On the Evaluation of Schedulability Tests for Real-Time Scheduling Algorithms

Robert I. Davis[1,2],

[1]Real-Time Systems Research Group, University of York, UK

[2]INRIA, Paris, France

Outline

- **Introduction**
  - Different ways of comparing schedulability tests
- **Advantages and disadvantages of different approaches**
- **Key aspects in Empirical Evaluation**
- **Task set generation**
  - Methods and pitfalls
  - Taking a systematic approach
- **Some suggestions**
- **Task set generation from case studies**
- **Questions and Open Discussion**

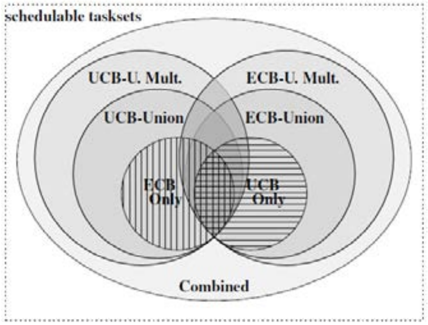
Comparison of schedulability tests for real-time scheduling algorithms

- **Exact tests**
  - All task sets are correctly classified by the test as either schedulable or unschedulable
  - Comparison of exact tests is in effect a comparison of the algorithms
- **Sufficient tests**
  - May classify some task sets that are in fact schedulable as unschedulable, but not vice-versa
  - Often trade effectiveness for efficiency
- **Evaluation**
  - Interested in guaranteed real-time performance – i.e. from whatever tests are available

Comparison of schedulability tests for real-time scheduling algorithms

- **Theoretical methods**
  - Dominance relationships
  - Utilisation bounds
  - Resource augmentation bounds or speedup factors

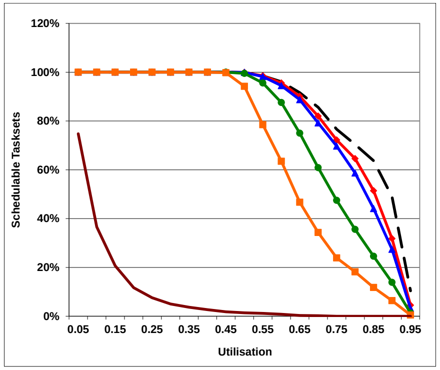
  Typically give a worst-case comparison



1/Ω

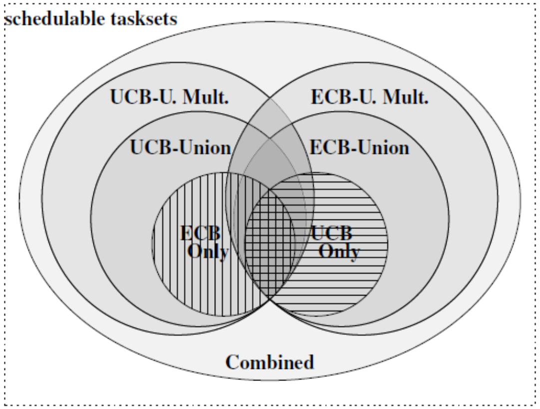
- **Empirical methods**
  - Comparisons using (many) task sets

  Typically give an average-case comparison



Theoretical methods

- **Dominance relationships**
  - Show that one test / algorithm always outperforms another



  Advantages
  - Dominant method always better
  - Examples: Exact v. sufficient tests, EDF v. FP

  Disadvantages
  - Typically only applies to a simplified model e.g. no scheduling overheads, no CRPD etc.
  - Gives no indication how good the methods actually are (dominant method may still have poor performance)

Theoretical methods

- **Utilisation Bounds**
  - All task sets with utilisation no greater than the bound are guaranteed to be schedulable

  Advantages
  - Illustrates worst-case behaviour for any implicit deadline task set ($D = T$)
  - Examples: EDF v. FP ($U = 1$ versus $U = 0.69$)

  Disadvantages
  - Worst-case behaviour may exist only for corner-cases that are of little interest in practice
  - Only applies to simple model, implicit deadlines, no overheads etc.

Theoretical methods

- **Speedup Factors**
  - Factor by which the speed of the system needs to be increased, so that any task set that was schedulable under algorithm B is guaranteed to become schedulable under algorithm A

  Advantages
  - Illustrates worst-case performance relative to a different algorithm (or test)
  - Used to explore sub-optimality w.r.t an optimal algorithm
  - Examples: FP v. EDF, constrained deadlines S = $\mathbf{1/\Omega}$

Theoretical methods

- **Speedup Factors**

  Disadvantages

  - Worst-case behaviour may exist only for corner-cases that are of little interest in practice
  - May not discriminate well between tests
  - Recent (as yet unpublished) work shows that speedup factors for FP-P v EDF-P and FP-NP v. EDF-NP appear to be the same when simple linear tests are used for FP as they are when exact tests are used

Empirical methods

- **Empirical evaluations**
  - Using synthetically generated task sets to evaluate schedulability tests
- **Simulations**
  - Using synthetically generated task sets to evaluate scheduling algorithms via simulated execution
- **Experiments**
  - Running real or synthetic task sets on real hardware
- **Case studies**
  - Empirical evaluations or simulations, using tasks / task parameters derived from real applications

Main Focus of this talk is Empirical evaluations

INVENTORS FOR THE DIGITAL WORLD

Empirical methods: pros and cons

- **Simulations**
  - Simulate the execution of a task set over a long time period, repeat for multiple task sets

  Advantages

  - Useful to explore average case behaviour
  - Useful as a form of *necessary* schedulability test: deadline misses prove that the task set is not schedulable (but no misses don't prove schedulability)

  Disadvantages

  - Typically no guarantee that worst-case behaviours are seen unless the worst-case scenario is known
  - Worst-case scenario may be very different for different algorithms e.g. FP and EDF

Empirical methods: pros and cons

- **Experiments**
  - Running real or synthetically generated tasks on real hardware

  Advantages
  - As per simulation (useful to explore average case behaviour, and acts as a necessary test)
  - Includes all **overheads** on the actual hardware
  - Can be used to collect overhead measurements to include in a model

  Disadvantages
  - Typically no guarantee that worst-case behaviours are seen unless the worst-case scenario is known

Empirical methods: pros and cons

- **Case Studies**
  - One or more example task sets taken from industry
  - Typically the case study provides specific parameter values, or they may be obtained from the code

  Advantages
  - The parameter values used are realistic
  - Detailed information available via analysis of code

  Disadvantages
  - Is the case study representative?
  - Limited coverage of the parameter space (e.g. one task set) may hide issues elsewhere

INVENTORS FOR THE DIGITAL WORLD

Empirical methods: pros and cons

- **Empirical evaluation**
  - Generate large numbers of task sets with parameters chosen in an appropriate way
  - Evaluate schedulability test performance on these task sets

  Advantages

  - Can provide good coverage of the parameter space
  - Can provide a fair (unbiased) comparison, but care is needed to achieve this

  Disadvantages

  - Are the parameter values covered representative of real systems?
  - What about overheads?

Sporadic task model: as an example

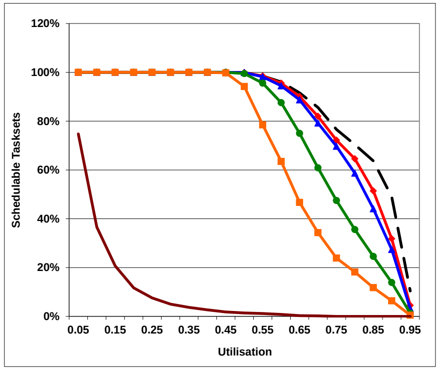
- **Sporadic task model**
  - Static set of *n* tasks τ_i with priorities 1..*n*
  - Bounded worst-case execution time C_i
  - Sporadic/periodic arrivals: minimum inter-arrival time T_i
  - Relative deadline D_i
  - Utilisation $U_i = C_i / T_i$
  - Independent execution (no resource sharing)
  - Independent arrivals (unknown a priori)
- **Processors**
  - *m* processors (multiprocessor)
  - $m = 1$ (uniprocessor)

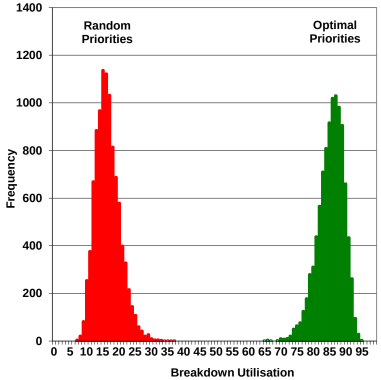
INVENTORS FOR THE DIGITAL WORLD

Empirical evaluation

- **Basic approach**
  - Generate large numbers of task sets with parameters chosen in an appropriate way
  - Determine the performance of different schedulability tests on these task sets
  - Plot graphs e.g. success ratio, weighted schedulability, frequency distributions etc. to illustrating performance

There are a number of key aspects to this





Empirical evaluation: key aspects

- **Systematic approach**
  - Ensure adequate coverage of full range of realistic parameter setting (i.e. avoid *cherry-picking*)
- **Avoid bias and confounding variables**
  - Examples: unintended bias in distributions of execution times, periods etc.
  - Some methods can confound variables, correlating them
- **Statistical confidence**
  - How might the results have changed with a different random seed
- **Standardisation of methods**
  - Enables direct comparison between results in different research papers (transitivity), aids reproducibility etc.

INVENTORS FOR THE DIGITAL WORLD

Empirical evaluation

- **Aim**
  - Generate a large number of task sets with different parameter settings that cover in an unbiased way, the range of possible task sets that could occur in practice
- **Basic framework**
  - Baseline approach to task set generation
  - Extensible as further parameters are needed

Task set generation: a systematic approach

- **Primary inputs**
  - Task set cardinality *n*, and Utilisation *U*
- **Utilisation**
  - Given *n* and *U* for the task set generate a set of *n* unbiased utilisation values for the tasks that add up to *U*

  Uunifast – for single processor systems

  Uunifast-discard – for multiprocessor (n > 2m)

  RandFixedSum – for multiprocessor

- **Avoids bias and confounding variables**

  Iteratively creating task sets by adding a task to a previous task set confounds (correlates) utilisation and the number of tasks, making it difficult to see the influence of these individual factors on schedulability

Task set generation: Uunifast

- **What does it do**
  - Utilisation values produced have the same distribution as obtained by choosing sets of *n* values at random from a uniform distribution [0,*U*] and then only taking those sets that sum to *U*

- **Code**

```
UUnifast(n,Ut)
{
   SumU = Ut;
   for (i = 1 to n-1)
   {
      nextSumU = SumU * pow(rand(), 1/(n-i));
      U[i] = SumU - nextSumU;
      sumU = nextSumU;
   }
   U[n] = SumU;
}
```

Task set generation: Uunifast-discard

- **Problem with Uunifast**
  - For U > 1 Uunifast can generate utilisation values >1 which are invalid for individual tasks

- **What does Uunifast-discard do**
  - Simply throws away task sets with invalid tasks, proven to produce an unbiased uniform distribution of utilisation values
  - Works well for $n > 2m$, but too many discards (invalid tasks) for smaller n
  - For n closer to m need to use a more general method provided by **Randfixedsum**

Task set generation: Randfixedsum

- **What does Randfixedsum do**
  - General algorithm derived by Roger Stafford for creating vectors uniformly distributed in an n-1 dimensional space whose components sum to a constant value
  - Can be used to generate utilisation values for multiprocessor task sets
  - Efficient since no random values need to be excluded
  - Open source MatLab implementation available

Task set generation: Task Periods

- **Periods can be selected from some distribution**
  - Which distribution(s) should we use?
  - Limit periods to a range between a min and max value

- **Uniform?**
  - Using a uniform distribution has some issues
  - Want to be able to vary range of task periods, since this is an important parameter w.r.t. non-preemptive scheduling and complexity of some schedulability tests
  - With a period range of [10, 1,000,000] then roughly 99% of periods are in [10,000, 1,000,000] i.e. 2 orders of magnitude when we expected 5
  - Uniform distribution **not** effective in showing differences due to range of periods

Task set generation: Task Periods

- **Log-Uniform?**
  - Random selection from a log-uniform distribution: random pick from a uniform distribution between the logs of the min and max periods and then raise the base of the log to the power of the value chosen to obtain the period
  - Expected number of tasks in any order of magnitude range is the same e.g. [10,100], [100,1000] etc.
  - Avoids previous issues with uniform distribution

  - Note Fixed Priority scheduling is more effective when there is a larger spread of periods, hence FP is more effective with Log-Uniform than with Uniform distributions with the same period range

Task set generation: Task Periods

- **Harmonics**
  - Task periods in real systems tend to be chosen from a set (or sets) of harmonic values
  - This can be simulated using the **bag of primes** method
- **Bag of primes method**
  - A set of small prime numbers (with some repeats) are chosen as a basis (e.g. 2,2,2,2,3,3,3,5,5...) and placed in the bag
  - A number of values are then selected at random from the bag without replacement
  - The product of the values chosen gives the task period
  - The LCM of task periods is limited to the LCM of all values in the bag

Task set generation: Task Periods

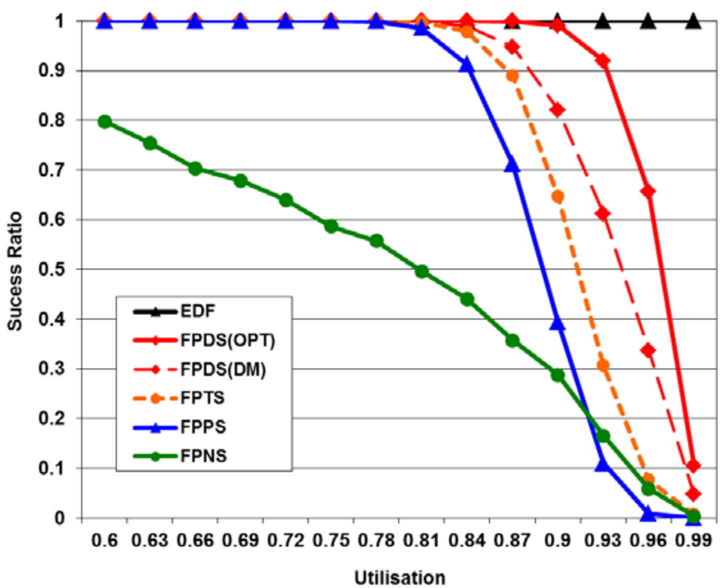
- **Harmonics – alternative method**
  - Simply specify a set of possible values, for example as may be used in automotive systems (5,10,20,50,100, 250, 1000ms)
  - Chose values at random from the list
  - Again the hyperperiod is limited to the LCM of the values specified
- **Notes**
  - Since harmonic and non-harmonic periods can differently impact schedulability (e.g. FP has a utilisation bound of 1 for harmonic task sets, and 0.69 for non-harmonic) best practice would be to repeat expts with both distributions

Task set generation: Task Deadlines

- **Deadlines**
  - Implicit deadlines equal to period
  - Constrained deadlines
    - Chosen at random between C and T
    - Varied in lock step as a proportion of period

Evaluation Framework: Baseline

- **Baseline settings**
  - Determine realistic settings as defaults for parameter values and vary utilisation
- **Success ratio plots**



  - Typically need about 1000 task sets per utilisation level

Evaluation Framework: Weighted schedulability

- **Varying parameters**
  - Need to vary parameters to cover a wide range of possible parameter values
  - Important to do this as some schedulability tests / algorithms may be sensitive to a particular parameter e.g. range of task periods, number of tasks, etc.
  - Typically not possible to cover the whole parameter space via simple success ratio plots – too many combinations (1000s of plots)
  - Can vary one parameter while holding others constant at default values
  - Use weighted schedulability plots to illustrate variation w.r.t. each parameter

Evaluation Framework: Weighted schedulability

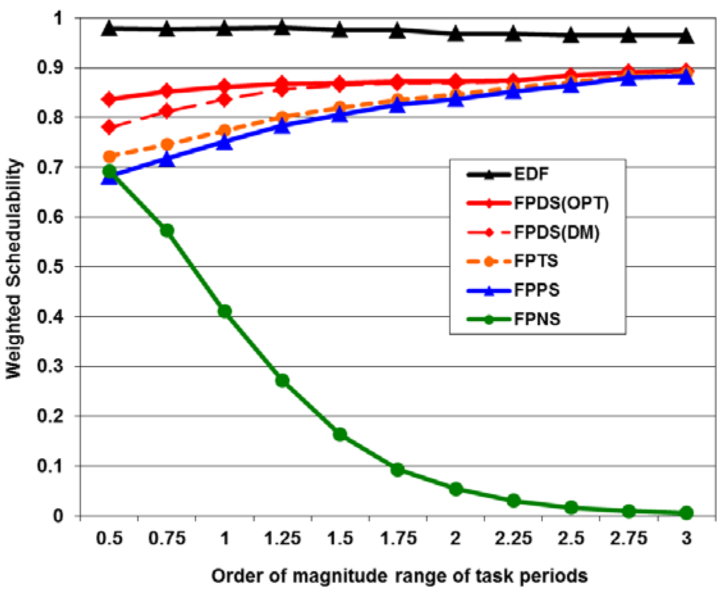
- **Weighted schedulability**
  - Combines results for all of the task sets generated for all of a set of equally spaced utilisation levels (i.e. from a line on a success ratio plot)

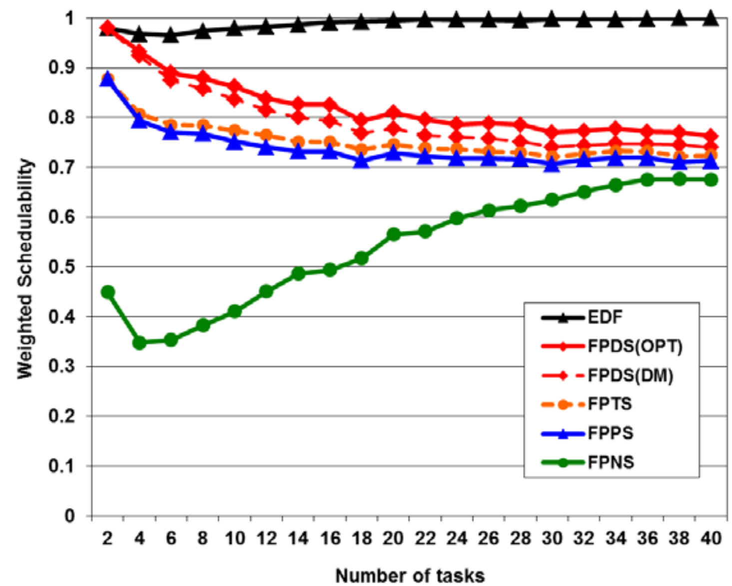
$$Z_y(p) = \sum_{\forall \tau} \frac{S_y(\tau).U(\tau)}{U(\tau)}$$

  - Effectively the area under the success ratio curve but weighted by utilisation – gives more emphasis to scheduling high utilisation task sets
  - Reduces multiple success ratio plots to a single weighted schedulability graph

Evaluation Framework: Weighted schedulability

- **Examples of weighted schedulability graphs**

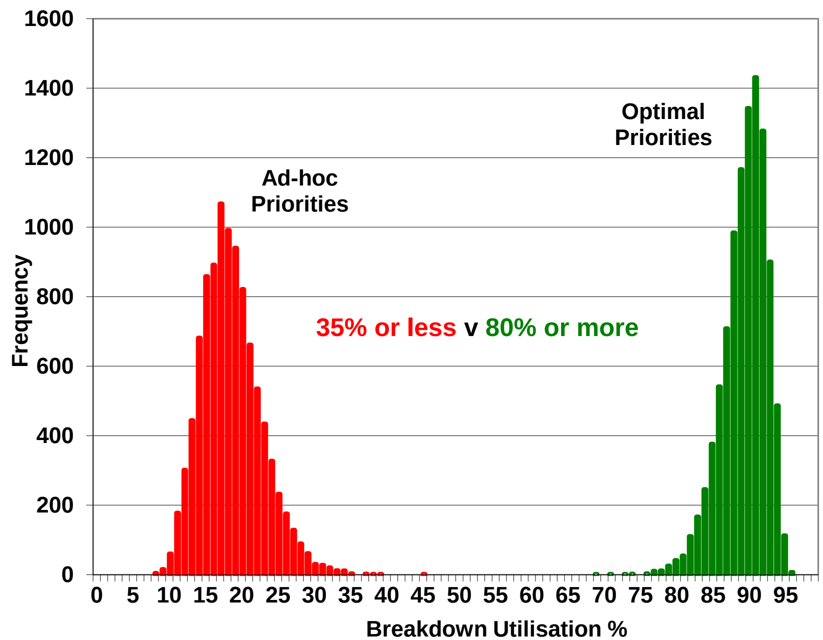




- Typically need about 100 task sets per utilisation level, since there are usually at least 10 utilisation levels that make up each data point

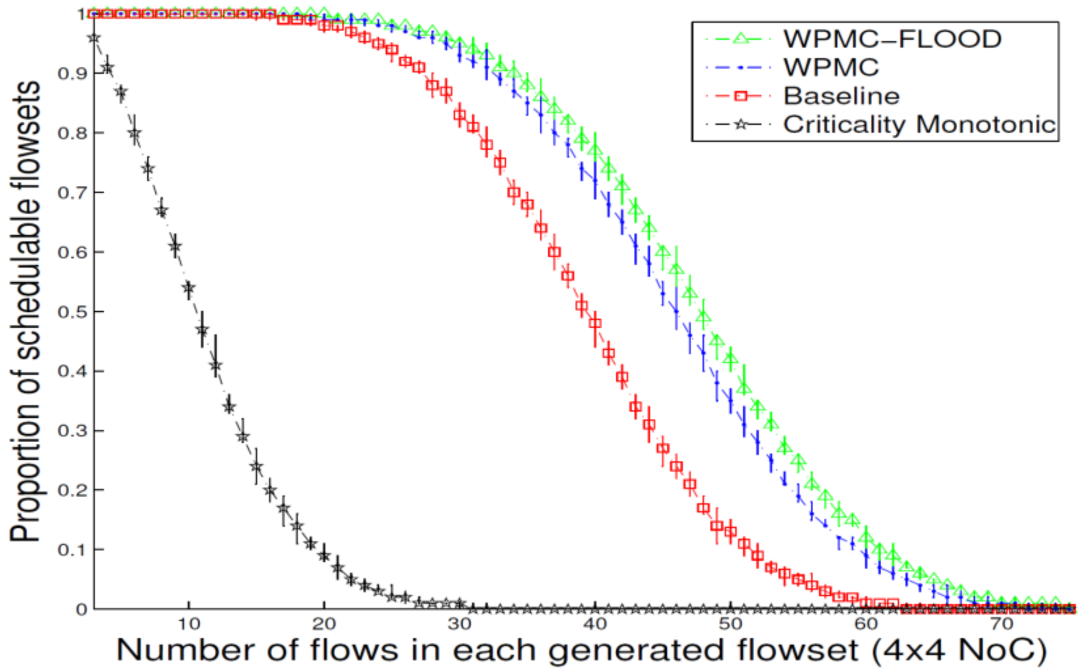
Evaluation Framework: Frequency distributions

- **Frequency distribution of breakdown utilisation**



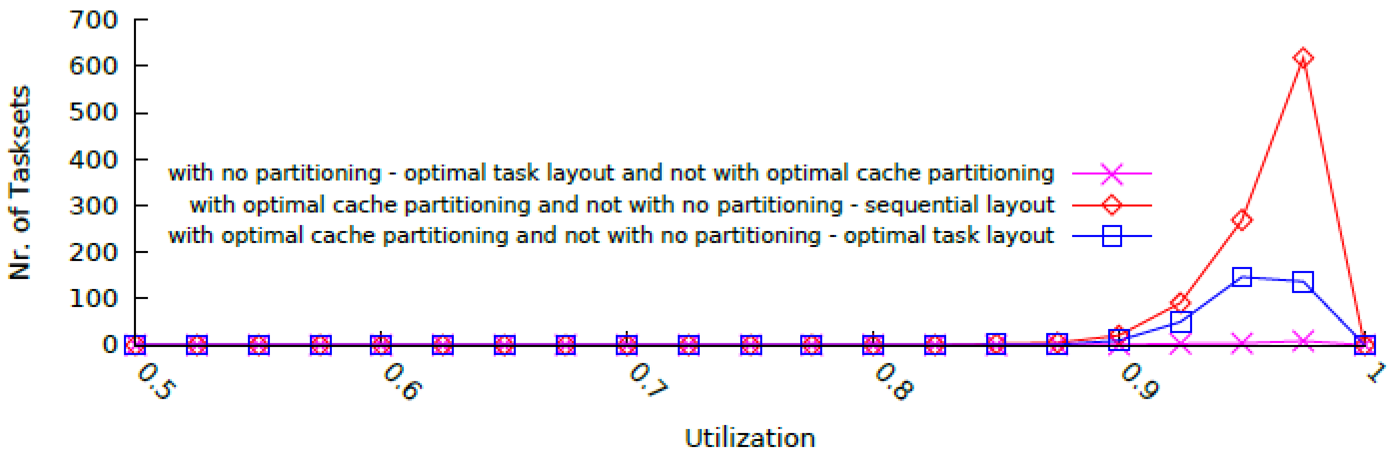
Evaluation Framework: Confidence intervals

- **How confident are we the picture wouldn't change if we run the experiment again with a different random seed?**
  - Multiple runs to show percentiles for each data point



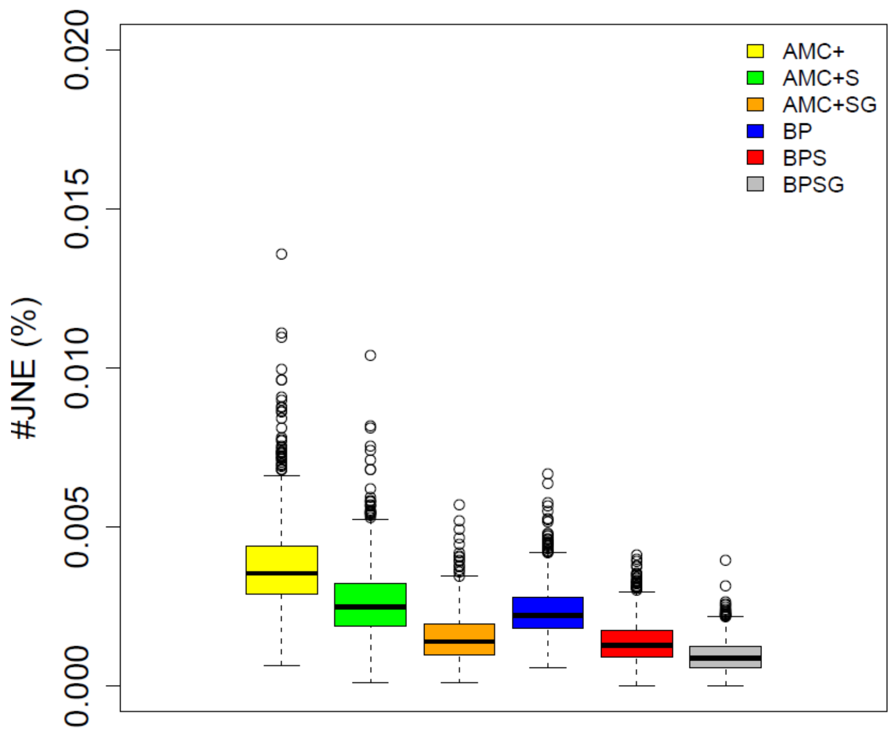
Evaluation Framework: Difference measures

- **One line being above another does not imply dominance**
  - Can plot number of task sets schedulable with test A but not with test B and vice-versa to show *incomparability*



Evaluation Framework: Variability: box and whisker plots

- **Schedulability is a binary result (yes/no)**
  - Interesting to look at other metrics and consider their variability



Empirical evaluation: Task sets from case studies / benchmarks

- **Case studies / benchmarks:**
  - Typically provide a small number of tasks / task sets
  - Can provide other detailed information e.g. WCETs, memory accesses, UCBs, ECBs used in CRPD analysis etc.
  - However, large numbers of task sets are needed for evaluation purposes
- **Making task sets from benchmarks**
  - Random selection of tasks from (larger) benchmark set
  - Chose utilisation values using Uunifast etc.
  - Compute period = C/U (can therefore use real WCETs)

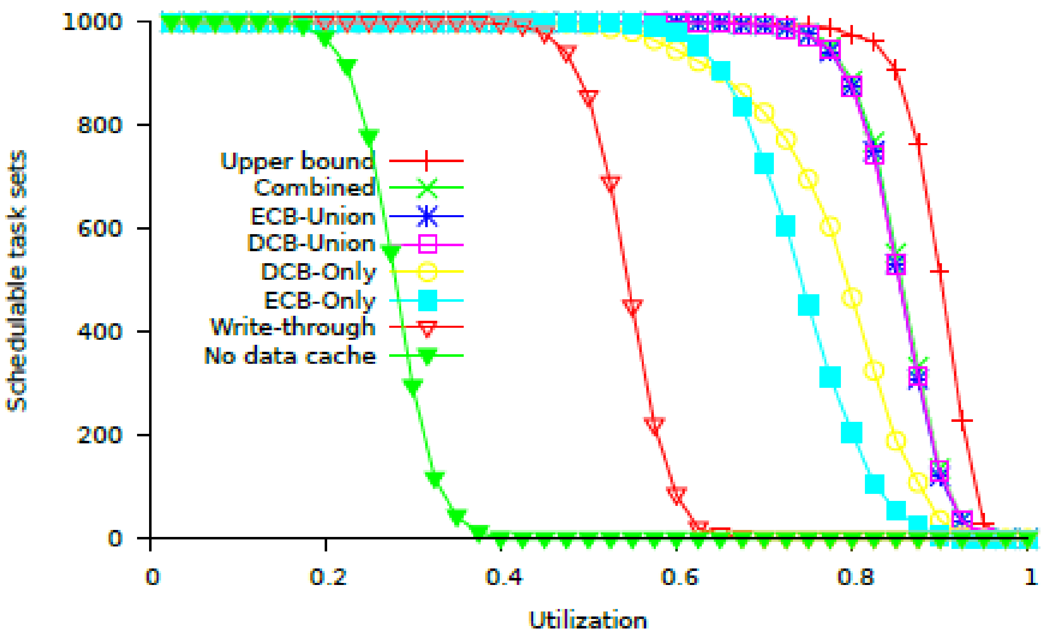
Empirical evaluation: Task sets from case studies / benchmarks

- **Advantages:**
  - More detailed and realistic information input into task set generation
  - Task parameters take on real values e.g. WCETs of actual code

- **Disadvantages**
  - All task sets generated share similarities since they are generated from the same limited set of benchmarks, so only representative of the input benchmarks
  - Period distribution correlates with WCET distribution
  - May need to exclude some benchmarks to control range of task periods (e.g. when investigating non-preemptive algorithms)

Empirical evaluation: Task sets from case studies / benchmarks

- **Example with task set generation using data from Malardalen benchmarks**



Empirical evaluation: Recap

- **Empirical evaluation**
  - Investigates schedulability test / scheduling algorithm performance w.r.t. large number of synthetically generated task sets

- **Evaluation framework:**
  - Baseline results using success ratio plots (from realistic default values)
  - Weighted schedulability results varying each relevant parameter over a broad range, keeping other parameters constant at default values
  - Consider statistical confidence in results
  - Use other metrics to illustrate specific properties

INVENTORS FOR THE DIGITAL WORLD

Empirical evaluation: A suggestion

- **A de-facto standard: If we all used the same framework for evaluation this would:**
  - Make it easier to review / assess different work
  - Make reproducing results easier
  - Facilitate direct comparison between results in different papers
  - Provide a set of expts we expect to see in papers

  - Would need to agree on the set of experiments expected, and some de-facto standard details such as defaults, parameter ranges etc.

Open discussion

- **More complex task models needed**
  - Presentation deliberately restricted to a simple task model
  - Many other attributes need to be modelled
  - Interaction / communication between tasks
  - Multiprocessor – cross core contention – memory demand and processor demand

INVENTORS FOR THE DIGITAL WORLD

Open discussion

- **Few real benchmarks available to build upon**
  - Use of synthetic task sets v. case studies, both have their pros and cons
  - Useful to build task sets from benchmarks - some caveats in doing so

Open discussion

- **Is some form of standard framework useful?**
  - Use the same task set generators?

Open discussion

- **Can we improve how we evaluate schedulability tests for real-time scheduling algorithms?**

Questions?