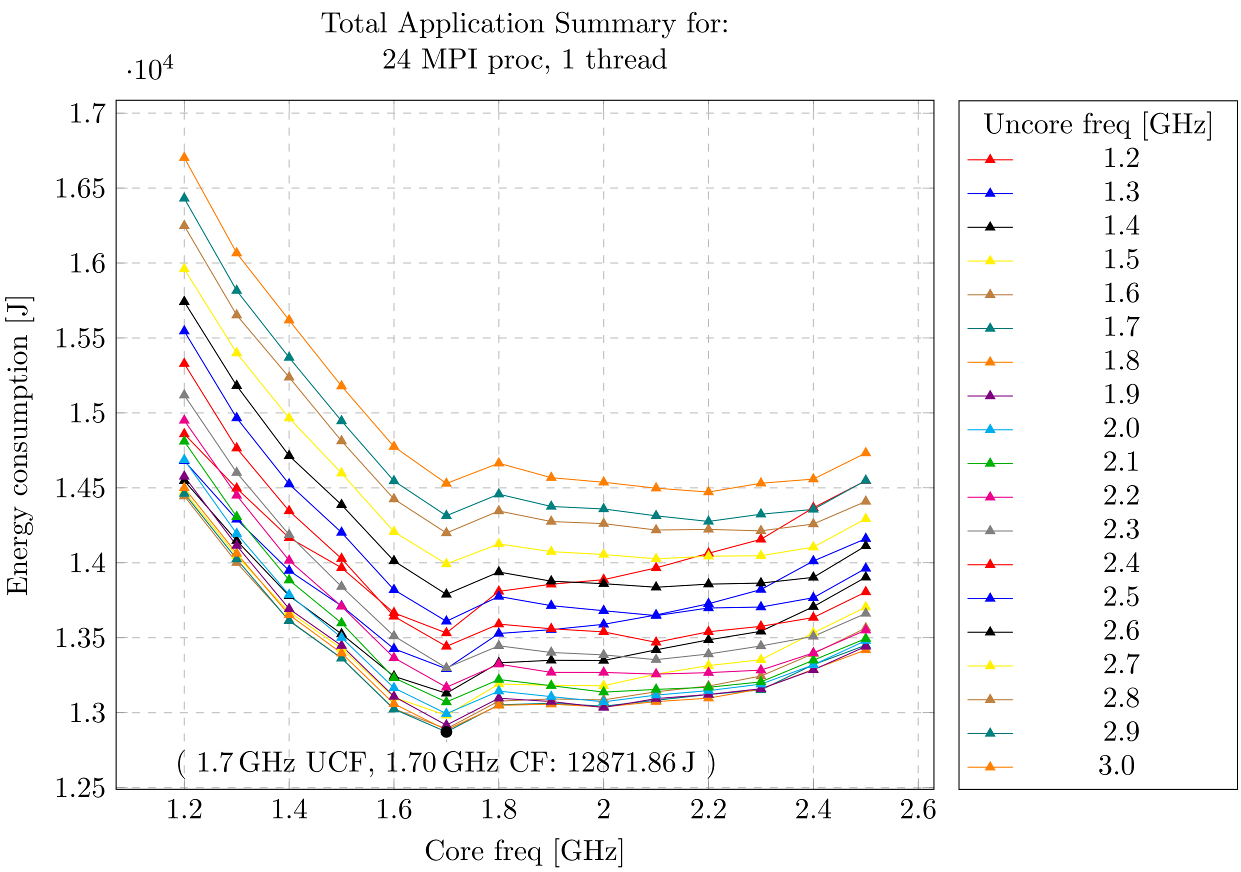
| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| LPlusTimes | 19.88 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 4.06 s | 24 MPI proc, 1 thread, 2.9 GHz UCF, 2.5 GHz CF | 4.05 s | 0.01 s (0.20%) |
| LTimes | 19.82 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 4.05 s | 24 MPI proc, 1 thread, 2.9 GHz UCF, 2.5 GHz CF | 4.03 s | 0.02 s (0.39%) |
| Source | 19.74 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 4.03 s | 24 MPI proc, 1 thread, 2.9 GHz UCF, 2.5 GHz CF | 4.00 s | 0.03 s (0.77%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Scattering | 19.71 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 4.02 s | 24 MPI proc, 1 thread, 2.9 GHz UCF, 2.5 GHz CF | 3.99 s | 0.04 s (0.93%) |
| Sweep | 20.85 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 4.26 s | 24 MPI proc, 1 thread, 2.7 GHz UCF, 2.5 GHz CF | 4.13 s | 0.12 s (2.89%) |
| **Total value for static tuning for significant regions** | | | 4.06 + 4.05 + 4.03 + 4.02 + 4.26 = 20.41 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.01 + 0.02 + 0.03 + 0.04 + 0.12 = 0.22 s of 20.41 s (1.05 %) | | | |
| **Dynamic savings for application runtime** | | | 0.22 s of 45.66 s (0.47 %) | | | |

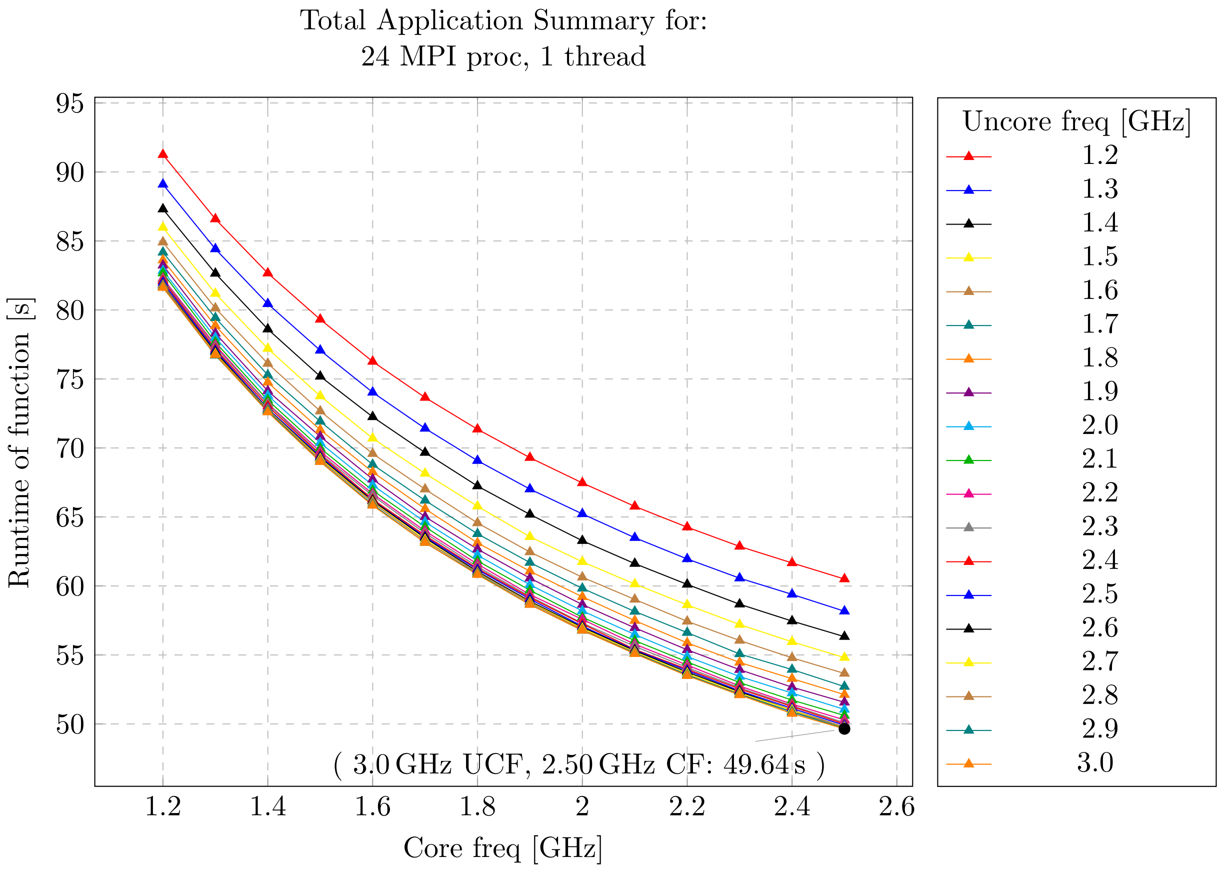
#### 6.7.2.2 `PX=PY=2, PZ=6, I=30, NEST=GZD, ZX=ZY=ZZ=32, L=8, D=32`

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J] , Blade summary | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 14732.36 J | 24 MPI proc, 1 thread, 1.7 GHz UCF, 1.7 GHz CF | 1860.50 J (12.63%) | 906.50 J of 12871.86 J (7.04 %) |
| Runtime of function [s], Job info - hdeem | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 49.64 s | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.04 s of 49.64 s (0.09 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 14,859 | 14,680 | 14,548 | 14,475 | 14,445 | 14,462 | 14,500 | 14,576 | 14,687 | 14,810 | 14,950 | 15,118 | 15,329 | 15,546 | 15,742 | 15,960 | 16,248 | 16,431 | 16,703 |
| 1.3 | 14,497 | 14,290 | 14,148 | 14,046 | 14,001 | 14,025 | 14,062 | 14,115 | 14,194 | 14,307 | 14,450 | 14,602 | 14,765 | 14,966 | 15,181 | 15,399 | 15,652 | 15,816 | 16,066 |
| 1.4 | 14,167 | 13,948 | 13,780 | 13,673 | 13,617 | 13,613 | 13,653 | 13,693 | 13,787 | 13,885 | 14,015 | 14,187 | 14,346 | 14,525 | 14,714 | 14,966 | 15,238 | 15,369 | 15,619 |
| 1.5 | 13,967 | 13,712 | 13,525 | 13,429 | 13,364 | 13,363 | 13,397 | 13,447 | 13,501 | 13,598 | 13,709 | 13,841 | 14,028 | 14,202 | 14,387 | 14,598 | 14,812 | 14,946 | 15,179 |
| 1.6 | 13,666 | 13,426 | 13,243 | 13,102 | 13,026 | 13,024 | 13,060 | 13,108 | 13,165 | 13,232 | 13,366 | 13,512 | 13,643 | 13,820 | 14,013 | 14,207 | 14,425 | 14,546 | 14,775 |
| 1.7 | 13,532 | 13,293 | 13,129 | 12,982 | 12,892 | 12,872 | 12,884 | 12,917 | 12,993 | 13,071 | 13,170 | 13,299 | 13,442 | 13,610 | 13,789 | 13,992 | 14,199 | 14,314 | 14,529 |
| 1.8 | 13,809 | 13,528 | 13,333 | 13,192 | 13,078 | 13,052 | 13,049 | 13,097 | 13,144 | 13,221 | 13,324 | 13,446 | 13,591 | 13,775 | 13,938 | 14,126 | 14,346 | 14,458 | 14,664 |
| 1.9 | 13,857 | 13,554 | 13,350 | 13,182 | 13,092 | 13,063 | 13,057 | 13,074 | 13,107 | 13,180 | 13,269 | 13,402 | 13,560 | 13,714 | 13,877 | 14,074 | 14,275 | 14,376 | 14,568 |
| 2 | 13,887 | 13,589 | 13,348 | 13,180 | 13,085 | 13,043 | 13,038 | 13,035 | 13,073 | 13,137 | 13,269 | 13,386 | 13,539 | 13,680 | 13,861 | 14,055 | 14,261 | 14,359 | 14,537 |
| 2.1 | 13,966 | 13,652 | 13,419 | 13,257 | 13,140 | 13,083 | 13,074 | 13,094 | 13,117 | 13,155 | 13,258 | 13,354 | 13,469 | 13,648 | 13,837 | 14,026 | 14,219 | 14,313 | 14,498 |
| 2.2 | 14,063 | 13,727 | 13,486 | 13,314 | 13,178 | 13,121 | 13,097 | 13,122 | 13,147 | 13,170 | 13,267 | 13,392 | 13,540 | 13,699 | 13,858 | 14,044 | 14,223 | 14,276 | 14,472 |
| 2.3 | 14,157 | 13,821 | 13,543 | 13,353 | 13,245 | 13,152 | 13,159 | 13,160 | 13,190 | 13,205 | 13,284 | 13,445 | 13,576 | 13,705 | 13,865 | 14,047 | 14,213 | 14,324 | 14,531 |
| 2.4 | 14,367 | 14,012 | 13,707 | 13,532 | 13,394 | 13,320 | 13,289 | 13,286 | 13,319 | 13,350 | 13,399 | 13,509 | 13,635 | 13,767 | 13,903 | 14,105 | 14,259 | 14,356 | 14,558 |
| 2.5 | 14,548 | 14,161 | 13,904 | 13,705 | 13,565 | 13,451 | 13,419 | 13,442 | 13,481 | 13,494 | 13,550 | 13,662 | 13,805 | 13,963 | 14,113 | 14,293 | 14,409 | 14,549 | 14,732 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 91.25 | 89.1 | 87.31 | 85.97 | 84.91 | 84.18 | 83.61 | 83.24 | 82.85 | 82.67 | 82.29 | 82.2 | 82.11 | 81.98 | 81.82 | 81.77 | 81.79 | 81.67 | 81.62 |
| 1.3 | 86.59 | 84.42 | 82.65 | 81.19 | 80.13 | 79.43 | 78.86 | 78.31 | 77.99 | 77.66 | 77.45 | 77.31 | 77.17 | 77.06 | 76.95 | 76.83 | 76.78 | 76.71 | 76.75 |
| 1.4 | 82.66 | 80.44 | 78.61 | 77.2 | 76.12 | 75.28 | 74.75 | 74.13 | 73.8 | 73.46 | 73.22 | 73.19 | 73.04 | 72.86 | 72.78 | 72.78 | 72.76 | 72.69 | 72.6 |
| 1.5 | 79.31 | 77.07 | 75.19 | 73.76 | 72.67 | 71.92 | 71.31 | 70.83 | 70.37 | 69.99 | 69.75 | 69.57 | 69.5 | 69.39 | 69.3 | 69.22 | 69.14 | 69.02 | 69 |
| 1.6 | 76.26 | 74.03 | 72.25 | 70.7 | 69.58 | 68.8 | 68.26 | 67.73 | 67.3 | 66.92 | 66.68 | 66.54 | 66.28 | 66.19 | 66.17 | 66.08 | 66.05 | 65.9 | 65.83 |
| 1.7 | 73.65 | 71.41 | 69.66 | 68.15 | 67.01 | 66.2 | 65.58 | 65.02 | 64.63 | 64.28 | 63.98 | 63.82 | 63.66 | 63.56 | 63.48 | 63.34 | 63.26 | 63.14 | 63.14 |
| 1.8 | 71.35 | 69.08 | 67.24 | 65.78 | 64.56 | 63.78 | 63.12 | 62.67 | 62.23 | 61.82 | 61.58 | 61.4 | 61.26 | 61.19 | 61.05 | 60.96 | 60.98 | 60.88 | 60.82 |
| 1.9 | 69.3 | 67.02 | 65.18 | 63.56 | 62.46 | 61.69 | 61.06 | 60.56 | 60.08 | 59.69 | 59.37 | 59.23 | 59.16 | 59.05 | 58.89 | 58.82 | 58.77 | 58.66 | 58.64 |
| 2 | 67.47 | 65.22 | 63.28 | 61.75 | 60.63 | 59.82 | 59.21 | 58.65 | 58.19 | 57.73 | 57.58 | 57.31 | 57.25 | 57.08 | 57 | 56.93 | 56.85 | 56.77 | 56.78 |
| 2.1 | 65.76 | 63.5 | 61.62 | 60.14 | 59.02 | 58.15 | 57.49 | 56.96 | 56.48 | 56.04 | 55.78 | 55.62 | 55.4 | 55.36 | 55.31 | 55.22 | 55.16 | 55.13 | 55.09 |
| 2.2 | 64.26 | 61.96 | 60.11 | 58.63 | 57.44 | 56.62 | 55.87 | 55.37 | 54.88 | 54.5 | 54.26 | 54.09 | 53.96 | 53.88 | 53.76 | 53.67 | 53.57 | 53.56 | 53.49 |
| 2.3 | 62.86 | 60.56 | 58.68 | 57.2 | 56.05 | 55.07 | 54.46 | 53.93 | 53.44 | 53 | 52.75 | 52.62 | 52.54 | 52.4 | 52.33 | 52.24 | 52.17 | 52.14 | 52.1 |
| 2.4 | 61.67 | 59.39 | 57.46 | 55.95 | 54.79 | 53.94 | 53.28 | 52.67 | 52.24 | 51.73 | 51.44 | 51.32 | 51.26 | 51.13 | 51.01 | 51.01 | 50.9 | 50.86 | 50.75 |
| 2.5 | 60.5 | 58.17 | 56.32 | 54.81 | 53.66 | 52.71 | 52.13 | 51.57 | 51.05 | 50.61 | 50.29 | 50.09 | 50 | 49.9 | 49.77 | 49.72 | 49.79 | 49.68 | 49.64 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| Source | 0.15 | 24 MPI proc, 1 thread, 1.7 GHz UCF, 1.7 GHz CF | 19.50 J | 24 MPI proc, 1 thread, 1.2 GHz UCF, 1.2 GHz CF | 17.83 J | 1.66 J (8.54%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| LTimes | 57.29 | 24 MPI proc, 1 thread, 1.7 GHz UCF, 1.7 GHz CF | 7264.09 J | 24 MPI proc, 1 thread, 1.2 GHz UCF, 2.3 GHz CF | 6652.07 J | 612.02 J (8.43%) |
| Scattering | 24.08 | 24 MPI proc, 1 thread, 1.7 GHz UCF, 1.7 GHz CF | 3053.29 J | 24 MPI proc, 1 thread, 1.9 GHz UCF, 1.2 GHz CF | 2869.10 J | 184.19 J (6.03%) |
| LPlusTimes | 14.01 | 24 MPI proc, 1 thread, 1.7 GHz UCF, 1.7 GHz CF | 1776.89 J | 24 MPI proc, 1 thread, 2.1 GHz UCF, 1.6 GHz CF | 1681.94 J | 94.95 J (5.34%) |
| Sweep | 4.47 | 24 MPI proc, 1 thread, 1.7 GHz UCF, 1.7 GHz CF | 566.36 J | 24 MPI proc, 1 thread, 1.8 GHz UCF, 2.3 GHz CF | 552.68 J | 13.68 J (2.41%) |
| **Total value for static tuning for significant regions** | | | 19.50 + 7264.09 + 3053.29 + 1776.89 + 566.36 = 12680.12 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 1.66 + 612.02 + 184.19 + 94.95 + 13.68 = 906.50 J of 12680.12 J (7.15 %) | | | |
| **Dynamic savings for application runtime** | | | 906.50 J of 12871.86 J (7.04 %) | | | |

**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| Source | 0.24 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 0.12 s | 24 MPI proc, 1 thread, 2.1 GHz UCF, 2.3 GHz CF | 0.11 s | 0.00 s (1.63%) |
| LTimes | 53.48 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 26.04 s | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 26.04 s | 0.00 s (0.00%) |
| Scattering | 28.08 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 13.67 s | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.3 GHz CF | 13.64 s | 0.03 s (0.24%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| LPlusTimes | 13.81 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 6.72 s | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.4 GHz CF | 6.72 s | 0.00 s (0.04%) |
| Sweep | 4.40 | 24 MPI proc, 1 thread, 3.0 GHz UCF, 2.5 GHz CF | 2.14 s | 24 MPI proc, 1 thread, 2.9 GHz UCF, 2.5 GHz CF | 2.14 s | 0.01 s (0.27%) |
| **Total value for static tuning for significant regions** | | | 0.12 + 26.04 + 13.67 + 6.72 + 2.14 = 48.69 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.00 + 0.00 + 0.03 + 0.00 + 0.01 = 0.04 s of 48.69 s (0.09 %) | | | |
| **Dynamic savings for application runtime** | | | 0.04 s of 49.64 s (0.09 %) | | | |

## 6.8 ProxyApps 3 - LULESH

The Shock Hydrodynamics Challenge Problem was originally defined and implemented by LLNL as one of five challenge problems in the DARPA UHPC program and has since become a widely studied proxy application in DOE co-design efforts for exascale. It has been ported to a number of programming models and optimized for a number of advanced platforms.

Computer simulations of a wide variety of science and engineering problems require modeling hydrodynamics, which describes the motion of materials relative to each other when subject to forces. Many important simulation problems of interest to DOE involve complex multi-material systems that undergo large deformations. LULESH is a highly simplified application, hard-coded to only solve a simple Sedov blast problem with analytic answers but represents the numerical algorithms, data motion, and programming style typical in scientific C or C++ based applications.

LULESH represents a typical hydrocode, like ALE3D. LULESH approximates the hydrodynamics equations discretely by partitioning the spatial problem domain into a collection of volumetric elements defined by a mesh. A node on the mesh is a point where mesh lines intersect. LULESH is built on the concept of an unstructured hex mesh. Instead, indirection arrays that define mesh relationships are used. The default test case for LULESH appears to be a regular cartesian mesh, but this is for simplicity only - it is important to retain the unstructured data structures as they are representative of what a more complex geometry will require. When modifying LULESH it is important to not take advantage of this or other simplifications in the application.

For more information on the package and download links we refer the reader to https://codesign.llnl.gov/lulesh.php.

### 6.8.1 Instrumentation with MERIC

To identify significant parts of the code, the Allinea Map tool was used to profile LULESH. Allinea revealed 14 kernels that took at least 1 % of the whole runtime in at least one of the tested runs, see Section 6.8.2 for a detailed list of these functions in the RADAR reports. Each kernel was then wrapped by a MERIC region.

LULESH was tested on a single node of the Taurus supercomputer. The MPI, OpenMP and hybrid implementations are provided, with the restriction that the total number of MPI processes has to be a cube (i.e. 1, 8, 27, ...). Two settings were chosen for the instrumented runs, namely with 1 MPI process, 24 OpenMP threads with no explicit MPI binding and 8 MPI processes, 3 OpenMP threads with MPI processes bound to every third core.

For both settings the environment variable `KMP_AFFINITY` was set to `compact` to avoid NUMA effects. We found out that employing fewer than 24 threads on a single node is counter-productive, mainly due to the rather high static power consumption of the node. Performance-wise, both settings are very similar, on a single node we recommend the pure

OpenMP parallelization due to potential MPI binding problems when testing with different MPI implementations.

For the testing the program was called as

```
mpirun -n $MPI_PROCS ./lulesh2.0 -s $S -i $I -b $B
```

with `MPI_PROCS`, `I` and `S` denoting the number of MPI processes, maximal number of iterations, and the size of the domain, respectively, and `B` affecting the load balancing. During experiments we have found out that the parameter `S` has the most significant impact on runtime and power consumption. The best static energy savings were obtained with powers of two, while primes lead to the best dynamic savings. The parameter `B` has not proven to have a significant impact on the energy consumption, which might be caused by the fact that we only ran the program on a single node and the MPI communication overhead was not significant.

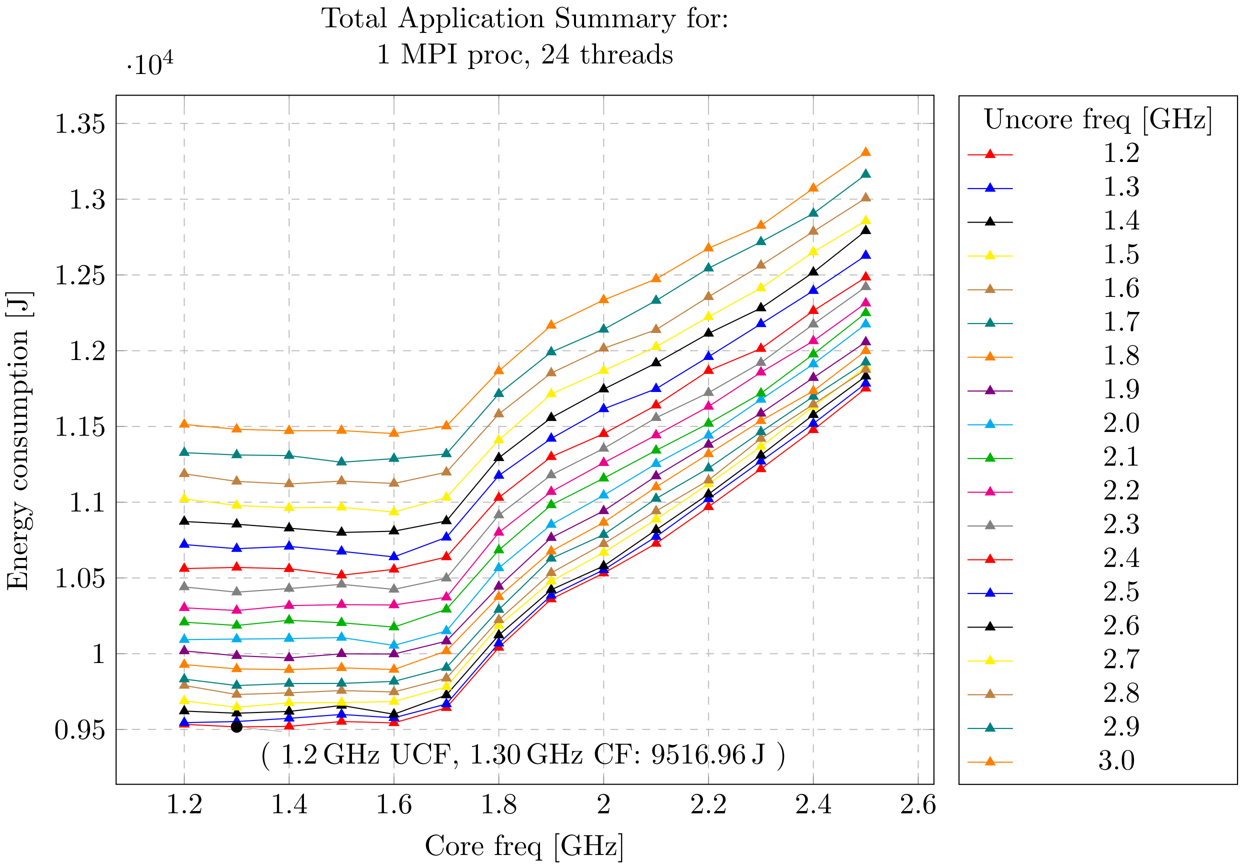
### 6.8.2 Results

We tested the application with the parameters `-s 32 -i 20` and `-s 97 -b 7 -i 20` which resulted in the best static and dynamic savings, respectively, out of all testing runs. All configurations were ran five times, RADAR reports represent an average run. The generated reports are provided below.

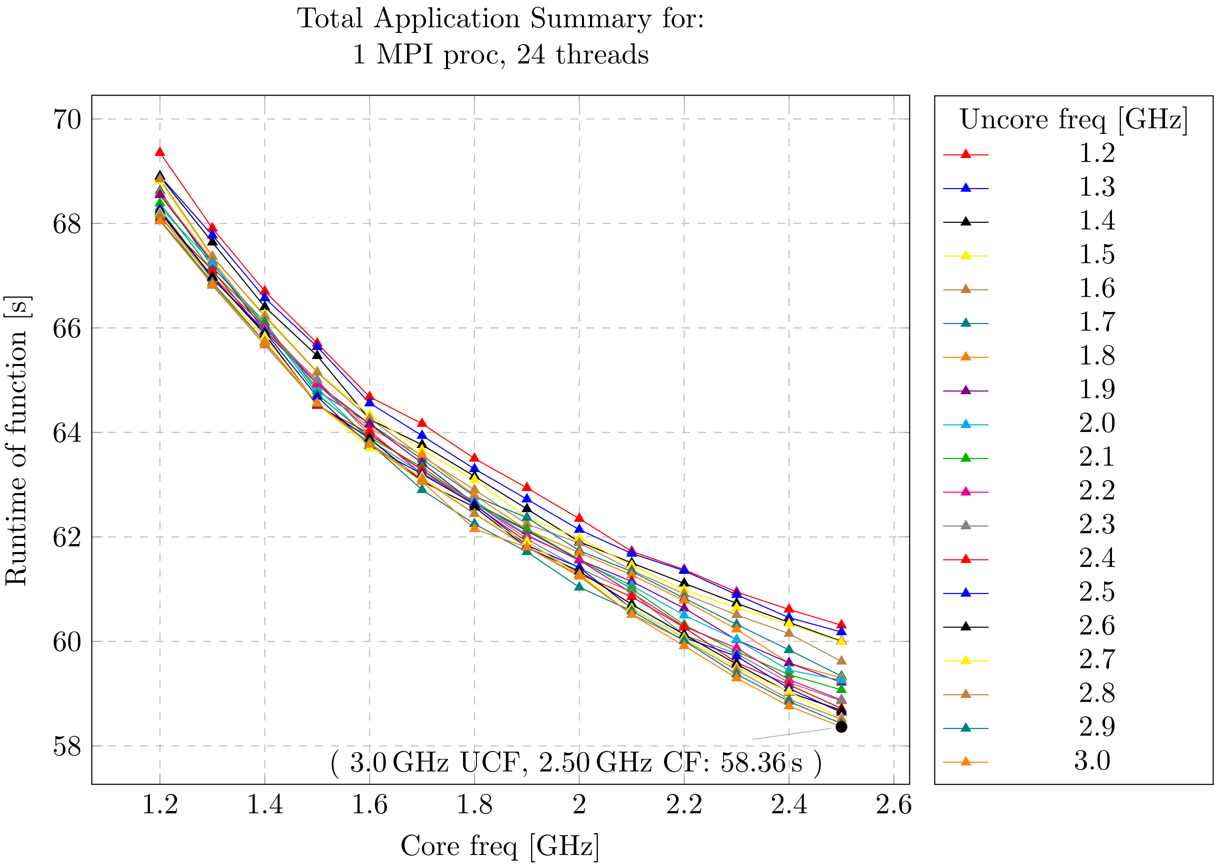
#### 6.8.2.1 `MPI_PROCS=1, S=32, I=20, B=20`

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 13307.00 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 3790.04 J (28.48%) | 52.40 J of 9516.96 J (0.55 %) |
| Runtime of function [s], Job info - hdeem | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 58.36 s | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.07 s of 58.36 s (0.11 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 9,534 | 9,545 | 9,621 | 9,689 | 9,790 | 9,832 | 9,928 | 10,018 | 10,093 | 10,208 | 10,303 | 10,440 | 10,562 | 10,720 | 10,873 | 11,022 | 11,187 | 11,327 | 11,513 |
| 1.3 | 9,517 | 9,552 | 9,607 | 9,646 | 9,731 | 9,790 | 9,900 | 9,987 | 10,096 | 10,186 | 10,285 | 10,406 | 10,570 | 10,693 | 10,855 | 10,979 | 11,137 | 11,312 | 11,482 |
| 1.4 | 9,520 | 9,573 | 9,619 | 9,676 | 9,742 | 9,803 | 9,895 | 9,972 | 10,100 | 10,221 | 10,317 | 10,430 | 10,561 | 10,708 | 10,829 | 10,963 | 11,120 | 11,307 | 11,472 |
| 1.5 | 9,552 | 9,599 | 9,658 | 9,678 | 9,757 | 9,804 | 9,907 | 9,999 | 10,107 | 10,204 | 10,324 | 10,458 | 10,518 | 10,676 | 10,800 | 10,967 | 11,139 | 11,264 | 11,473 |
| 1.6 | 9,543 | 9,577 | 9,600 | 9,684 | 9,747 | 9,817 | 9,896 | 9,998 | 10,055 | 10,175 | 10,322 | 10,425 | 10,557 | 10,639 | 10,809 | 10,935 | 11,124 | 11,288 | 11,453 |
| 1.7 | 9,643 | 9,668 | 9,727 | 9,781 | 9,838 | 9,908 | 10,018 | 10,083 | 10,150 | 10,293 | 10,373 | 10,498 | 10,638 | 10,768 | 10,876 | 11,031 | 11,198 | 11,319 | 11,502 |
| 1.8 | 10,041 | 10,069 | 10,123 | 10,186 | 10,223 | 10,291 | 10,376 | 10,444 | 10,566 | 10,684 | 10,800 | 10,915 | 11,030 | 11,176 | 11,293 | 11,410 | 11,582 | 11,715 | 11,866 |
| 1.9 | 10,360 | 10,385 | 10,422 | 10,478 | 10,534 | 10,629 | 10,677 | 10,766 | 10,852 | 10,982 | 11,069 | 11,179 | 11,300 | 11,421 | 11,557 | 11,714 | 11,853 | 11,991 | 12,167 |
| 2 | 10,532 | 10,553 | 10,579 | 10,668 | 10,725 | 10,785 | 10,866 | 10,942 | 11,045 | 11,158 | 11,260 | 11,355 | 11,452 | 11,616 | 11,746 | 11,868 | 12,016 | 12,141 | 12,335 |
| 2.1 | 10,727 | 10,773 | 10,817 | 10,887 | 10,941 | 11,024 | 11,100 | 11,172 | 11,254 | 11,342 | 11,443 | 11,557 | 11,640 | 11,749 | 11,919 | 12,026 | 12,138 | 12,331 | 12,473 |
| 2.2 | 10,969 | 11,022 | 11,053 | 11,120 | 11,145 | 11,224 | 11,319 | 11,380 | 11,441 | 11,520 | 11,632 | 11,723 | 11,868 | 11,960 | 12,114 | 12,223 | 12,356 | 12,544 | 12,676 |
| 2.3 | 11,220 | 11,270 | 11,310 | 11,367 | 11,420 | 11,464 | 11,538 | 11,586 | 11,678 | 11,719 | 11,857 | 11,921 | 12,014 | 12,177 | 12,281 | 12,413 | 12,563 | 12,718 | 12,826 |
| 2.4 | 11,478 | 11,519 | 11,577 | 11,630 | 11,646 | 11,698 | 11,734 | 11,822 | 11,912 | 11,977 | 12,064 | 12,174 | 12,264 | 12,396 | 12,517 | 12,652 | 12,787 | 12,905 | 13,072 |
| 2.5 | 11,752 | 11,784 | 11,832 | 11,892 | 11,876 | 11,924 | 11,999 | 12,057 | 12,175 | 12,249 | 12,314 | 12,421 | 12,485 | 12,628 | 12,791 | 12,857 | 13,007 | 13,163 | 13,307 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 69.4 | 68.9 | 68.9 | 68.8 | 68.8 | 68.6 | 68.6 | 68.5 | 68.3 | 68.4 | 68.2 | 68.2 | 68.1 | 68.3 | 68.2 | 68.2 | 68.2 | 68.1 | 68 |
| 1.3 | 67.9 | 67.8 | 67.6 | 67.3 | 67.4 | 67.2 | 67.3 | 67.3 | 67.2 | 67.1 | 67 | 66.9 | 67.1 | 67 | 67 | 66.9 | 66.8 | 66.9 | 66.8 |
| 1.4 | 66.7 | 66.6 | 66.4 | 66.3 | 66.2 | 66.1 | 66 | 65.9 | 66 | 66.1 | 66 | 66 | 65.9 | 65.9 | 65.9 | 65.8 | 65.7 | 65.7 | 65.7 |
| 1.5 | 65.7 | 65.6 | 65.5 | 65.2 | 65.1 | 64.8 | 65 | 64.9 | 64.9 | 64.7 | 64.9 | 65 | 64.5 | 64.7 | 64.5 | 64.5 | 64.6 | 64.5 | 64.6 |
| 1.6 | 64.7 | 64.6 | 64.3 | 64.3 | 64.3 | 64.2 | 64.1 | 64.2 | 63.9 | 63.9 | 64 | 64 | 64 | 63.7 | 63.9 | 63.7 | 63.8 | 63.8 | 63.8 |
| 1.7 | 64.2 | 63.9 | 63.8 | 63.7 | 63.5 | 63.5 | 63.6 | 63.4 | 63.2 | 63.3 | 63.2 | 63.3 | 63.3 | 63.2 | 63.1 | 63.2 | 63.1 | 62.9 | 63.1 |
| 1.8 | 63.5 | 63.3 | 63.2 | 63.1 | 62.9 | 62.8 | 62.8 | 62.6 | 62.7 | 62.6 | 62.6 | 62.7 | 62.6 | 62.6 | 62.6 | 62.4 | 62.4 | 62.2 | 62.2 |
| 1.9 | 62.9 | 62.7 | 62.5 | 62.4 | 62.2 | 62.4 | 62.1 | 62.1 | 62 | 62.1 | 62 | 62 | 61.9 | 61.8 | 61.8 | 61.9 | 61.8 | 61.7 | 61.8 |
| 2 | 62.3 | 62.1 | 61.9 | 62 | 61.9 | 61.7 | 61.7 | 61.6 | 61.5 | 61.6 | 61.6 | 61.4 | 61.3 | 61.4 | 61.3 | 61.3 | 61.3 | 61 | 61.2 |
| 2.1 | 61.7 | 61.7 | 61.5 | 61.5 | 61.4 | 61.3 | 61.3 | 61.1 | 61.1 | 61 | 60.9 | 60.9 | 60.9 | 60.6 | 60.7 | 60.6 | 60.5 | 60.6 | 60.5 |
| 2.2 | 61.4 | 61.4 | 61.1 | 61 | 60.9 | 60.8 | 60.8 | 60.6 | 60.5 | 60.3 | 60.3 | 60.1 | 60.3 | 60.1 | 60.1 | 60.1 | 60 | 60 | 59.9 |
| 2.3 | 60.9 | 60.9 | 60.7 | 60.6 | 60.5 | 60.3 | 60.2 | 60 | 60 | 59.8 | 59.9 | 59.8 | 59.6 | 59.7 | 59.6 | 59.5 | 59.5 | 59.4 | 59.3 |
| 2.4 | 60.6 | 60.5 | 60.4 | 60.3 | 60.1 | 59.8 | 59.6 | 59.6 | 59.4 | 59.4 | 59.3 | 59.2 | 59.2 | 59.1 | 59 | 59 | 58.9 | 58.9 | 58.8 |
| 2.5 | 60.3 | 60.2 | 60 | 60 | 59.6 | 59.3 | 59.3 | 59.2 | 59.3 | 59.1 | 58.9 | 58.9 | 58.7 | 58.6 | 58.7 | 58.5 | 58.5 | 58.4 | 58.4 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| CalcLa-grangeEle-ments | 0.36 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 13.56 J | 1 MPI proc, 24 threads, 1.3 GHz UCF, 1.2 GHz CF | 13.07 J | 0.49 J (3.58%) |
| EvalE-OSForElems_-parallel-Pragma | 10.99 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 417.84 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 413.17 J | 4.67 J (1.12%) |
| CalcCourant-Constraint-ForElems | 3.41 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 129.78 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 129.70 J | 0.07 J (0.06%) |
| CalcEnergy-ForElems4 | 10.99 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 417.97 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 412.18 J | 5.80 J (1.39%) |
| CalcSound-Speed-ForElems | 3.45 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 131.16 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 128.94 J | 2.22 J (1.69%) |
| CalcEnergy-ForElems1 | 10.90 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 414.64 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 409.35 J | 5.29 J (1.28%) |
| CalcEnergy-ForElems3 | 10.93 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 415.80 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 409.49 J | 6.31 J (1.52%) |
| CalcFBHour-glassForce-ForElems | 0.45 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 17.25 J | 1 MPI proc, 24 threads, 1.7 GHz UCF, 1.2 GHz CF | 16.92 J | 0.33 J (1.90%) |
| Integrat-eStress-ForElems | 0.36 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 13.59 J | 1 MPI proc, 24 threads, 1.3 GHz UCF, 1.3 GHz CF | 13.06 J | 0.53 J (3.93%) |
| CalcEnergy-ForElems2 | 10.97 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 417.19 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 413.11 J | 4.08 J (0.98%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| CalcHydro-Constraint-ForElems | 3.47 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 132.17 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 129.17 J | 3.00 J (2.27%) |
| CalcQ-ForElems | 0.38 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 14.56 J | 1 MPI proc, 24 threads, 1.5 GHz UCF, 1.2 GHz CF | 14.52 J | 0.04 J (0.27%) |
| CalcPressure-ForElems | 32.92 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 1252.25 J | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.2 GHz CF | 1233.31 J | 18.94 J (1.51%) |
| CalcHour-glassControl-ForElems_-parallel-Pragma | 0.41 | 1 MPI proc, 24 threads, 1.2 GHz UCF, 1.3 GHz CF | 15.78 J | 1 MPI proc, 24 threads, 1.7 GHz UCF, 1.2 GHz CF | 15.13 J | 0.64 J (4.06%) |
| **Total value for static tuning for significant regions** | | 13.56 + 417.84 + 129.78 + 417.97 + 131.16 + 414.64 + 415.80 + 17.25 + 13.59 + 417.19 + 132.17 + 14.56 + 1252.25 + 15.78 = 3803.54 J | | | | |
| **Total savings for dynamic tuning for significant regions** | | 0.49 + 4.67 + 0.07 + 5.80 + 2.22 + 5.29 + 6.31 + 0.33 + 0.53 + 4.08 + 3.00 + 0.04 + 18.94 + 0.64 = 52.40 J of 3803.54 J (1.38 %) | | | | |
| **Dynamic savings for application runtime** | | 52.40 J of 9516.96 J (0.55 %) | | | | |

**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| CalcLa-grangeEle-ments | 0.33 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.09 s | 1 MPI proc, 24 threads, 2.0 GHz UCF, 2.4 GHz CF | 0.08 s | 0.00 s (2.30%) |
| EvalE-OSForElems_-parallel-Pragma | 10.97 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.83 s | 1 MPI proc, 24 threads, 2.9 GHz UCF, 2.5 GHz CF | 2.83 s | 0.01 s (0.23%) |

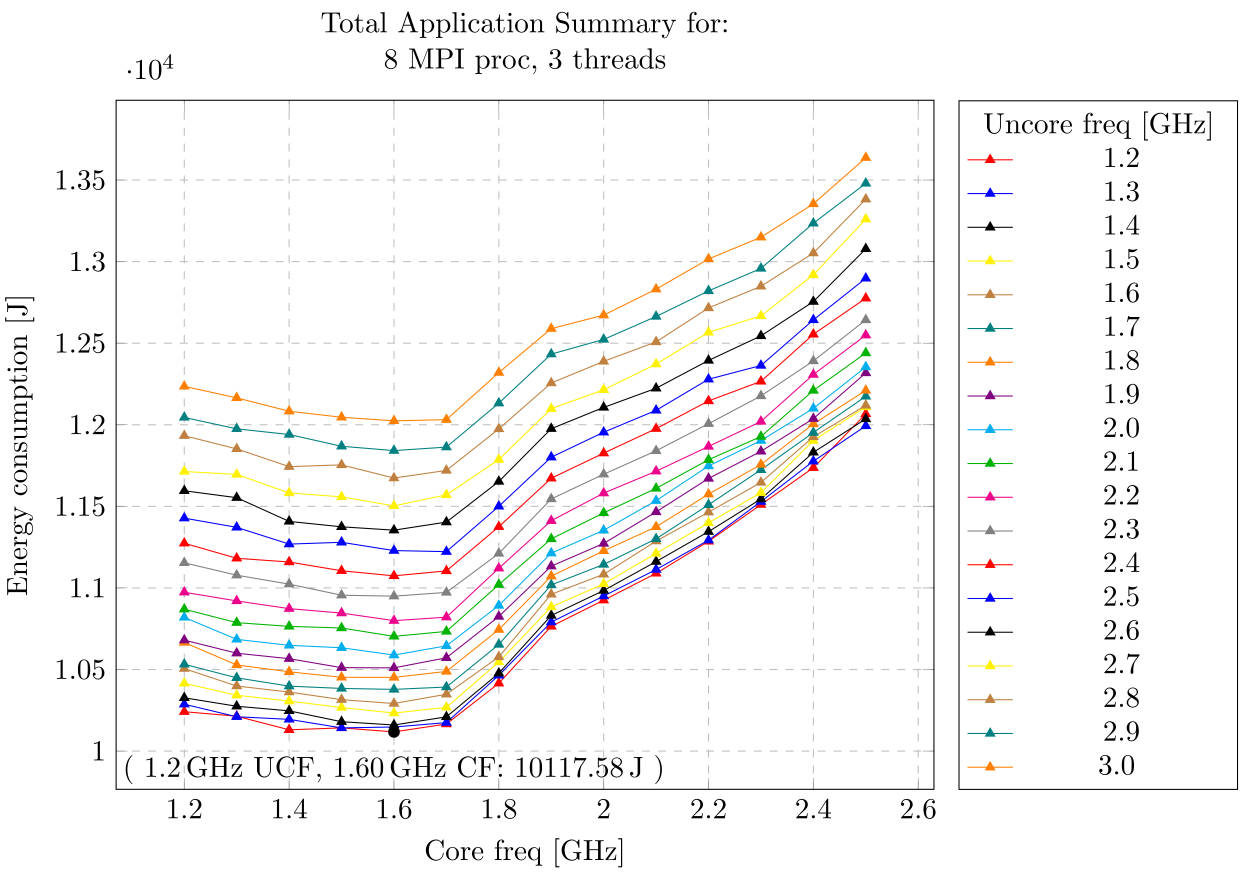
| | | | | | | |
|---|---|---|---|---|---|---|
| CalcCourant-Constraint-ForElems | 3.44 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.89 s | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.89 s | 0.00 s (0.00%) |
| CalcEnergy-ForElems4 | 10.98 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.83 s | 1 MPI proc, 24 threads, 2.8 GHz UCF, 2.5 GHz CF | 2.82 s | 0.01 s (0.31%) |
| CalcSound-Speed-ForElems | 3.44 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.89 s | 1 MPI proc, 24 threads, 2.7 GHz UCF, 2.5 GHz CF | 0.88 s | 0.00 s (0.33%) |
| CalcEnergy-ForElems1 | 10.99 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.84 s | 1 MPI proc, 24 threads, 2.9 GHz UCF, 2.5 GHz CF | 2.82 s | 0.01 s (0.42%) |
| CalcEnergy-ForElems3 | 11.01 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.84 s | 1 MPI proc, 24 threads, 2.7 GHz UCF, 2.5 GHz CF | 2.83 s | 0.01 s (0.24%) |
| CalcFBHour-glassForce-ForElems | 0.40 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.10 s | 1 MPI proc, 24 threads, 2.8 GHz UCF, 2.5 GHz CF | 0.10 s | 0.00 s (1.43%) |
| Integrat-eStress-ForElems | 0.34 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.09 s | 1 MPI proc, 24 threads, 2.6 GHz UCF, 2.4 GHz CF | 0.08 s | 0.00 s (4.06%) |
| CalcEnergy-ForElems2 | 10.99 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.84 s | 1 MPI proc, 24 threads, 2.8 GHz UCF, 2.5 GHz CF | 2.83 s | 0.00 s (0.15%) |
| CalcHydro-Constraint-ForElems | 3.47 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.90 s | 1 MPI proc, 24 threads, 2.7 GHz UCF, 2.5 GHz CF | 0.89 s | 0.01 s (1.21%) |
| CalcQ-ForElems | 0.36 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.09 s | 1 MPI proc, 24 threads, 2.9 GHz UCF, 2.4 GHz CF | 0.09 s | 0.00 s (5.10%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| CalcPressure-ForElems | 32.91 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 8.49 s | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 8.49 s | 0.00 s (0.00%) |
| CalcHour-glassControl-ForElems_-parallel-Pragma | 0.36 | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.09 s | 1 MPI proc, 24 threads, 3.0 GHz UCF, 2.3 GHz CF | 0.09 s | 0.00 s (1.56%) |
| **Total value for static tuning for significant regions** | | | 0.09 + 2.83 + 0.89 + 2.83 + 0.89 + 2.84 + 2.84 + 0.10 + 0.09 + 2.84 + 0.90 + 0.09 + 8.49 + 0.09 = 25.81 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.00 + 0.01 + 0.00 + 0.01 + 0.00 + 0.01 + 0.01 + 0.00 + 0.00 + 0.00 + 0.01 + 0.00 + 0.00 + 0.00 = 0.07 s of 25.81 s (0.25 %) | | | |
| **Dynamic savings for application runtime** | | | 0.07 s of 58.36 s (0.11 %) | | | |

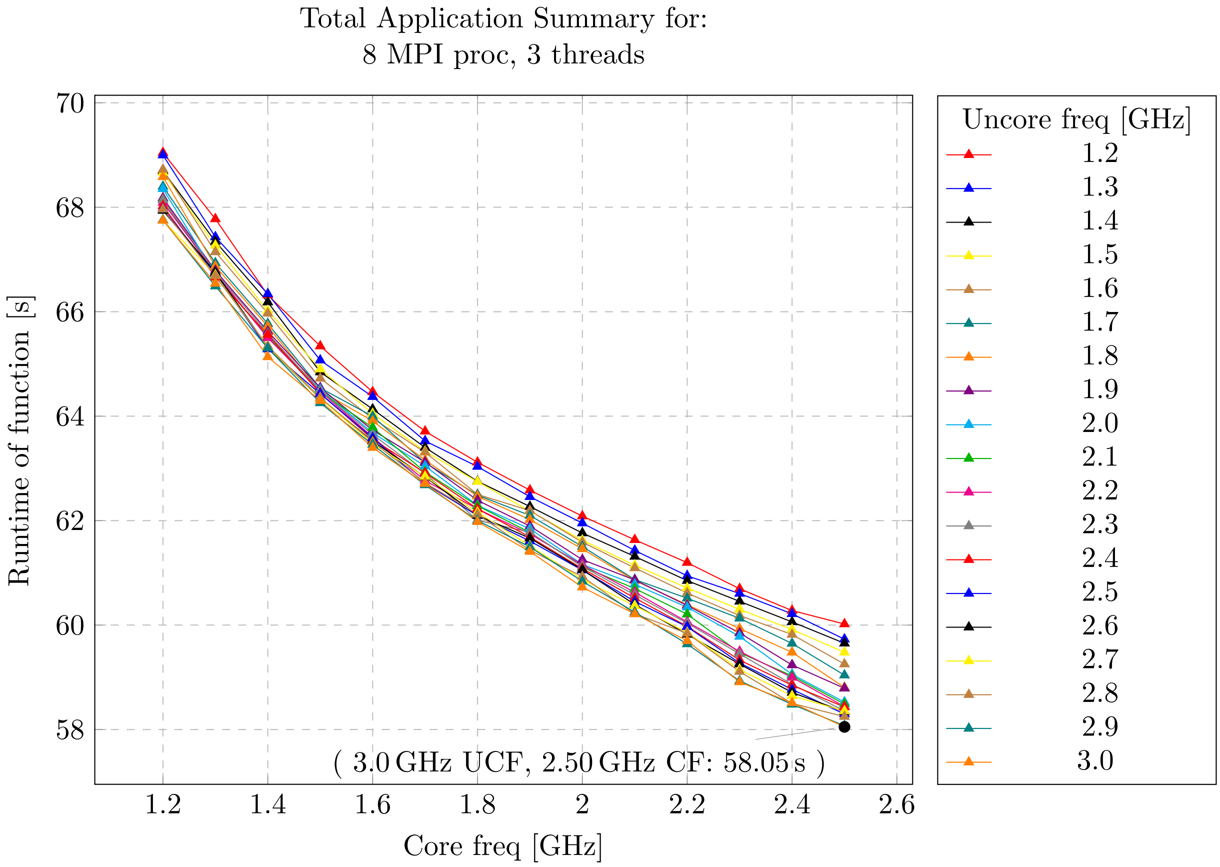
#### 6.8.2.2 `MPI_PROCS=8`, `S=97`, `I=20`, `B=7`

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 13636.90 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 3519.32 J (25.81%) | 124.38 J of 10117.58 J (1.23 %) |
| Runtime of function [s], Job info - hdeem | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 58.05 s | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.06 s of 58.05 s (0.10 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 10,241 | 10,287 | 10,327 | 10,415 | 10,506 | 10,532 | 10,666 | 10,680 | 10,820 | 10,870 | 10,974 | 11,154 | 11,274 | 11,428 | 11,596 | 11,714 | 11,933 | 12,045 | 12,236 |
| 1.3 | 10,214 | 10,210 | 10,275 | 10,342 | 10,399 | 10,449 | 10,528 | 10,600 | 10,685 | 10,787 | 10,920 | 11,078 | 11,182 | 11,371 | 11,553 | 11,696 | 11,852 | 11,975 | 12,165 |
| 1.4 | 10,130 | 10,195 | 10,247 | 10,306 | 10,362 | 10,398 | 10,486 | 10,566 | 10,648 | 10,764 | 10,873 | 11,023 | 11,159 | 11,269 | 11,408 | 11,582 | 11,743 | 11,940 | 12,083 |
| 1.5 | 10,142 | 10,142 | 10,180 | 10,267 | 10,315 | 10,384 | 10,452 | 10,511 | 10,633 | 10,754 | 10,846 | 10,955 | 11,105 | 11,280 | 11,375 | 11,558 | 11,754 | 11,868 | 12,046 |
| 1.6 | 10,118 | 10,148 | 10,160 | 10,233 | 10,292 | 10,378 | 10,451 | 10,510 | 10,588 | 10,703 | 10,799 | 10,949 | 11,074 | 11,229 | 11,354 | 11,503 | 11,673 | 11,842 | 12,024 |
| 1.7 | 10,166 | 10,174 | 10,210 | 10,268 | 10,348 | 10,393 | 10,488 | 10,572 | 10,645 | 10,733 | 10,821 | 10,972 | 11,104 | 11,222 | 11,403 | 11,571 | 11,720 | 11,863 | 12,031 |
| 1.8 | 10,416 | 10,464 | 10,477 | 10,546 | 10,577 | 10,653 | 10,745 | 10,825 | 10,892 | 11,021 | 11,121 | 11,211 | 11,375 | 11,500 | 11,652 | 11,786 | 11,975 | 12,133 | 12,320 |
| 1.9 | 10,764 | 10,791 | 10,831 | 10,883 | 10,961 | 11,018 | 11,072 | 11,133 | 11,213 | 11,301 | 11,412 | 11,545 | 11,672 | 11,801 | 11,976 | 12,099 | 12,256 | 12,433 | 12,589 |
| 2 | 10,925 | 10,950 | 10,984 | 11,025 | 11,083 | 11,144 | 11,227 | 11,272 | 11,353 | 11,460 | 11,581 | 11,697 | 11,826 | 11,954 | 12,106 | 12,214 | 12,389 | 12,523 | 12,672 |
| 2.1 | 11,089 | 11,113 | 11,161 | 11,211 | 11,287 | 11,301 | 11,374 | 11,466 | 11,535 | 11,610 | 11,715 | 11,840 | 11,976 | 12,088 | 12,224 | 12,372 | 12,508 | 12,664 | 12,831 |
| 2.2 | 11,285 | 11,293 | 11,345 | 11,399 | 11,464 | 11,509 | 11,575 | 11,671 | 11,747 | 11,786 | 11,867 | 12,006 | 12,146 | 12,279 | 12,394 | 12,567 | 12,716 | 12,821 | 13,016 |
| 2.3 | 11,511 | 11,529 | 11,545 | 11,583 | 11,646 | 11,724 | 11,756 | 11,837 | 11,903 | 11,928 | 12,020 | 12,177 | 12,266 | 12,363 | 12,545 | 12,667 | 12,849 | 12,958 | 13,149 |
| 2.4 | 11,737 | 11,777 | 11,831 | 11,903 | 11,926 | 11,952 | 12,005 | 12,037 | 12,100 | 12,210 | 12,308 | 12,391 | 12,554 | 12,643 | 12,755 | 12,919 | 13,052 | 13,235 | 13,354 |
| 2.5 | 12,066 | 11,993 | 12,036 | 12,110 | 12,119 | 12,174 | 12,210 | 12,318 | 12,354 | 12,440 | 12,549 | 12,643 | 12,775 | 12,898 | 13,078 | 13,260 | 13,382 | 13,479 | 13,637 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 69.04 | 69 | 68.7 | 68.66 | 68.72 | 68.4 | 68.58 | 68.18 | 68.35 | 68.14 | 68.09 | 68.14 | 68.02 | 67.97 | 67.94 | 67.75 | 67.96 | 67.76 | 67.75 |
| 1.3 | 67.78 | 67.43 | 67.34 | 67.27 | 67.14 | 66.93 | 66.87 | 66.79 | 66.71 | 66.72 | 66.74 | 66.76 | 66.66 | 66.73 | 66.75 | 66.7 | 66.68 | 66.49 | 66.54 |
| 1.4 | 66.32 | 66.34 | 66.18 | 66.02 | 65.97 | 65.77 | 65.72 | 65.62 | 65.51 | 65.52 | 65.5 | 65.58 | 65.56 | 65.29 | 65.32 | 65.33 | 65.34 | 65.3 | 65.13 |
| 1.5 | 65.34 | 65.07 | 64.85 | 64.9 | 64.72 | 64.54 | 64.49 | 64.54 | 64.51 | 64.47 | 64.48 | 64.48 | 64.44 | 64.43 | 64.34 | 64.34 | 64.36 | 64.25 | 64.3 |
| 1.6 | 64.46 | 64.37 | 64.13 | 64.05 | 63.95 | 64 | 63.91 | 63.73 | 63.68 | 63.78 | 63.6 | 63.65 | 63.56 | 63.58 | 63.52 | 63.47 | 63.51 | 63.45 | 63.4 |
| 1.7 | 63.71 | 63.52 | 63.4 | 63.32 | 63.31 | 63.11 | 63.16 | 63.12 | 63.04 | 62.93 | 62.77 | 62.9 | 62.91 | 62.71 | 62.84 | 62.84 | 62.73 | 62.68 | 62.71 |
| 1.8 | 63.12 | 63.04 | 62.75 | 62.75 | 62.5 | 62.49 | 62.47 | 62.39 | 62.29 | 62.28 | 62.22 | 62.01 | 62.23 | 62.1 | 62.1 | 62.16 | 62.12 | 62 | 61.98 |
| 1.9 | 62.58 | 62.46 | 62.27 | 62.18 | 62.19 | 62.1 | 62.02 | 61.9 | 61.84 | 61.77 | 61.75 | 61.78 | 61.69 | 61.61 | 61.66 | 61.51 | 61.43 | 61.5 | 61.41 |
| 2 | 62.09 | 61.95 | 61.76 | 61.62 | 61.59 | 61.5 | 61.46 | 61.25 | 61.16 | 61.12 | 61.15 | 61.12 | 61.08 | 61.05 | 61.06 | 60.87 | 60.93 | 60.84 | 60.73 |
| 2.1 | 61.63 | 61.43 | 61.31 | 61.14 | 61.09 | 60.87 | 60.85 | 60.86 | 60.78 | 60.7 | 60.63 | 60.58 | 60.52 | 60.45 | 60.39 | 60.37 | 60.21 | 60.25 | 60.21 |
| 2.2 | 61.2 | 60.94 | 60.85 | 60.71 | 60.61 | 60.51 | 60.39 | 60.38 | 60.34 | 60.21 | 60.06 | 60.04 | 59.97 | 59.97 | 59.82 | 59.86 | 59.84 | 59.64 | 59.7 |
| 2.3 | 60.7 | 60.6 | 60.45 | 60.3 | 60.18 | 60.13 | 59.93 | 59.85 | 59.78 | 59.47 | 59.49 | 59.45 | 59.33 | 59.27 | 59.25 | 59.15 | 59.11 | 58.93 | 58.91 |
| 2.4 | 60.28 | 60.22 | 60.06 | 59.91 | 59.82 | 59.65 | 59.48 | 59.24 | 59.06 | 59.03 | 59 | 58.87 | 58.85 | 58.77 | 58.71 | 58.64 | 58.5 | 58.48 | 58.51 |
| 2.5 | 60.02 | 59.73 | 59.65 | 59.48 | 59.25 | 59.04 | 58.81 | 58.79 | 58.52 | 58.49 | 58.44 | 58.36 | 58.43 | 58.3 | 58.34 | 58.36 | 58.25 | 58.07 | 58.05 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| CalcQ-ForElems | 0.53 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 22.17 J | 8 MPI proc, 3 threads, 1.4 GHz UCF, 1.6 GHz CF | 21.81 J | 0.36 J (1.64%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| CalcEnergy-ForElems1 | 10.78 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 453.05 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 439.60 J | 13.45 J (2.97%) |
| Integrat-eStress-ForElems | 0.64 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 27.04 J | 8 MPI proc, 3 threads, 1.5 GHz UCF, 1.7 GHz CF | 26.32 J | 0.72 J (2.67%) |
| CalcEnergy-ForElems4 | 10.86 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 456.21 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 442.49 J | 13.72 J (3.01%) |
| EvalE-OSForElems_-parallel-Pragma | 10.91 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 458.32 J | 8 MPI proc, 3 threads, 1.3 GHz UCF, 1.2 GHz CF | 444.67 J | 13.65 J (2.98%) |
| CalcSound-Speed-ForElems | 3.40 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 142.79 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 138.04 J | 4.75 J (3.32%) |
| CalcEnergy-ForElems3 | 10.86 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 456.33 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 441.44 J | 14.89 J (3.26%) |
| CalcEnergy-ForElems2 | 10.81 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 454.41 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 440.31 J | 14.10 J (3.10%) |
| CalcLa-grangeEle-ments | 0.52 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 21.94 J | 8 MPI proc, 3 threads, 1.3 GHz UCF, 1.7 GHz CF | 21.39 J | 0.55 J (2.50%) |
| CalcPressure-ForElems | 32.39 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 1361.06 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 1324.79 J | 36.27 J (2.67%) |
| CalcHydro-Constraint-ForElems | 3.40 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 142.79 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 138.25 J | 4.54 J (3.18%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| CalcFBHourglassForceForElems | 0.77 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 32.49 J | 8 MPI proc, 3 threads, 1.4 GHz UCF, 1.7 GHz CF | 30.93 J | 1.56 J (4.80%) |
| CalcHourglassControlForElems_parallelPragma | 0.72 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 30.11 J | 8 MPI proc, 3 threads, 1.6 GHz UCF, 1.7 GHz CF | 29.13 J | 0.98 J (3.27%) |
| CalcCourantConstraintForElems | 3.40 | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.6 GHz CF | 143.03 J | 8 MPI proc, 3 threads, 1.2 GHz UCF, 1.2 GHz CF | 138.19 J | 4.83 J (3.38%) |
| **Total value for static tuning for significant regions** | | | 22.17 + 453.05 + 27.04 + 456.21 + 458.32 + 142.79 + 456.33 + 454.41 + 21.94 + 1361.06 + 142.79 + 32.49 + 30.11 + 143.03 = 4201.72 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.36 + 13.45 + 0.72 + 13.72 + 13.65 + 4.75 + 14.89 + 14.10 + 0.55 + 36.27 + 4.54 + 1.56 + 0.98 + 4.83 = 124.38 J of 4201.72 J (2.96 %) | | | |
| **Dynamic savings for application runtime** | | | 124.38 J of 10117.58 J (1.23 %) | | | |

**Intra-Phase Dynamism Evaluation**
**Runtime of function [s]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| CalcQForElems | 0.45 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.12 s | 8 MPI proc, 3 threads, 2.7 GHz UCF, 2.5 GHz CF | 0.11 s | 0.00 s (2.71%) |
| CalcEnergyForElems1 | 10.90 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.81 s | 8 MPI proc, 3 threads, 2.4 GHz UCF, 2.5 GHz CF | 2.81 s | 0.00 s (0.11%) |
| IntegrateStressForElems | 0.48 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.12 s | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.12 s | 0.00 s (0.00%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| CalcEnergy-ForElems4 | 10.90 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.81 s | 8 MPI proc, 3 threads, 2.8 GHz UCF, 2.4 GHz CF | 2.81 s | 0.00 s (0.02%) |
| EvalE-OSForElems_-parallel-Pragma | 10.95 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.82 s | 8 MPI proc, 3 threads, 2.9 GHz UCF, 2.5 GHz CF | 2.81 s | 0.01 s (0.36%) |
| CalcSound-Speed-ForElems | 3.42 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.88 s | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.88 s | 0.00 s (0.00%) |
| CalcEnergy-ForElems3 | 10.91 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.81 s | 8 MPI proc, 3 threads, 2.9 GHz UCF, 2.5 GHz CF | 2.80 s | 0.02 s (0.54%) |
| CalcEnergy-ForElems2 | 10.89 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 2.81 s | 8 MPI proc, 3 threads, 2.8 GHz UCF, 2.5 GHz CF | 2.80 s | 0.00 s (0.14%) |
| CalcLa-grangeEle-ments | 0.44 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.11 s | 8 MPI proc, 3 threads, 2.5 GHz UCF, 2.5 GHz CF | 0.11 s | 0.00 s (3.04%) |
| CalcPressure-ForElems | 32.71 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 8.43 s | 8 MPI proc, 3 threads, 2.7 GHz UCF, 2.5 GHz CF | 8.42 s | 0.01 s (0.07%) |
| CalcHydro-Constraint-ForElems | 3.45 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.89 s | 8 MPI proc, 3 threads, 2.5 GHz UCF, 2.4 GHz CF | 0.88 s | 0.01 s (0.99%) |
| CalcFBHour-glassForce-ForElems | 0.54 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.14 s | 8 MPI proc, 3 threads, 2.8 GHz UCF, 2.5 GHz CF | 0.14 s | 0.00 s (0.80%) |
| CalcHour-glassControl-ForElems_-parallel-Pragma | 0.53 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.14 s | 8 MPI proc, 3 threads, 2.9 GHz UCF, 2.5 GHz CF | 0.14 s | 0.00 s (0.16%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| CalcCourant-Constraint-ForElems | 3.43 | 8 MPI proc, 3 threads, 3.0 GHz UCF, 2.5 GHz CF | 0.88 s | 8 MPI proc, 3 threads, 2.7 GHz UCF, 2.3 GHz CF | 0.88 s | 0.01 s (0.59%) |
| **Total value for static tuning for significant regions** | | | 0.12 + 2.81 + 0.12 + 2.81 + 2.82 + 0.88 + 2.81 + 2.81 + 0.11 + 8.43 + 0.89 + 0.14 + 0.14 + 0.88 = 25.77 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.00 + 0.00 + 0.00 + 0.00 + 0.01 + 0.00 + 0.02 + 0.00 + 0.00 + 0.01 + 0.01 + 0.00 + 0.00 + 0.01 = 0.06 s of 25.77 s (0.24 %) | | | |
| **Dynamic savings for application runtime** | | | 0.06 s of 58.05 s (0.10 %) | | | |

## 6.9 ProxyApps 4 - MCB

The Monte Carlo Benchmark (MCB) is intended for use in exploring the computational performance of Monte Carlo algorithms on parallel architectures. It models the solution of a simple heuristic transport equation using a Monte Carlo technique. The MCB employs typical features of Monte Carlo algorithms such as particle creation, particle tracking, tallying particle information, and particle destruction. Particles are also traded among processors using MPI calls.

The heuristic transport equation models the behavior of particles that are born, travel with a constant velocity, scatter, and are absorbed. Its implementation in MCB ignores a number of effects that are important in real world problems. The particles in the MCB simulation do not interact with material by depositing energy, do not use physical cross sections, and do not model real transport effects such as frequency dependent properties or material motion corrections. The MCB is implemented on a simple orthogonal grid. Because of these limitations, the MCB is solely intended to serve as a benchmark and is not intended to model real physics.

The MCB is designed to confirm correct hybrid MPI + OpenMP performance, single CPU performance, and parallel scaling on new computers. It achieves parallelism through domain decomposition and threading. Domain decomposition means that the physical space simulated by the code is cut up into distinct sections (domains), each of which is simulated by a different MPI process. When particles hit the boundary of a domain, they are buffered. The buffers are sent using a non-blocking MPI call to the processor simulating the domain on the other side of the boundary. OpenMP threads can be used within an MPI task to cooperatively track the particles in its domain.

For more information on the package and download links we refer the reader to https://codesign.llnl.gov/mcb.php.

### 6.9.1 Instrumentation with MERIC

Before inserting MERIC regions, the MCB app was profiled by Allinea Map. The `advance` function and the functions it calls do most of the work in MCB. Inside of this function we identified several significant regions. The first one comprises calls to the functions `setUp` and `get_source_photons` preparing data for the subsequent simulation. The computationally most intensive part is included in the function `advancePhotonList`. This function also includes the above mentioned non-blocking MPI calls representing a good candidate for a significant region. However, this part of the code is not accessed by all MPI processes the same number of times, which implies that it is not possible to insert a global MPI barrier before and after the MPI send/receive calls without further changes in the code. Thus, for measurements with MERIC we could not further separate the `advancePhotonList` function into the computation and communication phases. This results in two MERIC regions, first one including both preparatory functions `setUp` and `get_source_photons`, and the second one for the computationally intensive `advancePhotonList`. All these functions are called in

| | | | |
|---|---|---|---|
| MPI_PROCS | 1 | 2 | 4 |
| PX | 1 | 1 | 2 |
| PY | 1 | 2 | 2 |
| OMP_THREADS | 24 | 12 | 6 |
| Default consumption [J] | 2325 | 3439 | 5880 |
| Static savings [J] | 96 (4.13 %) | 163 (4.75 %) | 365 (6.21 %) |
| Dynamic savings [J] | 32 (1.42 %) | 50 (1.51 %) | 119 (2.15 %) |
| Total savings [J] | 128 (5.51 %) | 213 (6.19 %) | 484 (8.23 %) |

Table 31: Energy savings for various settings, part 1.

every time step. The time stepping is thus denoted as an iteration region for visualization purposes.

Testing runs were chosen such that the runtime of a single simulation is reasonable, i.e., tens of seconds. In particular, the program MCBenchmark.exe was called as

```
srun -n $MPI_PROCS ./MCBenchmark.exe
--nMpiTasksX=$MPI_X
--nMpiTasksY=$MPI_Y
--nCores=$OMP_THREADS
--nThreadCore=1
--numParticles=8000000
```

with the parameters `MPI_PROCS`, `PX`, `PY`, `MCB_OMP_THREADS` denoting the number of MPI processes, number of subdomains in $x$ and $y$ axes, and number of OpenMP threads, respectively. Each MPI process is assigned a single subdomain, i.e., it must hold

$$\texttt{MPI\_PROCS} = \texttt{PX} \cdot \texttt{PY}.$$

The experiments were performed on a single Taurus node and in every instance all available cores were utilized. The tuning parameters thus included core and uncore frequencies, number of MPI processes and OpenMP threads, such that

$$\texttt{MPI\_PROCS} \cdot \texttt{OMP\_THREADS} = 24.$$

To overcome NUMA effects, in particular for the case with a single MPI process and 24 OpenMP threads, the environment variable `OMP_PROC_BIND` was set to `close`.

### 6.9.2 Results

In Tables 31 and 32 we present possible energy savings for different configurations by tuning the core and uncore frequencies. First three rows describe the configuration of MCB as described in the previous section. The following row corresponds to the energy consumed

| | | | |
|---|---|---|---|
| MPI_PROCS | 6 | 12 | 24 |
| PX | 2 | 3 | 4 |
| PY | 3 | 4 | 6 |
| OMP_THREADS | 4 | 2 | 1 |
| Default consumption [J] | 8539 | 13259 | 18681 |
| Static savings [J] | 444 (5.20 %) | 573 (4.32 %) | 636 (3.40 %) |
| Dynamic savings [J] | 210 (2.59 %) | 306 (2.41 %) | 753 (4.18 %) |
| Total savings [J] | 654 (7.66 %) | 879 (6.63 %) | 1389 (7.44 %) |

Table 32: Energy savings for various settings, part 2.

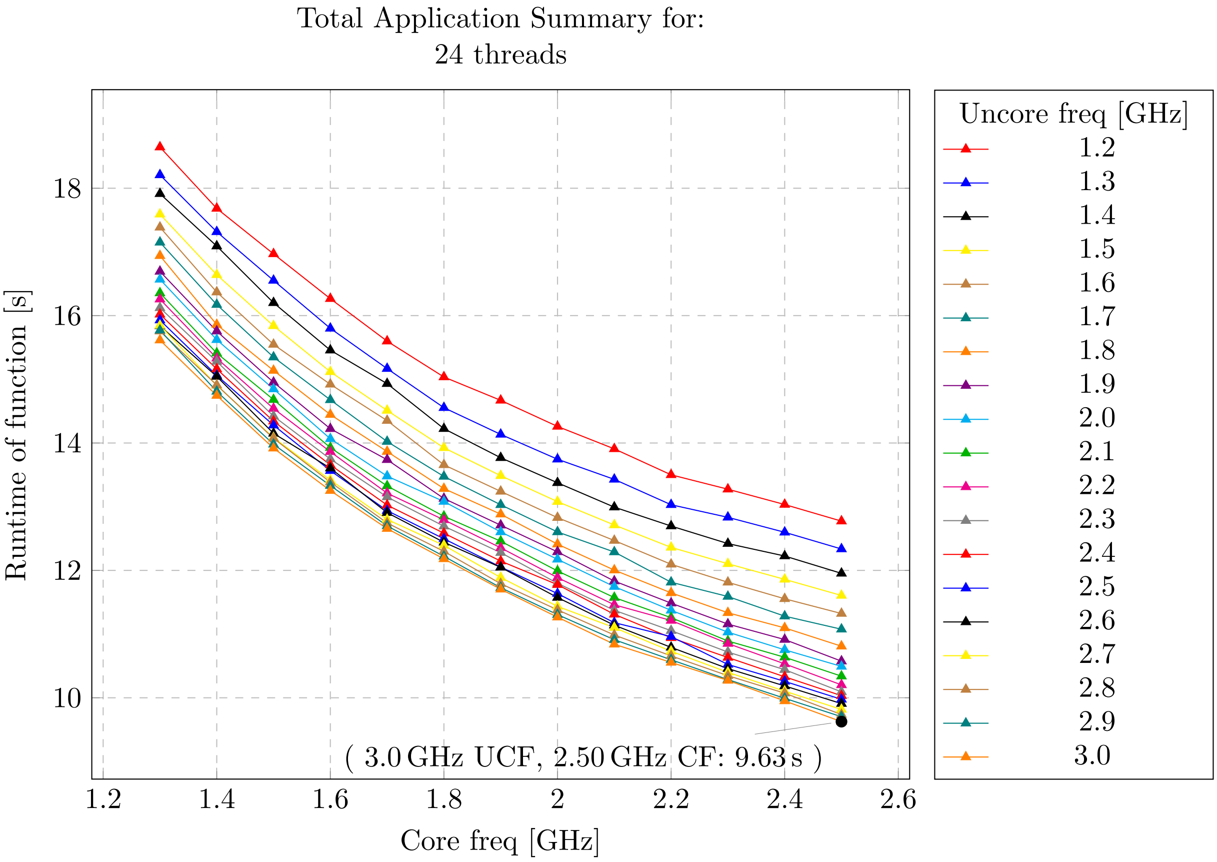
by the program running in the default configuration, i.e., 2.5 GHz and 3.0 GHz for core and uncore frequencies, respectively. Tuning these frequencies for the whole runtime of the program leads to the static savings summarized in the next row. Dynamic tuning, i.e., tuning for every significant region independently results in further savings, note that the value in percent corresponds to savings with respect to the static optimum. In the last row we present total savings achieved by both static and dynamic tuning of the parameters.

We present the results obtained by MERIC and visualized by RADAR for two configurations, namely the runs with a single MPI process and 24 OpenMP threads and the other extreme with 24 MPI processes and a single OpenMP thread per process. All configurations were ran five times, RADAR reports represent an average run. It can be clearly seen that the behaviour changes dynamically both between the two significant regions and the two configurations. In particular, the methods `setUp` and `get_source_photons` cease to be compute bound in the latter setting. Moreover, the energy consumption also differs for the first and subsequent iterations, see Section 7.1. This gives some room both for intra- and inter-phase tuning.

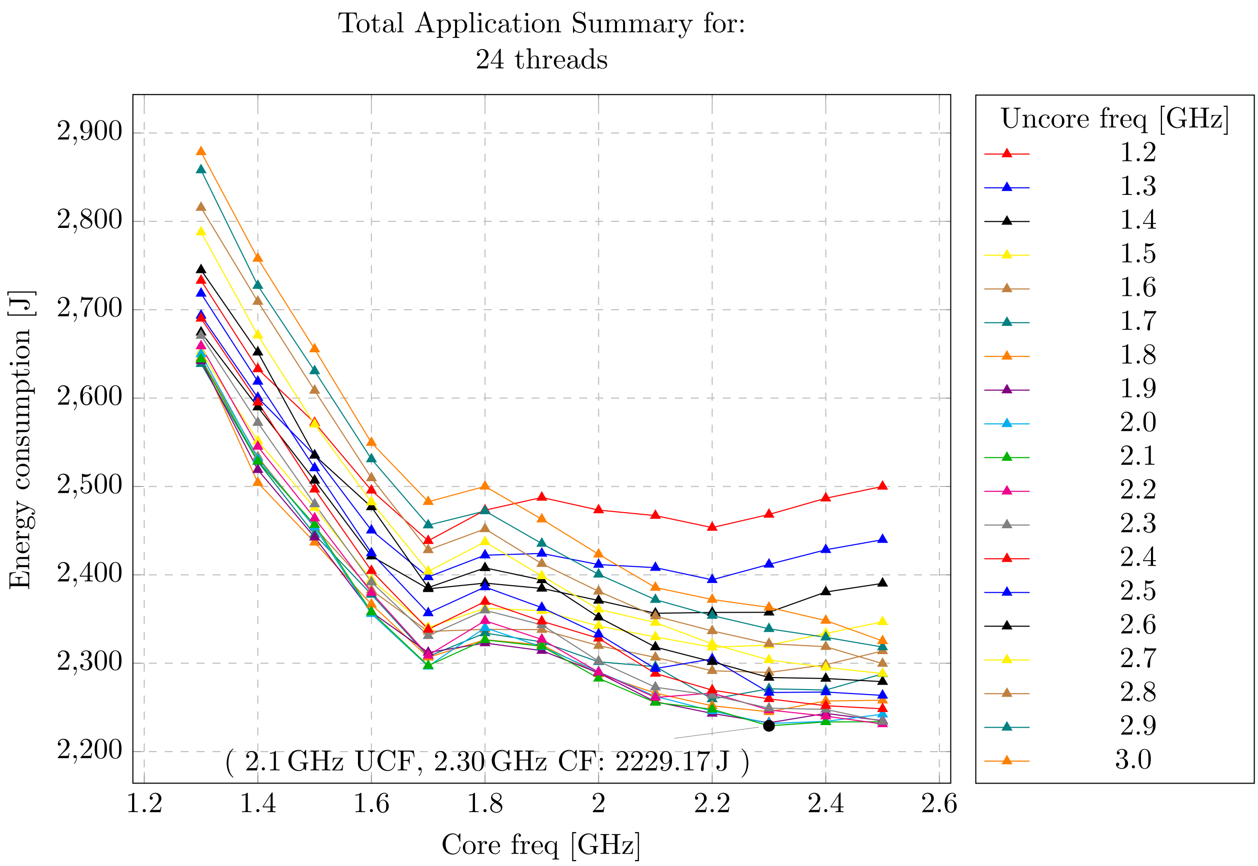
#### 6.9.2.1 `MPI_PROCS=1`, `PX=PY=1`, `OMP_THREADS=24`

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Runtime of function [s], Job info - hdeem | 3.0 GHz UCF, 2.5 GHz CF | 9.63 s | 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.01 s of 9.63 s (0.12 %) |
| Energy consumption [J], Blade summary | 3.0 GHz UCF, 2.5 GHz CF | 2325.22 J | 2.1 GHz UCF, 2.3 GHz CF | 96.04 J (4.13%) | 31.73 J of 2229.17 J (1.42 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 18.65 | 18.21 | 17.91 | 17.59 | 17.39 | 17.15 | 16.94 | 16.69 | 16.57 | 16.35 | 16.26 | 16.12 | 16.02 | 15.93 | 15.84 | 15.85 | 15.76 | 15.77 | 15.62 |
| 1.4 | 17.68 | 17.32 | 17.09 | 16.64 | 16.37 | 16.17 | 15.86 | 15.76 | 15.62 | 15.41 | 15.33 | 15.28 | 15.16 | 15.06 | 15.04 | 14.91 | 14.91 | 14.81 | 14.75 |
| 1.5 | 16.97 | 16.55 | 16.2 | 15.84 | 15.55 | 15.35 | 15.14 | 14.95 | 14.85 | 14.68 | 14.54 | 14.42 | 14.34 | 14.28 | 14.15 | 14.08 | 14.07 | 13.98 | 13.92 |
| 1.6 | 16.27 | 15.8 | 15.46 | 15.12 | 14.92 | 14.68 | 14.45 | 14.22 | 14.07 | 13.93 | 13.86 | 13.75 | 13.66 | 13.57 | 13.6 | 13.42 | 13.39 | 13.33 | 13.25 |
| 1.7 | 15.6 | 15.17 | 14.93 | 14.51 | 14.35 | 14.02 | 13.87 | 13.74 | 13.48 | 13.33 | 13.21 | 13.15 | 13.02 | 12.94 | 12.91 | 12.8 | 12.74 | 12.7 | 12.66 |
| 1.8 | 15.04 | 14.55 | 14.23 | 13.92 | 13.66 | 13.47 | 13.28 | 13.13 | 13.08 | 12.85 | 12.79 | 12.69 | 12.58 | 12.5 | 12.44 | 12.39 | 12.3 | 12.22 | 12.18 |
| 1.9 | 14.67 | 14.14 | 13.77 | 13.49 | 13.24 | 13.03 | 12.88 | 12.71 | 12.6 | 12.46 | 12.35 | 12.28 | 12.15 | 12.05 | 12.05 | 11.89 | 11.79 | 11.73 | 11.7 |
| 2 | 14.26 | 13.75 | 13.38 | 13.08 | 12.83 | 12.6 | 12.41 | 12.29 | 12.17 | 11.99 | 11.89 | 11.8 | 11.78 | 11.64 | 11.57 | 11.44 | 11.38 | 11.31 | 11.27 |
| 2.1 | 13.91 | 13.43 | 12.99 | 12.71 | 12.47 | 12.29 | 12 | 11.83 | 11.75 | 11.57 | 11.46 | 11.37 | 11.31 | 11.18 | 11.14 | 11.1 | 10.99 | 10.91 | 10.84 |
| 2.2 | 13.5 | 13.03 | 12.7 | 12.36 | 12.1 | 11.81 | 11.65 | 11.49 | 11.37 | 11.26 | 11.21 | 11.05 | 10.94 | 10.96 | 10.79 | 10.73 | 10.66 | 10.6 | 10.56 |
| 2.3 | 13.27 | 12.83 | 12.42 | 12.1 | 11.81 | 11.59 | 11.33 | 11.16 | 11.03 | 10.89 | 10.85 | 10.72 | 10.63 | 10.52 | 10.46 | 10.4 | 10.35 | 10.29 | 10.27 |
| 2.4 | 13.03 | 12.6 | 12.23 | 11.86 | 11.55 | 11.28 | 11.1 | 10.91 | 10.75 | 10.64 | 10.53 | 10.44 | 10.33 | 10.26 | 10.19 | 10.1 | 10.07 | 9.99 | 9.95 |
| 2.5 | 12.77 | 12.34 | 11.95 | 11.61 | 11.32 | 11.08 | 10.81 | 10.58 | 10.49 | 10.34 | 10.2 | 10.09 | 10.03 | 9.98 | 9.91 | 9.82 | 9.74 | 9.7 | 9.63 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 2,733 | 2,694 | 2,674 | 2,652 | 2,645 | 2,639 | 2,646 | 2,642 | 2,650 | 2,644 | 2,659 | 2,671 | 2,690 | 2,718 | 2,745 | 2,788 | 2,816 | 2,858 | 2,879 |
| 1.4 | 2,633 | 2,601 | 2,590 | 2,551 | 2,533 | 2,528 | 2,504 | 2,519 | 2,532 | 2,529 | 2,545 | 2,572 | 2,595 | 2,619 | 2,652 | 2,671 | 2,709 | 2,727 | 2,758 |
| 1.5 | 2,572 | 2,535 | 2,507 | 2,476 | 2,454 | 2,446 | 2,437 | 2,443 | 2,454 | 2,457 | 2,464 | 2,480 | 2,497 | 2,521 | 2,535 | 2,570 | 2,609 | 2,631 | 2,655 |
| 1.6 | 2,496 | 2,450 | 2,421 | 2,394 | 2,383 | 2,378 | 2,367 | 2,358 | 2,356 | 2,358 | 2,380 | 2,392 | 2,405 | 2,425 | 2,477 | 2,482 | 2,510 | 2,531 | 2,550 |
| 1.7 | 2,439 | 2,398 | 2,384 | 2,340 | 2,336 | 2,308 | 2,307 | 2,312 | 2,296 | 2,297 | 2,309 | 2,331 | 2,338 | 2,357 | 2,386 | 2,404 | 2,428 | 2,456 | 2,483 |
| 1.8 | 2,473 | 2,422 | 2,391 | 2,362 | 2,338 | 2,334 | 2,327 | 2,323 | 2,340 | 2,326 | 2,348 | 2,360 | 2,370 | 2,386 | 2,408 | 2,437 | 2,452 | 2,472 | 2,500 |
| 1.9 | 2,488 | 2,424 | 2,385 | 2,359 | 2,338 | 2,324 | 2,321 | 2,314 | 2,319 | 2,319 | 2,327 | 2,343 | 2,348 | 2,363 | 2,394 | 2,399 | 2,413 | 2,435 | 2,463 |
| 2 | 2,473 | 2,412 | 2,371 | 2,342 | 2,320 | 2,302 | 2,288 | 2,289 | 2,290 | 2,283 | 2,290 | 2,302 | 2,328 | 2,333 | 2,352 | 2,361 | 2,381 | 2,401 | 2,423 |
| 2.1 | 2,467 | 2,408 | 2,357 | 2,330 | 2,307 | 2,296 | 2,266 | 2,256 | 2,263 | 2,256 | 2,261 | 2,273 | 2,288 | 2,294 | 2,318 | 2,346 | 2,353 | 2,372 | 2,386 |
| 2.2 | 2,454 | 2,394 | 2,357 | 2,318 | 2,291 | 2,260 | 2,252 | 2,243 | 2,246 | 2,248 | 2,266 | 2,264 | 2,270 | 2,305 | 2,302 | 2,322 | 2,337 | 2,354 | 2,372 |
| 2.3 | 2,468 | 2,412 | 2,358 | 2,321 | 2,290 | 2,271 | 2,245 | 2,233 | 2,232 | 2,229 | 2,247 | 2,249 | 2,260 | 2,267 | 2,284 | 2,304 | 2,322 | 2,339 | 2,363 |
| 2.4 | 2,487 | 2,428 | 2,381 | 2,334 | 2,298 | 2,270 | 2,257 | 2,243 | 2,234 | 2,234 | 2,240 | 2,248 | 2,252 | 2,267 | 2,283 | 2,295 | 2,319 | 2,329 | 2,348 |
| 2.5 | 2,500 | 2,440 | 2,390 | 2,347 | 2,314 | 2,288 | 2,258 | 2,235 | 2,242 | 2,234 | 2,231 | 2,234 | 2,248 | 2,264 | 2,279 | 2,288 | 2,300 | 2,318 | 2,325 |

**Job info - hdeem, Runtime of function [s]**

| Region | % of 1 phase | Def set. | Def val. | Optim set. | Optim val. | Savings |
|---|---|---|---|---|---|---|
| advance | 40.62 | 3.0 GHz UCF, 2.5 GHz CF | 3.75 s | 2.8 GHz UCF, 2.5 GHz CF | 3.73 s | 0.01 s (0.31%) |
| setUp | 59.38 | 3.0 GHz UCF, 2.5 GHz CF | 5.48 s | 3.0 GHz UCF, 2.5 GHz CF | 5.48 s | 0.00 s (0.00%) |
| **Total value for static tuning for significant regions** | | | 3.75 + 5.48 = 9.22 s | | | |

| | |
|---|---|
| **Total savings for dynamic tuning for significant regions** | 0.01 + 0.00 = 0.01 s of 9.22 s (0.13 %) |
| **Dynamic savings for application runtime** | 0.01 s of 9.63 s (0.12 %) |

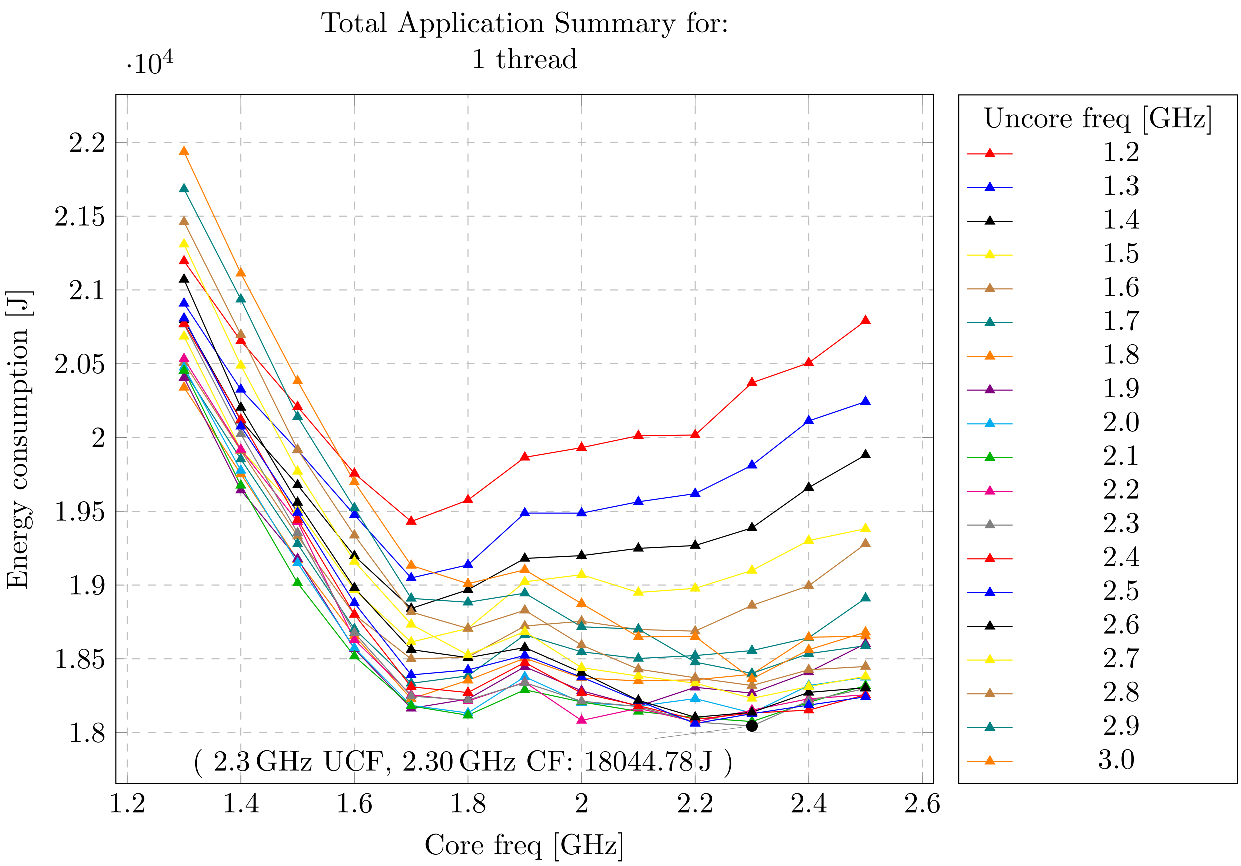
**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| **Region** | **% of 1 phase** | **Best static configuration** | **Value** | **Best dynamic configuration** | **Value** | **Dynamic savings** |
|---|---|---|---|---|---|---|
| advance | 44.92 | 2.1 GHz UCF, 2.3 GHz CF | 958.43 J | 1.5 GHz UCF, 2.3 GHz CF | 937.92 J | 20.51 J (2.14%) |
| setUp | 55.08 | 2.1 GHz UCF, 2.3 GHz CF | 1175.06 J | 2.3 GHz UCF, 2.5 GHz CF | 1163.84 J | 11.22 J (0.95%) |
| **Total value for static tuning for significant regions** | | | 958.43 + 1175.06 = 2133.49 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 20.51 + 11.22 = 31.73 J of 2133.49 J (1.49 %) | | | |
| **Dynamic savings for application runtime** | | | 31.73 J of 2229.17 J (1.42 %) | | | |

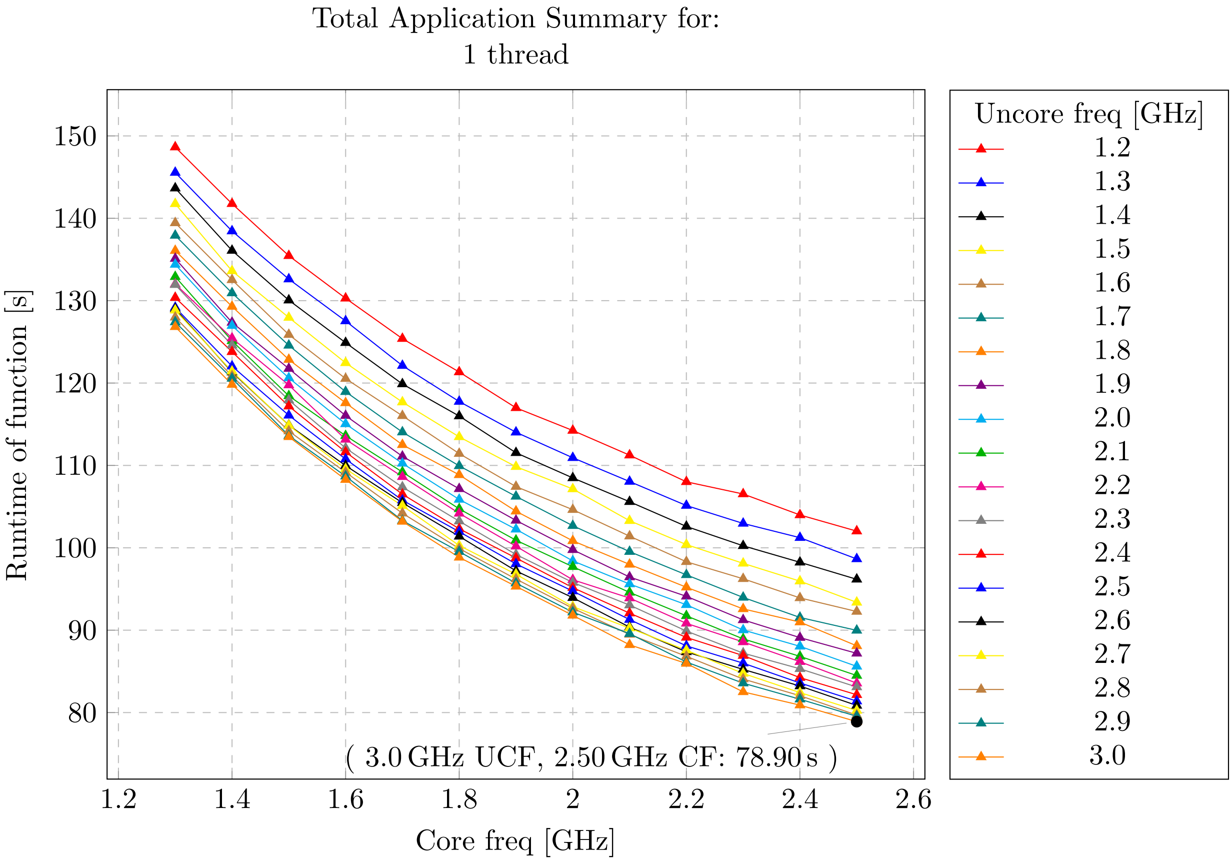
#### 6.9.2.2 `MPI_PROCS=24`, `PX=4`, `PY=6`, `OMP_THREADS=1`

**Overall application evaluation**

| | **Default settings** | **Default values** | **Best static configuration** | **Static Savings** | **Dynamic Savings** |
|---|---|---|---|---|---|
| Energy consumption [J], Blade summary | 3.0 GHz UCF, 2.5 GHz CF | 18680.76 J | 2.3 GHz UCF, 2.3 GHz CF | 635.98 J (3.40%) | 753.48 J of 18044.78 J (4.18 %) |
| Runtime of function [s], Job info - hdeem | 3.0 GHz UCF, 2.5 GHz CF | 78.90 s | 3.0 GHz UCF, 2.5 GHz CF | 0.00 s (0.00%) | 0.00 s of 78.90 s (0.00 %) |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 21,195 | 20,909 | 20,796 | 20,685 | 20,507 | 20,453 | 20,340 | 20,406 | 20,476 | 20,454 | 20,533 | 20,768 | 20,772 | 20,808 | 21,071 | 21,310 | 21,461 | 21,684 | 21,936 |
| 1.4 | 20,655 | 20,326 | 20,117 | 19,917 | 19,911 | 19,854 | 19,753 | 19,643 | 19,777 | 19,676 | 19,919 | 20,024 | 20,122 | 20,076 | 20,203 | 20,489 | 20,697 | 20,937 | 21,113 |
| 1.5 | 20,208 | 19,915 | 19,678 | 19,509 | 19,331 | 19,279 | 19,171 | 19,178 | 19,150 | 19,014 | 19,428 | 19,354 | 19,443 | 19,492 | 19,559 | 19,770 | 19,918 | 20,141 | 20,382 |
| 1.6 | 19,756 | 19,476 | 19,198 | 18,968 | 18,799 | 18,702 | 18,657 | 18,567 | 18,573 | 18,518 | 18,629 | 18,676 | 18,801 | 18,879 | 18,981 | 19,160 | 19,337 | 19,522 | 19,698 |
| 1.7 | 19,431 | 19,048 | 18,841 | 18,614 | 18,499 | 18,334 | 18,229 | 18,165 | 18,184 | 18,180 | 18,256 | 18,247 | 18,310 | 18,391 | 18,563 | 18,733 | 18,817 | 18,910 | 19,133 |
| 1.8 | 19,576 | 19,137 | 18,968 | 18,706 | 18,512 | 18,384 | 18,355 | 18,227 | 18,133 | 18,117 | 18,214 | 18,221 | 18,271 | 18,425 | 18,508 | 18,526 | 18,706 | 18,883 | 19,009 |
| 1.9 | 19,866 | 19,488 | 19,180 | 19,022 | 18,722 | 18,662 | 18,504 | 18,446 | 18,378 | 18,290 | 18,342 | 18,338 | 18,475 | 18,523 | 18,576 | 18,684 | 18,829 | 18,945 | 19,103 |
| 2 | 19,931 | 19,487 | 19,199 | 19,070 | 18,755 | 18,547 | 18,370 | 18,284 | 18,204 | 18,208 | 18,082 | 18,213 | 18,268 | 18,376 | 18,407 | 18,440 | 18,593 | 18,717 | 18,875 |
| 2.1 | 20,012 | 19,564 | 19,249 | 18,950 | 18,699 | 18,502 | 18,350 | 18,179 | 18,178 | 18,144 | 18,165 | 18,176 | 18,182 | 18,215 | 18,219 | 18,383 | 18,430 | 18,701 | 18,649 |
| 2.2 | 20,017 | 19,619 | 19,268 | 18,978 | 18,687 | 18,522 | 18,358 | 18,307 | 18,231 | 18,102 | 18,073 | 18,072 | 18,090 | 18,062 | 18,104 | 18,335 | 18,371 | 18,478 | 18,651 |
| 2.3 | 20,371 | 19,812 | 19,387 | 19,099 | 18,862 | 18,556 | 18,395 | 18,267 | 18,133 | 18,075 | 18,152 | 18,045 | 18,133 | 18,128 | 18,138 | 18,232 | 18,319 | 18,401 | 18,364 |
| 2.4 | 20,506 | 20,112 | 19,661 | 19,302 | 18,995 | 18,643 | 18,646 | 18,410 | 18,319 | 18,204 | 18,229 | 18,216 | 18,152 | 18,186 | 18,272 | 18,312 | 18,426 | 18,535 | 18,562 |
| 2.5 | 20,791 | 20,243 | 19,881 | 19,382 | 19,279 | 18,911 | 18,653 | 18,603 | 18,375 | 18,319 | 18,256 | 18,299 | 18,257 | 18,242 | 18,304 | 18,381 | 18,448 | 18,589 | 18,681 |




| Uncore freq [GHz] / Core freq [GHz] | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | 148.6 | 145.6 | 143.7 | 141.8 | 139.4 | 137.9 | 136.1 | 135.1 | 134.4 | 132.9 | 132 | 131.9 | 130.4 | 129.2 | 129 | 128.8 | 128 | 127.4 | 126.8 |
| 1.4 | 141.8 | 138.4 | 136.1 | 133.6 | 132.5 | 130.9 | 129.3 | 127.4 | 127 | 125.1 | 125.4 | 124.6 | 123.8 | 122 | 121.3 | 121.4 | 120.9 | 120.6 | 119.8 |
| 1.5 | 135.5 | 132.6 | 130.1 | 128 | 125.9 | 124.6 | 122.8 | 121.8 | 120.6 | 118.4 | 119.8 | 117.9 | 117.2 | 116.1 | 114.9 | 114.9 | 114.2 | 113.6 | 113.5 |
| 1.6 | 130.3 | 127.5 | 124.9 | 122.5 | 120.5 | 118.9 | 117.6 | 116 | 115 | 113.6 | 113.2 | 112.1 | 111.6 | 110.8 | 110 | 109.6 | 109.2 | 108.7 | 108.3 |
| 1.7 | 125.4 | 122.1 | 119.9 | 117.7 | 116 | 114 | 112.5 | 111.1 | 110.2 | 109.2 | 108.6 | 107.4 | 106.5 | 105.8 | 105.5 | 105.1 | 104.2 | 103.3 | 103.2 |
| 1.8 | 121.3 | 117.8 | 116 | 113.5 | 111.4 | 109.9 | 108.9 | 107.2 | 105.9 | 104.7 | 104.2 | 103.2 | 102.3 | 102 | 101.4 | 100.3 | 99.9 | 99.5 | 98.8 |
| 1.9 | 117 | 114 | 111.5 | 109.8 | 107.4 | 106.2 | 104.4 | 103.3 | 102.2 | 100.9 | 100.2 | 99.2 | 98.8 | 98 | 97.2 | 96.8 | 96.2 | 95.7 | 95.3 |
| 2 | 114.2 | 110.9 | 108.5 | 107.1 | 104.6 | 102.7 | 100.8 | 99.8 | 98.4 | 97.7 | 96.1 | 95.8 | 95.2 | 94.7 | 93.9 | 92.9 | 92.7 | 92.2 | 91.8 |
| 2.1 | 111.2 | 108 | 105.6 | 103.3 | 101.4 | 99.5 | 98 | 96.5 | 95.6 | 94.6 | 93.9 | 93 | 92.1 | 91.3 | 90.4 | 90.3 | 89.5 | 89.6 | 88.2 |
| 2.2 | 108 | 105.1 | 102.6 | 100.4 | 98.3 | 96.7 | 95.2 | 94.1 | 93.1 | 91.7 | 90.8 | 89.9 | 89.1 | 88.1 | 87.4 | 87.6 | 86.8 | 86.1 | 86 |
| 2.3 | 106.5 | 103 | 100.2 | 98.1 | 96.2 | 94 | 92.6 | 91.3 | 90 | 88.9 | 88.6 | 87.2 | 86.9 | 86 | 85.2 | 84.8 | 84.1 | 83.6 | 82.5 |
| 2.4 | 104 | 101.2 | 98.2 | 96 | 93.9 | 91.5 | 91 | 89.1 | 88 | 86.8 | 86.2 | 85.3 | 84.2 | 83.6 | 83.2 | 82.4 | 82 | 81.6 | 80.9 |
| 2.5 | 102 | 98.6 | 96.2 | 93.4 | 92.3 | 90 | 88.1 | 87.2 | 85.6 | 84.5 | 83.6 | 83.1 | 82.2 | 81.4 | 80.9 | 80.2 | 79.7 | 79.5 | 78.9 |

**Intra-Phase Dynamism Evaluation**
**Blade summary, Energy consumption [J]**

| Region | % of 1 phase | Best static configuration | Value | Best dynamic configuration | Value | Dynamic savings |
|---|---|---|---|---|---|---|
| setUp | 30.56 | 2.3 GHz UCF, 2.3 GHz CF | 5383.30 J | 2.9 GHz UCF, 1.7 GHz CF | 4773.10 J | 610.20 J (11.34%) |
| advance | 69.44 | 2.3 GHz UCF, 2.3 GHz CF | 12233.56 J | 1.8 GHz UCF, 2.5 GHz CF | 12090.29 J | 143.28 J (1.17%) |
| **Total value for static tuning for significant regions** | | | 5383.30 + 12233.56 = 17616.86 J | | | |
| **Total savings for dynamic tuning for significant regions** | | | 610.20 + 143.28 = 753.48 J of 17616.86 J (4.28 %) | | | |
| **Dynamic savings for application runtime** | | | 753.48 J of 18044.78 J (4.18 %) | | | |

**Job info - hdeem, Runtime of function [s]**

| Region | % of 1 phase | Def set. | Def val. | Optim set. | Optim val. | Savings |
|---|---|---|---|---|---|---|
| setUp | 31.08 | 3.0 GHz UCF, 2.5 GHz CF | 23.93 s | 3.0 GHz UCF, 2.5 GHz CF | 23.93 s | 0.00 s (0.00%) |
| advance | 68.92 | 3.0 GHz UCF, 2.5 GHz CF | 53.07 s | 3.0 GHz UCF, 2.5 GHz CF | 53.07 s | 0.00 s (0.00%) |
| **Total value for static tuning for significant regions** | | | 23.93 + 53.07 = 77.00 s | | | |
| **Total savings for dynamic tuning for significant regions** | | | 0.00 + 0.00 = 0.00 s of 77.00 s (0.00 %) | | | |
| **Dynamic savings for application runtime** | | | 0.00 s of 78.90 s (0.00 %) | | | |

# 7 Results – Inter-Phase Dynamism

The previous sections provided energy and time measurements focusing on the possible intra-phase dynamism, i.e., dynamism between different significant regions. In this section we would thus like to focus on the inter-phase dynamism, where the same region exhibits different behaviour in different phases (iterations, time-steps, etc.). Not all applications studied above demonstrate such behaviour. For example PCG iterations used in Espreso or AMG2013 usually behave similarly regardless on the iteration number. This may change with the transition, e.g., to (restarted) GMRES, which iteratively builds a Hessenberg system to be solved. In the rest of this section we restrict our attention to a subset of applications studied in Section 6.

## 7.1 MCB

From the results presented in Section 6.9.2 one can deduce that the nature of the individual significant regions, i.e., the set-up and photon advancing, is rather different. While advancing the photons seems to be more or less compute bound (at least for our settings on a single Taurus node), the set-up phase prefers a higher uncore frequency and lower core frequency. However, this is not entirely true for the first couple of time-steps. From the tables in Section 7.1.1, we can see that in the first time-step the set-up phase takes over 90 % of both the energy consumption and the runtime. This ratio drops down in the subsequent time-steps to less than 40 %. The optimal core and uncore frequencies thus differ and such tuning leads to further dynamic savings with respect to the best static scenario. The inter-phase dynamism with more MPI processes is presented in Section 7.1.2.

### 7.1.1 `MPI_PROCS=1`, `PX=PY=1`, `OMP_THREADS=24`

**advancePhotonList - average program start**

| **Phase ID** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Default Energy consumption (Samples) [J]** | 57.69 | 83.48 | 92.95 | 97.67 | 100.72 |
| **% per 1 phase** | 8.46 | 62.62 | 60.90 | 60.83 | 61.39 |
| **Per phase optimal settings** | 1.2 GHz UCF, 2.3 GHz CF | 1.3 GHz UCF, 2.5 GHz CF | 1.5 GHz UCF, 2.3 GHz CF | 1.5 GHz UCF, 2.3 GHz CF | 1.5 GHz UCF, 2.3 GHz CF |
| **Dynamic savings [J]** | 2.92 | 2.71 | 2.14 | 2.07 | 2.08 |
| **Dynamic savings [%]** | 5.05 | 3.25 | 2.31 | 2.12 | 2.07 |

| Phase ID | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| Default Energy consumption (Samples) [J] | 102.69 | 104.23 | 105.37 | 106.33 | 107.29 |
| % per 1 phase | 61.83 | 62.29 | 62.60 | 62.89 | 63.10 |
| Per phase optimal settings | 1.5 GHz UCF, 2.3 GHz CF | 1.5 GHz UCF, 2.3 GHz CF | 1.5 GHz UCF, 2.3 GHz CF | 1.5 GHz UCF, 2.3 GHz CF | 1.5 GHz UCF, 2.3 GHz CF |
| Dynamic savings [J] | 2.09 | 1.82 | 1.96 | 1.97 | 1.98 |
| Dynamic savings [%] | 2.03 | 1.75 | 1.86 | 1.85 | 1.85 |

## setUp + get_source_photons - average program start

| Phase ID | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Default Energy consumption (Samples) [J] | 624.35 | 49.83 | 59.68 | 62.89 | 63.35 |
| % per 1 phase | 91.54 | 37.38 | 39.10 | 39.17 | 38.61 |
| Per phase optimal settings | 2.0 GHz UCF, 2.5 GHz CF | 2.1 GHz UCF, 1.7 GHz CF | 2.2 GHz UCF, 1.7 GHz CF | 2.1 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF |
| Dynamic savings [J] | 14.63 | 1.37 | 3.76 | 4.78 | 5.51 |
| Dynamic savings [%] | 2.34 | 2.74 | 6.30 | 7.61 | 8.70 |

| Phase ID | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| Default Energy consumption (Samples) [J] | 63.40 | 63.10 | 62.96 | 62.75 | 62.74 |
| % per 1 phase | 38.17 | 37.71 | 37.40 | 37.11 | 36.90 |
| Per phase optimal settings | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF |
| Dynamic savings [J] | 6.22 | 6.65 | 6.86 | 7.09 | 7.34 |
| Dynamic savings [%] | 9.81 | 10.54 | 10.89 | 11.30 | 11.70 |

### 7.1.2 `MPI_PROCS=24`, `PX=4`, `PY=6`, `OMP_THREADS=1`

## advancePhotonList - average program start

| Phase ID | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 741.88 | 1084.73 | 1208.26 | 1265.27 | 1296.45 |
| % per 1 phase | 80.87 | 76.40 | 70.14 | 68.18 | 68.25 |
| Per phase optimal settings | 1.5 GHz UCF, 2.5 GHz CF | 1.8 GHz UCF, 2.5 GHz CF | 1.8 GHz UCF, 2.5 GHz CF | 1.8 GHz UCF, 2.5 GHz CF | 1.8 GHz UCF, 2.5 GHz CF |
| Dynamic savings [J] | 32.76 | 24.38 | 16.15 | 14.12 | 11.17 |
| Dynamic savings [%] | 4.42 | 2.25 | 1.34 | 1.12 | 0.86 |

| Phase ID | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 1313.10 | 1323.57 | 1330.75 | 1333.10 | 1336.46 |
| % per 1 phase | 68.13 | 67.86 | 67.65 | 67.52 | 67.42 |
| Per phase optimal settings | 1.9 GHz UCF, 2.3 GHz CF | 1.9 GHz UCF, 2.3 GHz CF | 1.9 GHz UCF, 2.3 GHz CF | 1.9 GHz UCF, 2.3 GHz CF | 1.9 GHz UCF, 2.3 GHz CF |
| Dynamic savings [J] | 11.04 | 10.50 | 10.44 | 10.61 | 10.83 |
| Dynamic savings [%] | 0.84 | 0.79 | 0.78 | 0.80 | 0.81 |

## setUp + get_source_photons - average program start

| Phase ID | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 175.49 | 335.05 | 514.33 | 590.44 | 603.19 |
| % per 1 phase | 19.13 | 23.60 | 29.86 | 31.82 | 31.75 |
| Per phase optimal settings | 1.7 GHz UCF, 2.5 GHz CF | 2.6 GHz UCF, 1.7 GHz CF | 2.9 GHz UCF, 1.7 GHz CF | 2.6 GHz UCF, 1.6 GHz CF | 2.8 GHz UCF, 1.7 GHz CF |
| Dynamic savings [J] | 4.71 | 28.49 | 78.50 | 92.89 | 84.14 |
| Dynamic savings [%] | 2.69 | 8.50 | 15.26 | 15.73 | 13.95 |

| Phase ID | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 614.35 | 626.84 | 636.44 | 641.34 | 645.83 |
| % per 1 phase | 31.87 | 32.14 | 32.35 | 32.48 | 32.58 |
| Per phase optimal settings | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF | 2.5 GHz UCF, 1.7 GHz CF |
| Dynamic savings [J] | 74.42 | 75.38 | 76.27 | 76.31 | 76.38 |
| Dynamic savings [%] | 12.11 | 12.02 | 11.98 | 11.90 | 11.83 |

## 7.2 MiniMD

The phase region in miniMD, which is the `for`-loop in function `Integrate::run()`, was also analysed for inter-phase dynamism by the MERIC tool with the results summarised in RADAR. Since the regions `build()` and `compute()` were observed to be significant, the inter-phase dynamism analysis results are summarized in Section 7.2.1. Though the experiment was performed for 100 phases (iterations of the `for`-loop), the results are presented only presented for the first 20 phases for brevity. We observe that these results are similar for the remaining phases in the experiment results.

From the results in Section 7.2.1 we observe that once every 20 phases, the `build()` region contributes around 75% of the energy consumption and the execution time, while it is negligible during the other phases. Consequently, once every 20 phases the `compute()` region contributes only around 25% of the energy consumption and the execution time, while it contributes around 100% during the other phases. This periodicity (once every 20 phases) in the dynamism is associated to one of the input parameters to miniMD – reneighbouring atoms once every N steps/iterations. In the inputs for the experiments reported here, this reneighbouring of atoms is performed once every 20 steps/iterations. This results in the inter-phase dynamism of energy consumption and execution time that is observed in miniMD.

However, we also observe that the optimal configurations for the processor core and uncore frequencies in response for the observed dynamism are the same as the best configurations identified from static tuning. As a result, even though we observe inter-phase dynamism in miniMD, it does not result in any significant dynamic savings for energy consumption and execution time.

### 7.2.1 Experiment 1

**Build - average program start**

| **Phase ID** | **1** | **2** | **...** | **19** | **20** |
|---|---|---|---|---|---|
| **Default Energy consumption [J]** | - | - | - | - | 26.89 |
| **% per 1 phase** | - | - | - | - | 74.83 |
| **Per phase optimal settings** | - | - | - | - | 1 thread, 1.2 GHz UCF, 2.5 GHz CF |
| **Dynamic savings [J]** | - | - | - | - | 0.00 |
| **Dynamic savings [%]** | - | - | - | - | 0.00 |

**Total sum of values from dynamic savings from all phases**

**Energy consumption [J] (Samples)**
134.43 J → 134.43 J (savings 0.00%)
**Runtime of function [s]**
1.30 s → 1.30 s (savings 0.00%)

## Compute - average program start

| Phase ID | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 7.56 | 7.57 | 7.56 | 7.58 | 7.64 |
| % per 1 phase | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Per phase optimal settings | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF |
| Dynamic savings [J] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Dynamic savings [%] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Phase ID | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 7.57 | 7.56 | 7.65 | 7.94 | 7.97 |
| % per 1 phase | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Per phase optimal settings | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF |
| Dynamic savings [J] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Dynamic savings [%] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Phase ID | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 8.19 | 8.26 | 8.29 | 8.33 | 8.37 |
| % per 1 phase | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Per phase optimal settings | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF |
| Dynamic savings [J] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Dynamic savings [%] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Phase ID | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|
| Default Energy consumption [J] | 8.41 | 8.44 | 8.46 | 8.50 | 8.68 |
| % per 1 phase | 100.00 | 100.00 | 100.00 | 100.00 | 24.17 |
| Per phase optimal settings | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF | 1 thread, 1.2 GHz UCF, 2.5 GHz CF |
| Dynamic savings [J] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Dynamic savings [%] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Total sum of values from dynamic savings from all phases**

**Energy consumption [J] (Samples)**
854.43 J → 853.76 J (savings 0.08%)
**Runtime of function [s]**
7.90 s → 7.90 s (savings 0.00%)

## 7.3 Indeed

The forming simulation code Indeed has also been investigated with respect to its inter-phase dynamism. Due to the nature of Indeed as a finite element program with an implicit time integration method, this investigation has turned out to provide interesting insight into the question of inter-phase dynamism from a rather abstract point of view.

Specifically, the first attempts to analyze Indeed's inter-phase dynamism were based on the observation that the code simulates a process that runs over a certain period of time by cutting the process time into a number of small time increments and by looking at the process one time step after the other. Therefore it seemed to be quite natural to assume that each phase corresponds to one such time step. The analysis of the run time and energy requirements then produced, for a typical input data sets, results such as those indicated in Figure 6.

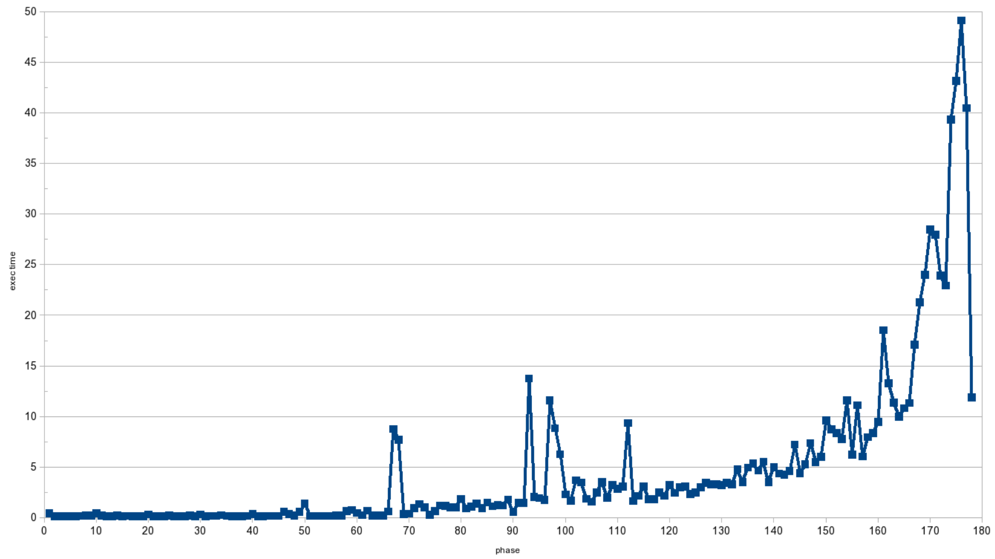



Figure 6: Inter-phase dynamism of Indeed: Run time vs. number of time step.

However, the above mentioned structure of Indeed implies that, within each iteration of the time stepping loop, further loops are nested (see Figure 7), and the number of iterations that these inner loops perform vary strongly from time step to time step, depending on what is physically happening in the real process during each time step. On the other hand, what happens within each iteration of the innermost loop shows much less variation from one instance to the next.

This behavior is indicated in Figure 8. In this figure we show the run time that each inner iteration takes. The graph shows one remarkable very high spike whose origin is not yet clear and is presently under investigation. Apart from that, the variation is much smaller than in Figure 6, and seems to indicate a clear upward trend upon which some mild noise is superimposed.

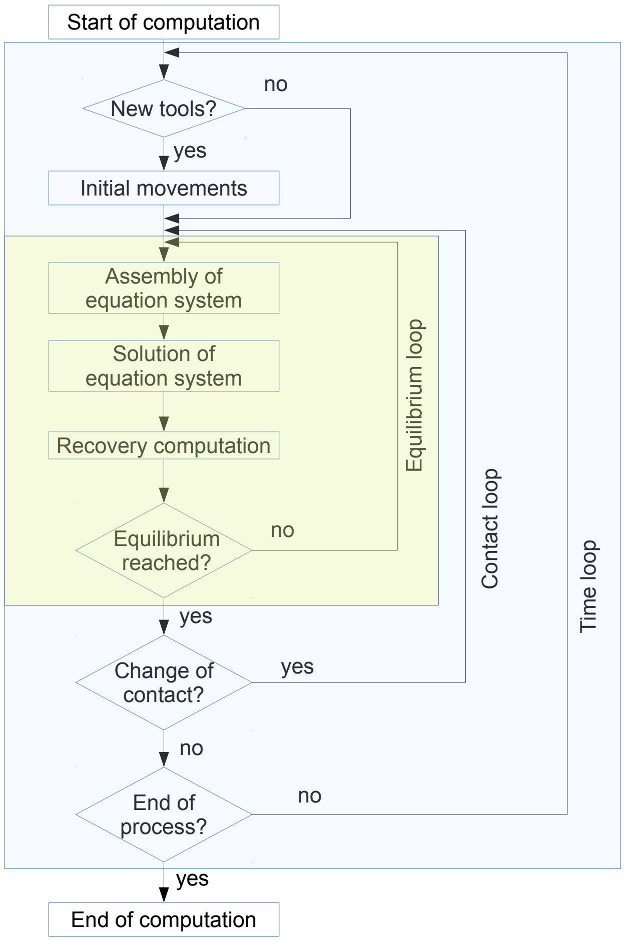



Figure 7: Structure of Indeed code.

This upward trend can easily be traced back to Indeed's adaptive mesh refinement feature. In fact, if one divides the run time per iteration by the number of currently active finite elements, one obtains the results indicated in Figure 9. Here we again see the single strong spike apart from which the amount of time per element remains almost constant over the course of the inner iterations, especially during the second half of the programs runtime.

The conclusions that need to be drawn from this significant difference in the results depending on the precise definition of the concept of the phase are currently under discussion.

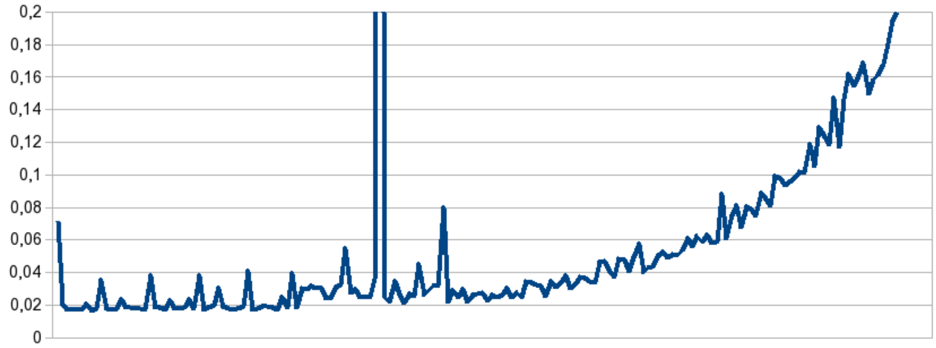



Figure 8: Inter-phase dynamism of Indeed: Normalized runtime vs. number of inner iteration step.

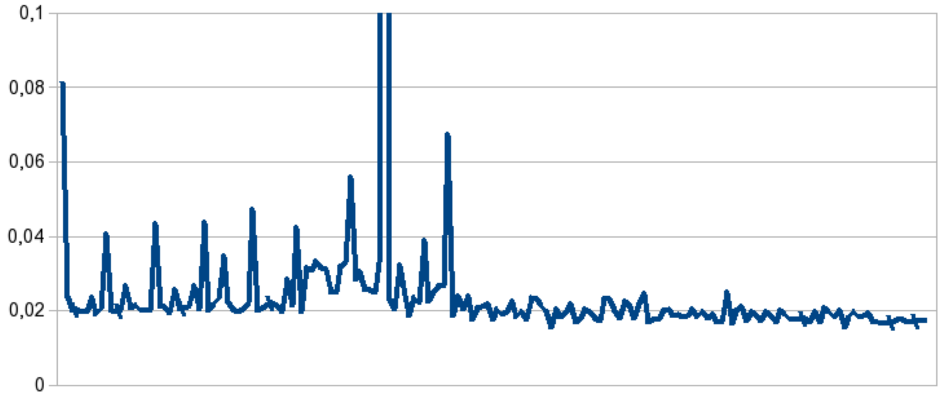



Figure 9: Inter-phase dynamism of Indeed: Normalized runtime divided by number of elements vs. number of inner iteration step.

# 8 Summary

In this repot we present evaluation of (1) key sparse BLAS routines from the Intel MKL library (2) OpenMP parallel I/O (3) a set of proxy-apps (AMG2013, Kripke, LULESH and MCB) and (4) selected full fledge applications (ESPRESO, MiniMD, Indeed) and the potential energy savings due to dynamic tuning of the selected hardware parameters.

We have implemented a parallel I/O benchmark, that reads sparse matrices stored in IJV/-COO format from file. The evaluation of this benchmark shows, that parallel I/O within a single compute node does not scale to more that 4 OpenMP threads. From the frequency point of view, to maximize the energy efficiency of the I/O the CPU core frequency has to high, 2.5 GHz, while the uncore frequency should be 2.1 GHz. When compared to default settings (24 threads, 2.5 GHz core frequency and 3.0 Ghz uncore frequency) the savings are as high as 56%. This significant potential for dynamic tuning should be taken into account in every application that contains heavy I/O workload.

Our experiments with variation of the computation intensity show that with increasing CI the effect of the uncore frequency becomes less important and optimal setting is decreases from 2.5 GHz to 1.2 GHz. On the other hand, the optimal core frequency should be high (2.5 GHz) for applications with high CI and it is decreasing with lower CI. It can be also observed that core frequency tuning is the most efficient for kernels with high CI. Finally we can observe, that the highest static energy savings, 12.5%, have been achieved by compute bound codes while memory bounded kernel achieved only 5.6%.

We have also presented the energy consumption evaluation of selected sparse BLAS routines from the Intel MKL library. The measured characteristics illustrate a different energy consumption for different sparse BLAS routines and different sparse matrices. We also show that some of the routines suffer significantly from the NUMA effect and should be executed on a single CPU socket. The significant savings up to 66% can be achieved in case when NUMA effect is active. The result of the same experiment but in this case running on one CPU socket only (no NUMA effect) shows reduced savings to 2.7% – 12.3%.

In the case of the ProxyApps suite we have selected applications that support hybrid parallelization (MPI+OpenMP). By changing the core and uncore frequencies and the number of OpenMP threads we were able to achieve the *static/dynamic* savings summarized in Table 43. Although the main purpose of these applications is to provide simple benchmarks and the codes are usually rather short, they are able to deliver significant static savings (up to over 25 %) over all instrumented regions. On the other hand, since none of the programs contains any extensive I/O regions and they were tested on a single node of the Taurus supercomputer, the further dynamic savings (maximum reached by Kripke is 7 %, otherwise mostly below 3 %) are quite unsatisfactory. The situation may change when testing on a reasonable number of nodes, where the applications may become communication bound. However, the exhaustive search algorithm (sweeping over all combinations of tuning parameters) would have to be replaced by a more efficient minimization algorithm. A more detailed output causing some I/O overhead would lead to higher dynamism as well.

| Application | Static savings [%] | Dynam. savings [%] | Total Savings [%] |
|---|---|---|---|
| Parallel OpenMP I/O | 56 | — | 56 |
| Dense BLAS - DGEMV - without NUMA | 5.6 | — | 5.6 |
| Dense BLAS - DGEMM - without NUMA | 10.4 | — | 10.4 |
| Compute only kernel | 12.8 | — | 12.8 |
| Sparse BLAS Routines - without NUMA | 3.1-12.3 | — | 3.1 – 12.3 |
| Sparse BLAS Routines - with NUMA | 4.2-66.2 | — | 4.2 – 66.2 |
| ProxyApps 1 - AMG2013, configuration 1 | 6.53 | 2.89 | 9.23 |
| ProxyApps 1 - AMG2013, configuration 2 | 25.66 | 2.80 | 27.74 |
| ProxyApps 2 - Kripke, configuration 1 | 28.16 | 1.56 | 29.28 |
| ProxyApps 2 - Kripke, configuration 2 | 12.63 | 7.04 | 18.78 |
| ProxyApps 3 - LULESH, configuration 1 | 28.58 | 0.55 | 28.88 |
| ProxyApps 3 - LULESH, configuration 2 | 25.81 | 1.23 | 26.72 |
| ProxyApps 4 - MCB, configuration 1 | 4.13 | 1.42 | 5.51 |
| ProxyApps 4 - MCB, configuration 2 | 3.40 | 4.18 | 7.44 |
| ESPRESO - configuration 0 | 5.6 | 8.7 | 14.3 |
| ESPRESO - configuration 1 | 12.3 | 9.1 | 21.4 |
| ESPRESO - configuration 2 | 7.8 | 4.7 | 12.5 |
| ESPRESO - configuration 3 | 7.8 | 5.4 | 13.1 |
| OpenFOAM (Motorbike benchmark) | 15.9 | 1.8 | 17.7 |
| Indeed | 17.6 | to be evaluated | 17.6 |
| MiniMD | 21.92 | 0.00 | 21.92 |

Table 43: Overview of the static and dynamic energy savings achieved by the applications selected for this report.

The ESPRESO library contains both FEM preprocessing tools and sparse iterative solvers based on FETI method. We have annotated more than 20 regions, which includes all types of operations including I/O, communication, sparse BLAS and dense BLAS. The tests also focus on the variation of the arithmetical intensity in form of sparse and dense data structures. Two key kernels of the FETI iterative solver (i) the $F$ operator and (ii) the preconditioner can be represented by both dense and sparse matrices providing different type of workload. The results show that static savings are 5.6–12.3% and dynamic savings 4.7–9.1%. The highest total savings for ESPRESO are 21.4% as a combination of 12.3% static savings and 9.1% dynamic savings.

The investigation of Indeed has shown a relatively high static tuning potential. Moreover, the tools developed within the READEX project have also been successfully used to detect a significant amount of intra-phase and inter-phase dynamism in Indeed. Therefore we expect to find a substantial dynamic tuning potential in the code. At the moment, the READEX team is actively discussing possible ways that can be used to realize this potential.

In case of the OpenFOAM application a simpleFoam solver was used on the motorBike benchmark, that is part of the OpenFOAM repository. The experiment were done on one single node with 24 MPI processes. The simpleFoam was set to use GAMG solver and PBiCG solvers. The results were written twice during the runtime into binary uncompressed format. Since the most time consuming regions, the GAMG and PBiCG solvers, perform similar sparse BLAS operations the optimal configuration for these regions is either identical or very similar. Due to this reason the most of the saving can be achieved by static tuning, 15.9%, while only the remaining regions provide some potential for dynamic savings. Since the runtime of remaining regions is only $\tilde{1}4.5\%$ the overall dynamic savings are only 1.7%.

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