In Search of Butterflies: Exceedance Analysis for Real-Time Systems under Transient Overload

M. Zini[1], F. Marković[2], D. Casini[1], A. Biondi[1], and B. Brandenburg[2]

[1]*Scuola Superiore Sant'Anna, Pisa, Italy*

[2]*Max Planck Institute for Software Systems, Kaiserslautern, Germany*

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MAX PLANCK INSTITUTE FOR SOFTWARE SYSTEMS

WCET

- The theoretical analysis of real-time systems often relies on the concept of **worst-case execution time** (WCET).

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WCET can be found with:

Analytical methods

Empirical methods

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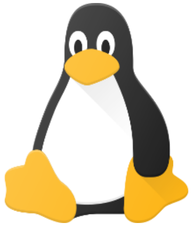
PROBLEM

High complexity of modern hardware and software stacks.

Linux-based solutions in critical systems:

- Unmanned aerial vehicles
- Autonomous driving (e.g., Tesla)
- Spacecrafts (e.g., SpaceX)



Experimental Methods

Empirical methods

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WCET is estimated with an experimental approach

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Empirical methods

In practice, we are not dealing with a **worst-case execution time**, but rather with a

Nominal execution time (NET)

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Nominal execution time (NET)

NETs can be **exceeded at run-time** due to many factors:

- Unaccounted interference effects
- Intentionally under-provisioned systems
  - The WATERS 2017 challenge's task set is unschedulable with WCETs
  - E.g., NET = 99^{th} percentile of observed execution times
- …

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Nominal Execution Time (NET)

NETs cannot be trusted!

QUESTION

What happens if jobs **exceed** their NET at runtime?

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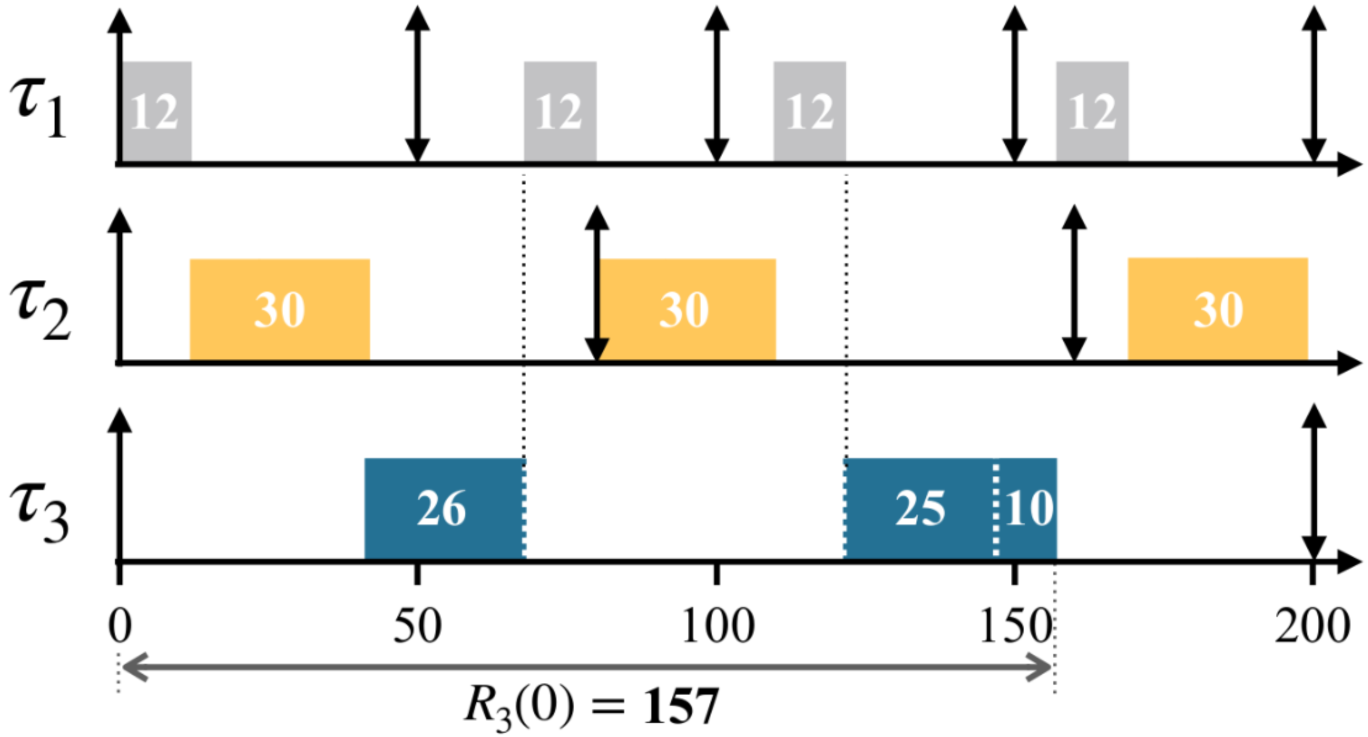
We refer to the extra execution time as **exceedance**

Motivating Example

For example, consider this simple limited-preemptive taskset:

Task	Period	NET
τ_1	50	<12>
τ_2	80	<30>
τ_3	200	<26,25,10>



Motivating Example

We **add 1 unit of exceedance** to the second job of task τ_1

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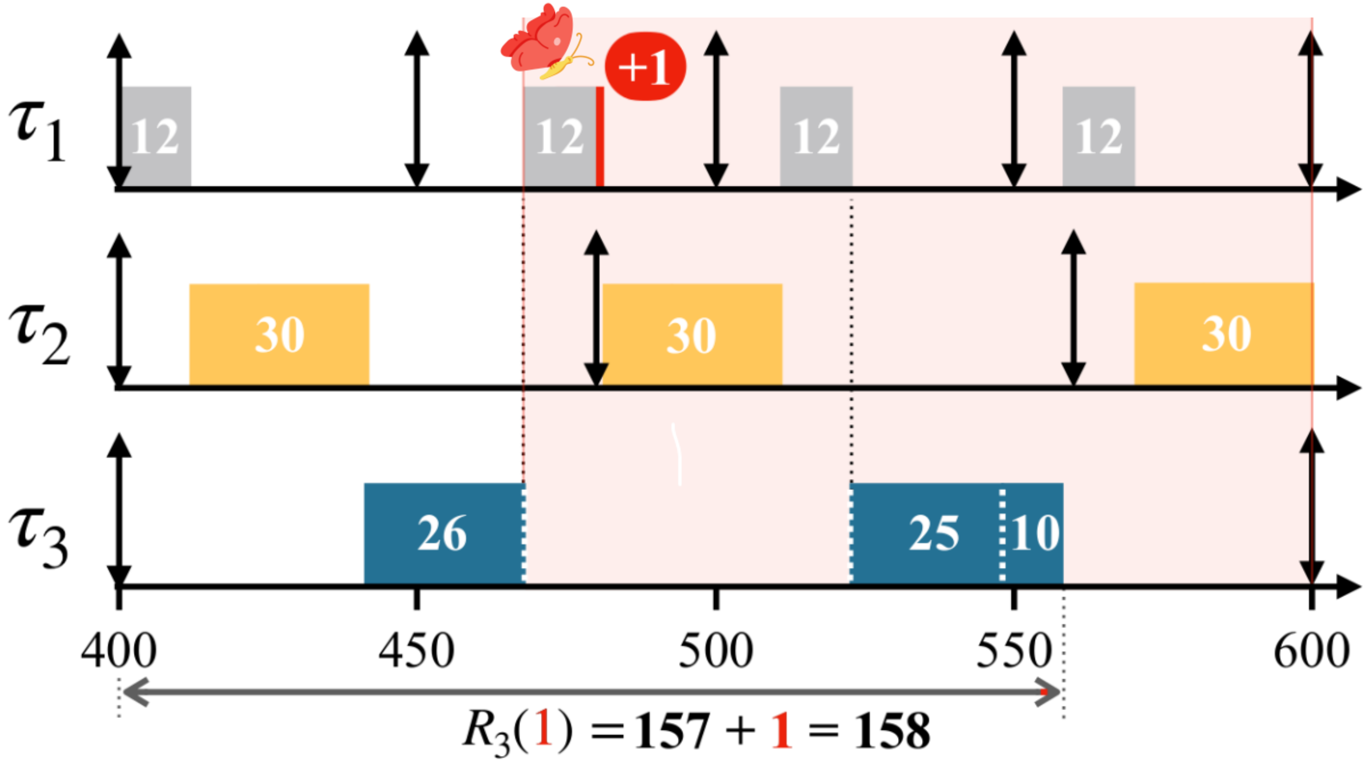

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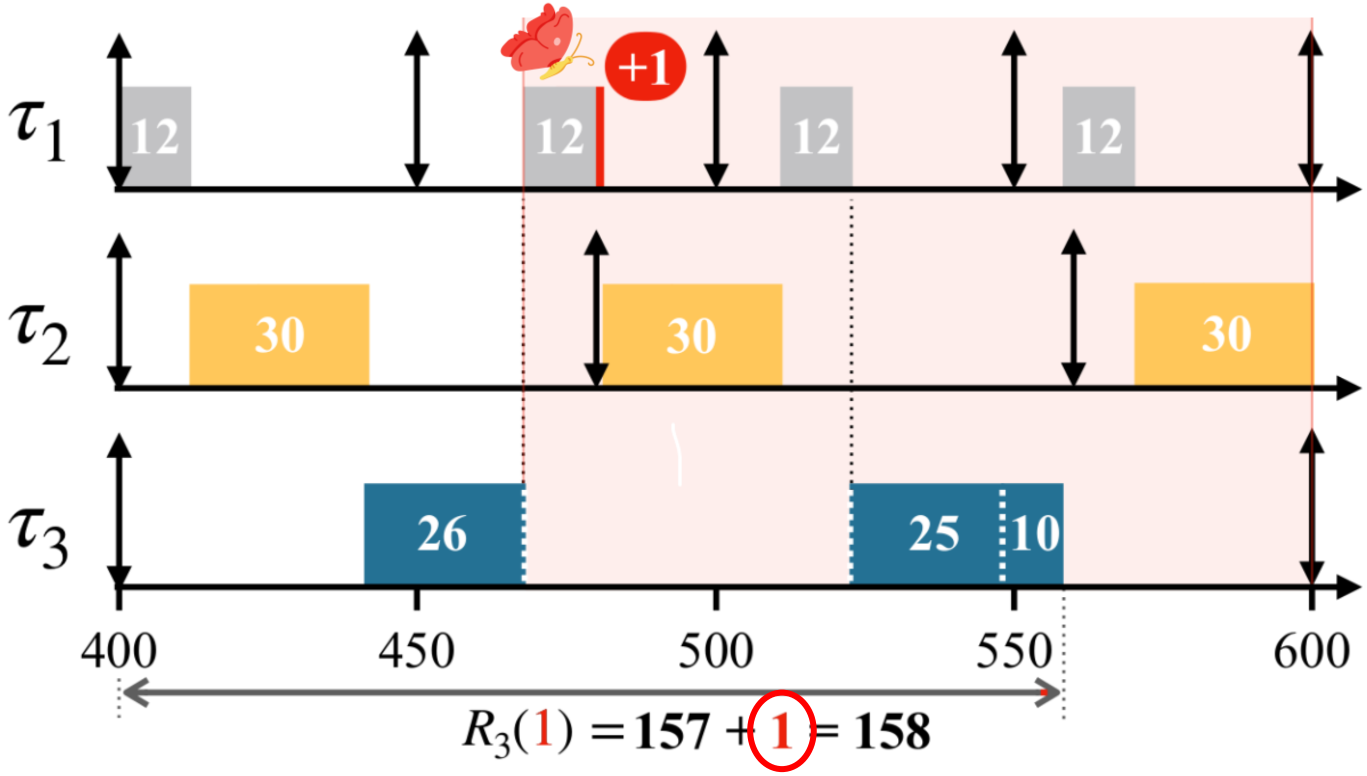

τ_3's response time increased by 1 time unit

Motivating Example

We add 1 unit of exceedance to the first job of task τ_2 and τ_3

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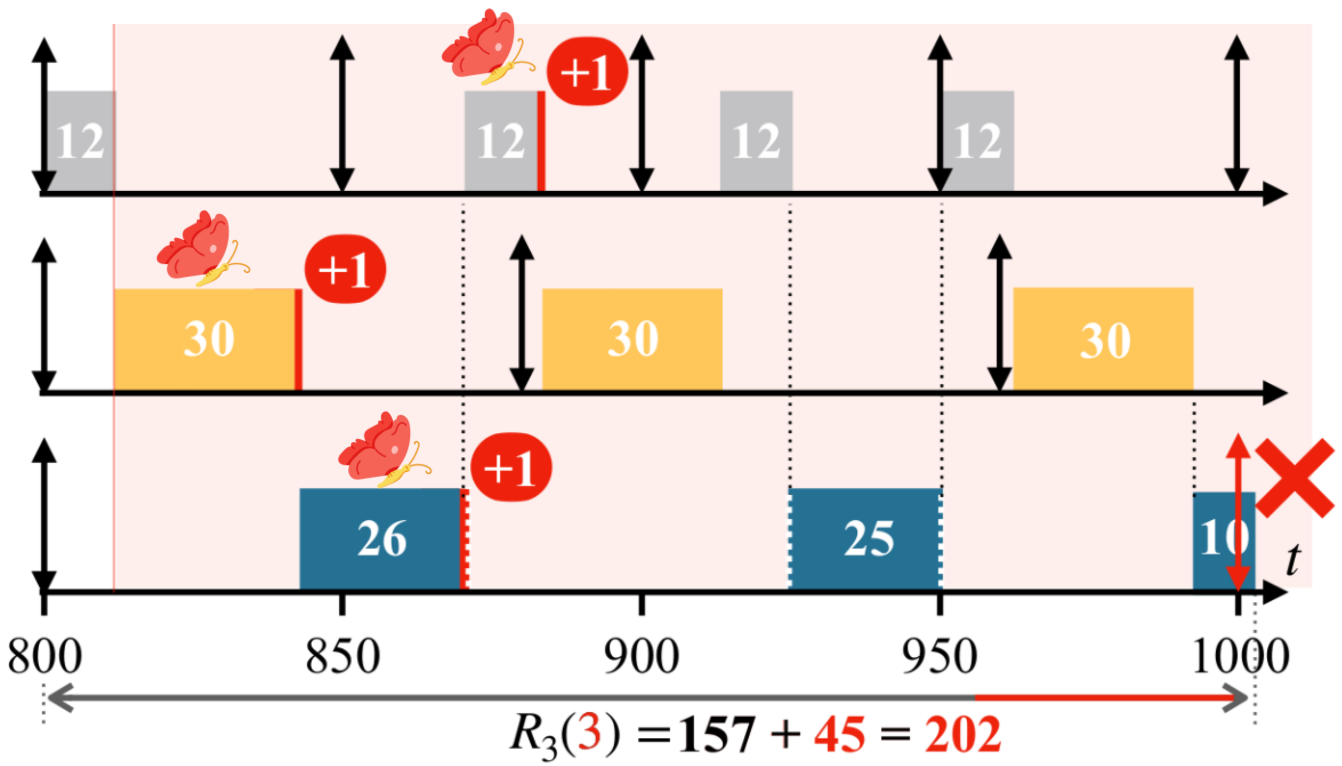

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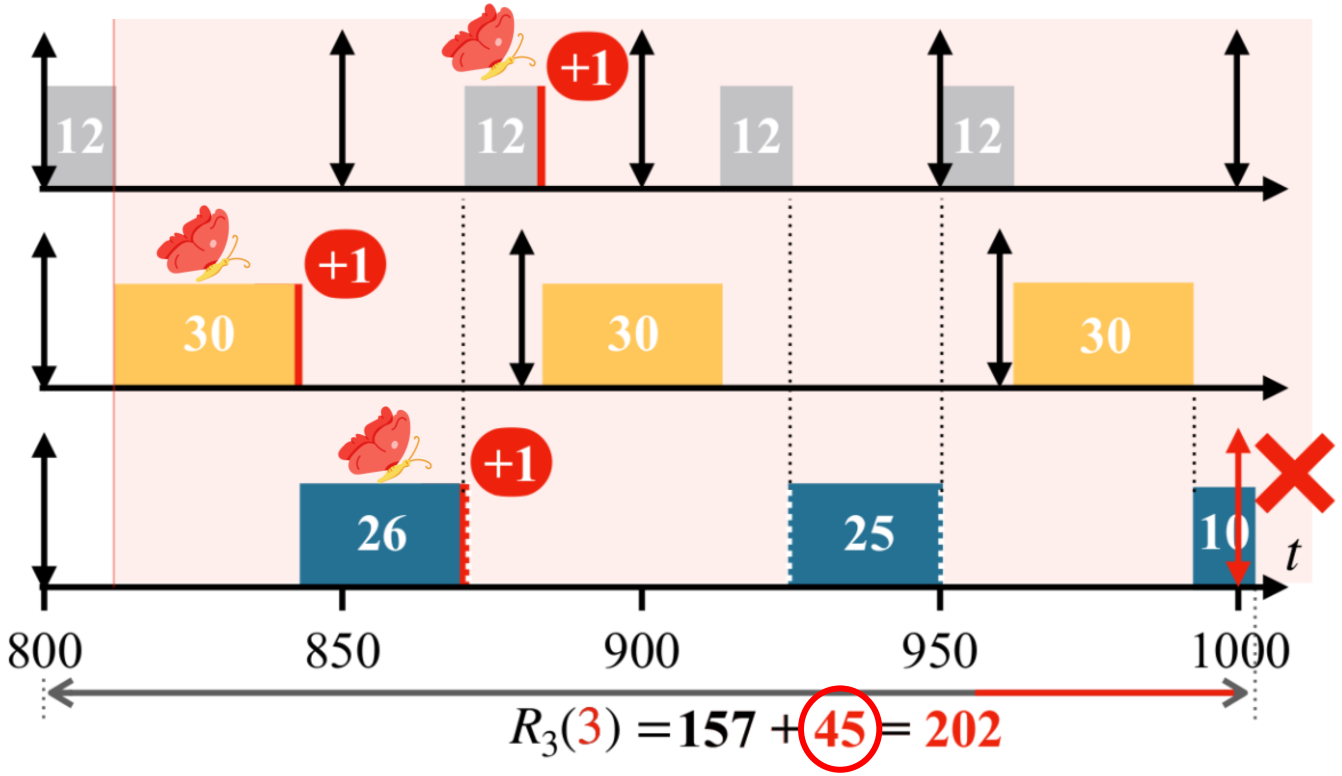

τ_3's response time increased by additional 43 time units!!!

Response-Time Nonlinearities

The consequences of **NET exceedance** are not easy to predict:

- NET + 1 ⟹ Response time + 1
- NET + 2 ⟹ Response time + 2
- NET + 3 ⟹ Response time **+ 45**
- …

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If we are neglect this phenomena, we might **over-estimate the system's temporal safety margin**

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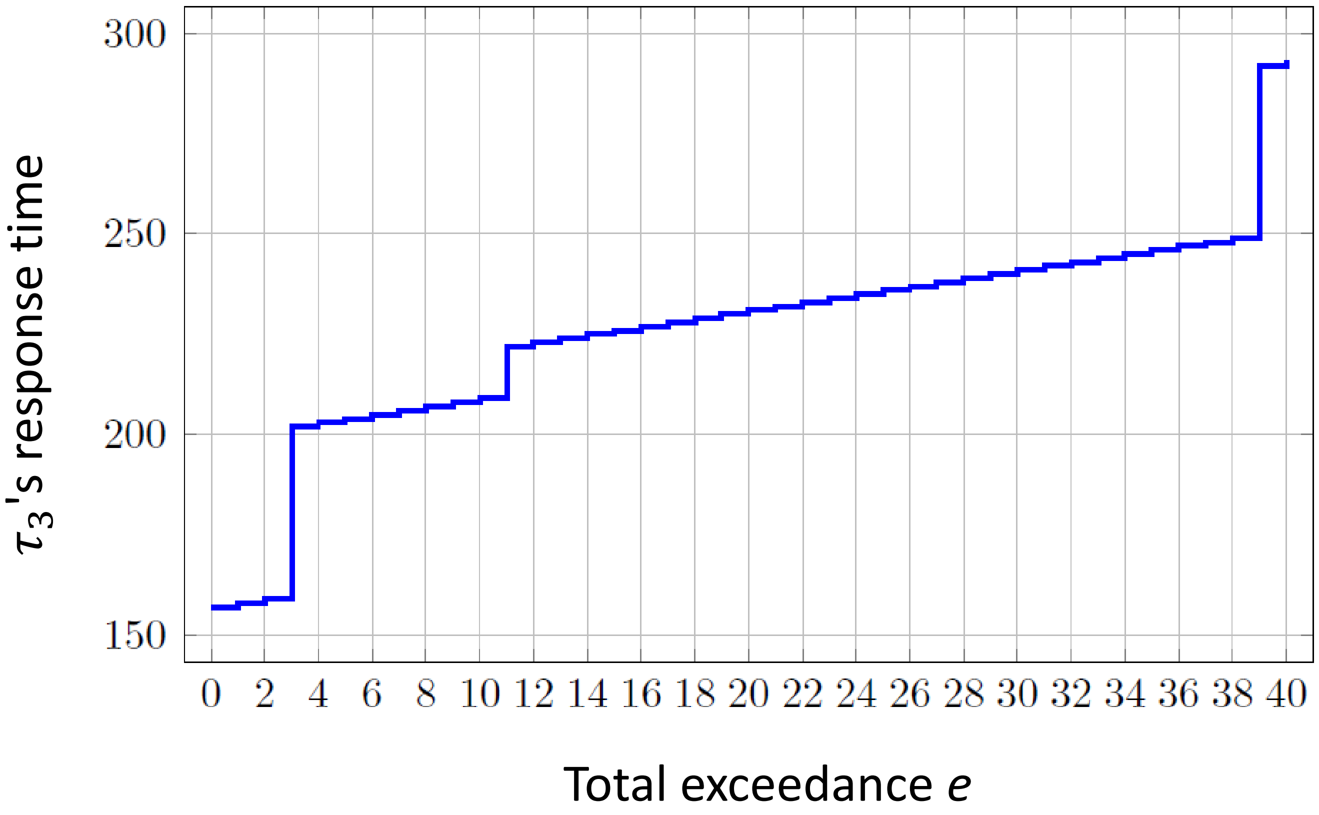

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We need a strategy to understand

how much the tasks can exceed the NETs

before generating a nonlinearity

Is It Sensitivity Analysis?

A similar problem has already been faced in literature with **sensitivity analysis**.

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Gives no information on nonlinearities before or after the deadlines

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Exceedance-Aware RTA

Our solution is based on the **abstract Response-Time Analysis** framework [1] by Bozhko et al.

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- Fixed priority
- EDF
- FIFO

- Fully preemptive
- Fully non-preemptive
- Segmented non-preemptive
- Floating non-preemptive

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Search for Nonlinearities

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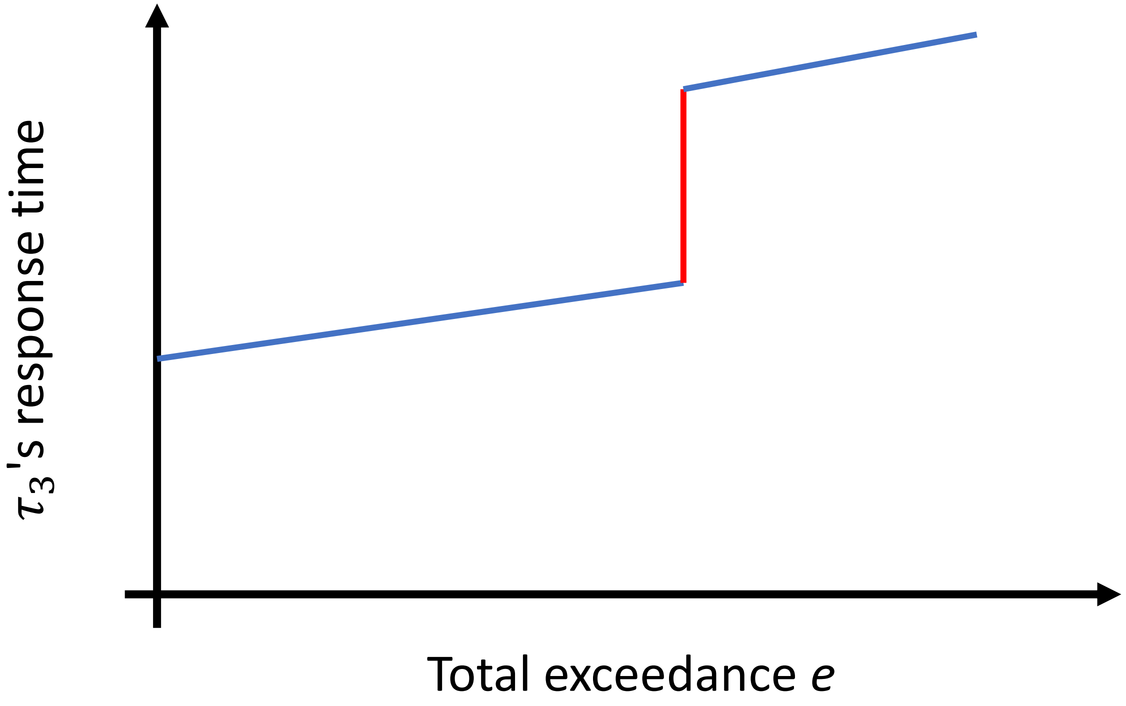
We developed an algorithm to **find such ”jumps”** efficiently

Search Algorithm

The search algorithm is based on:

1. An exponential search of the **nonlinearity interval**



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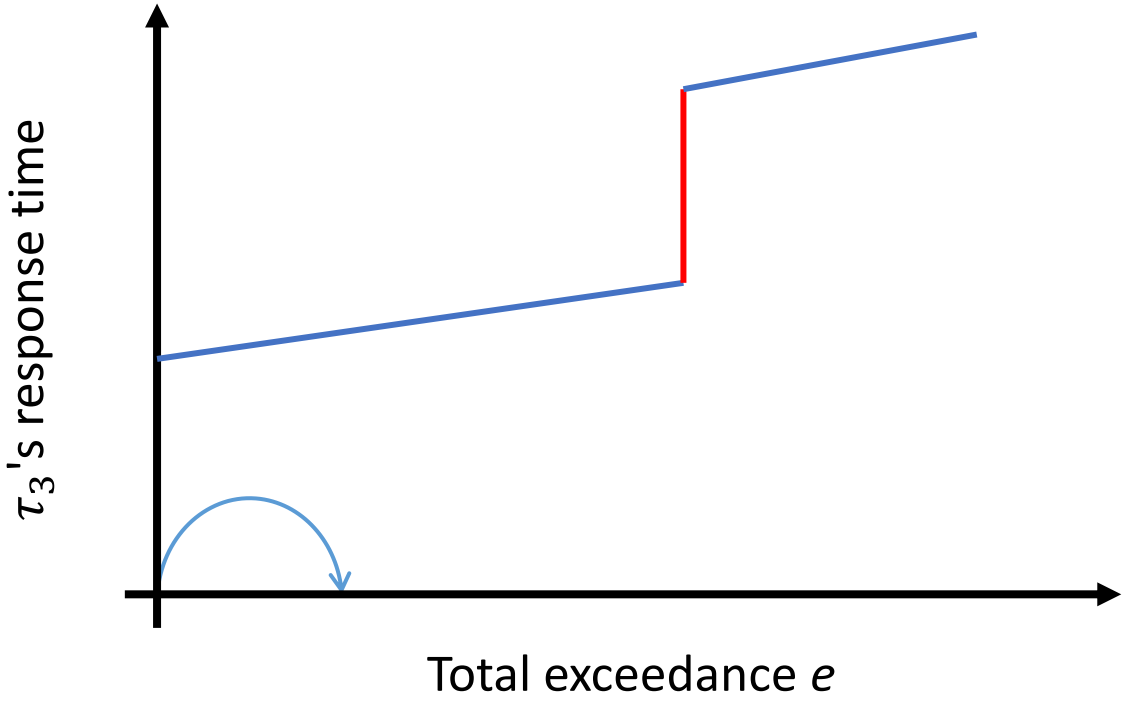

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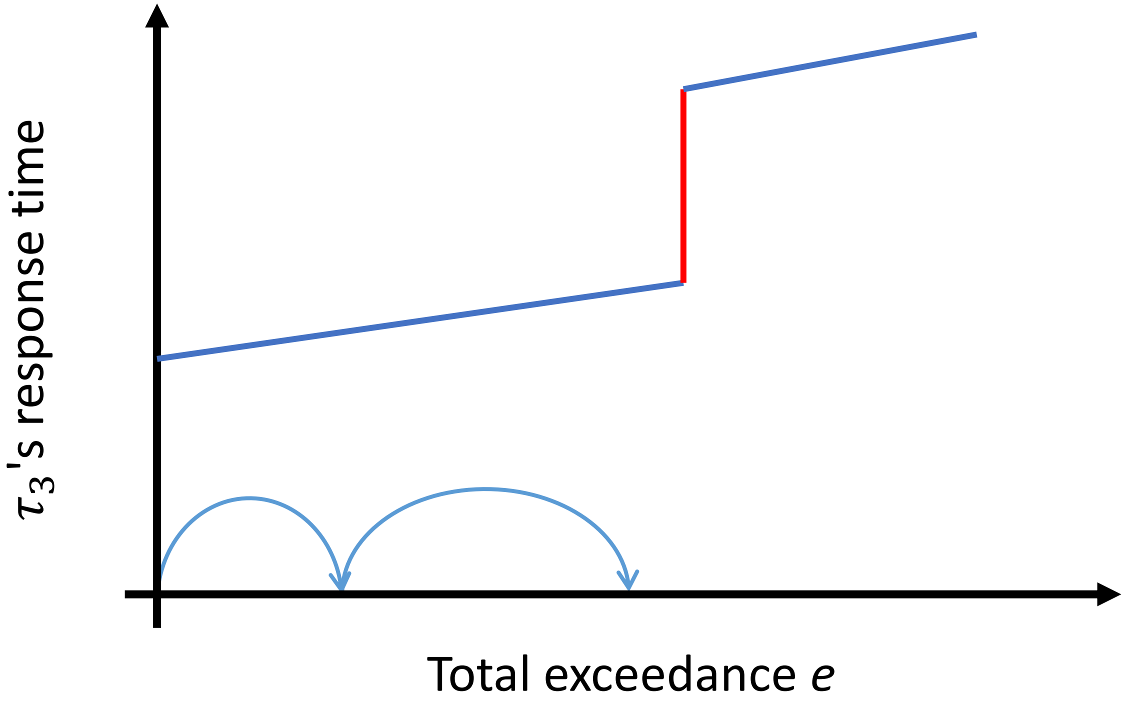

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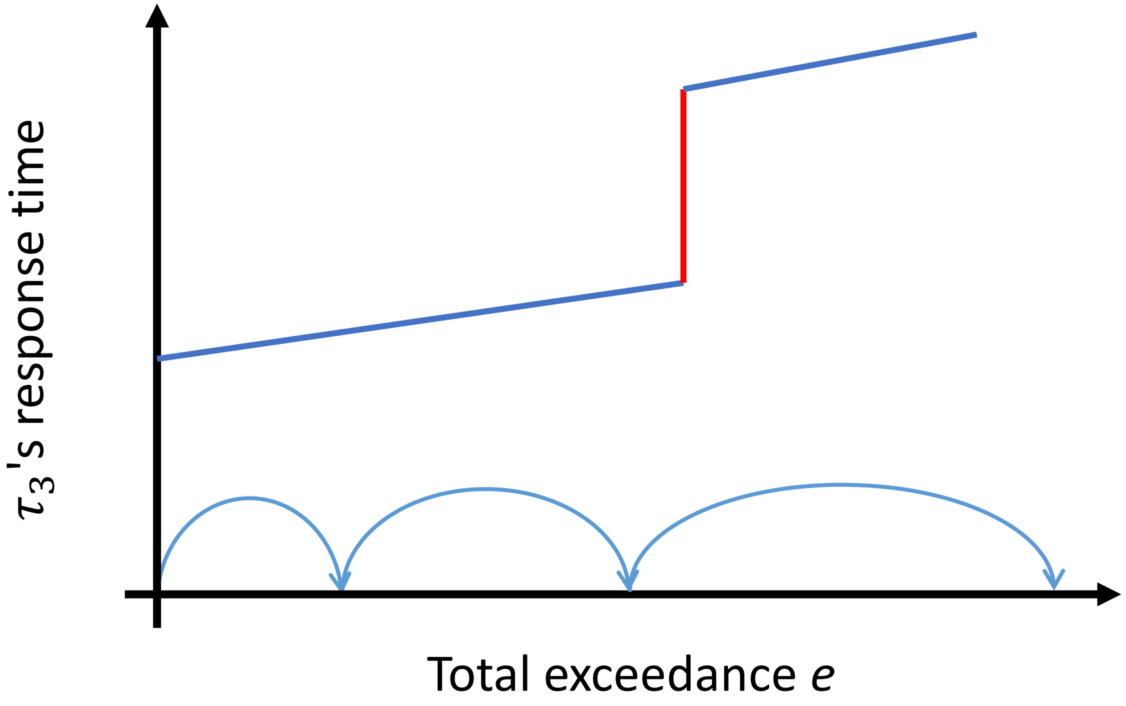

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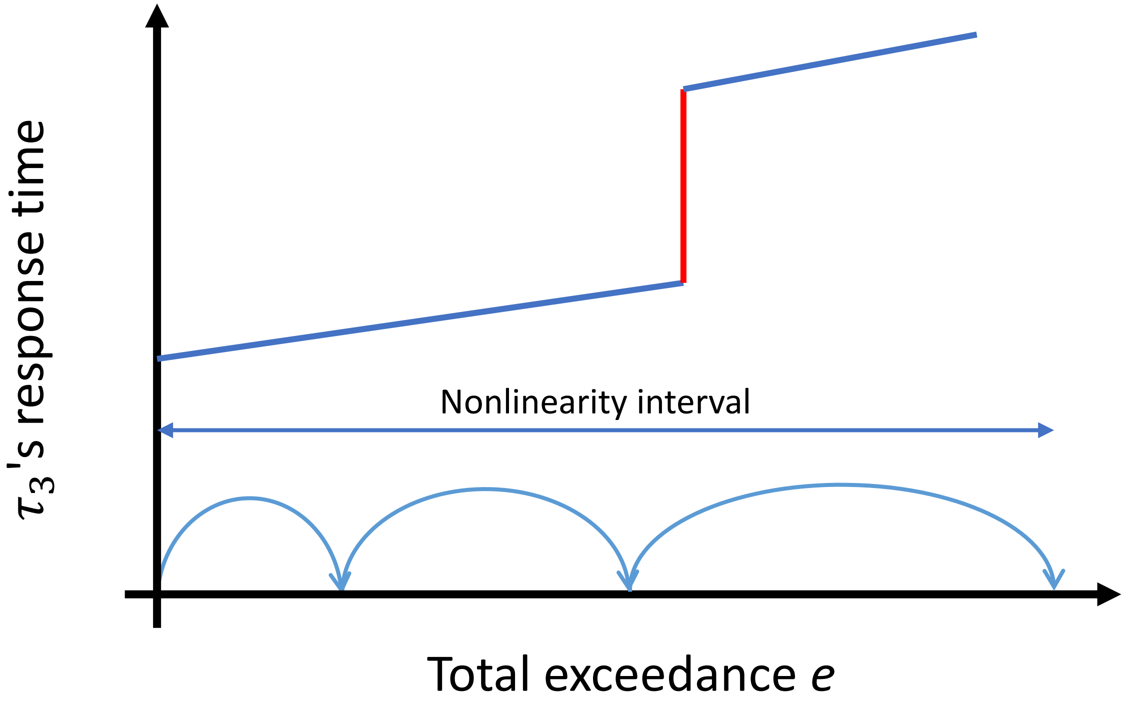

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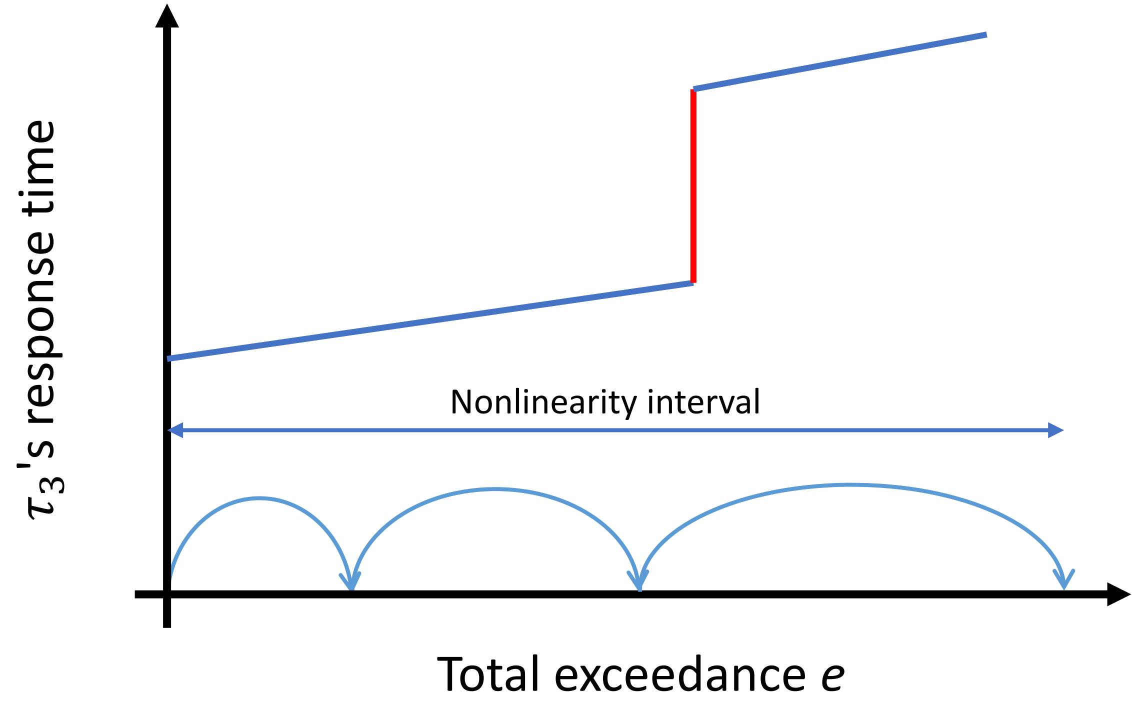

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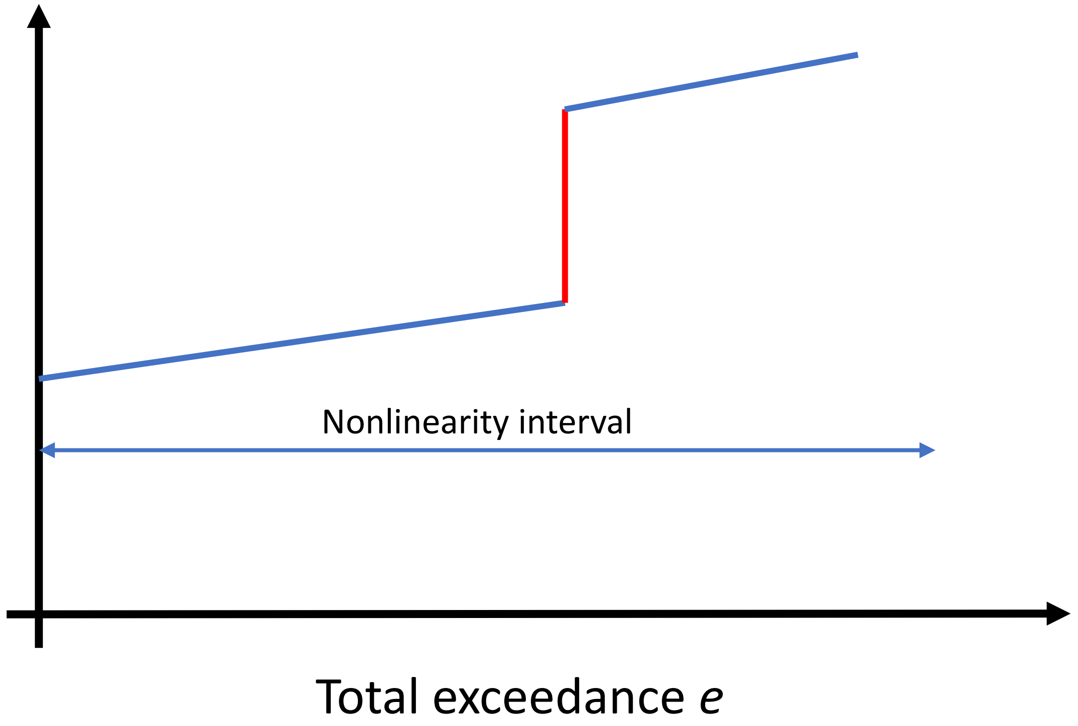

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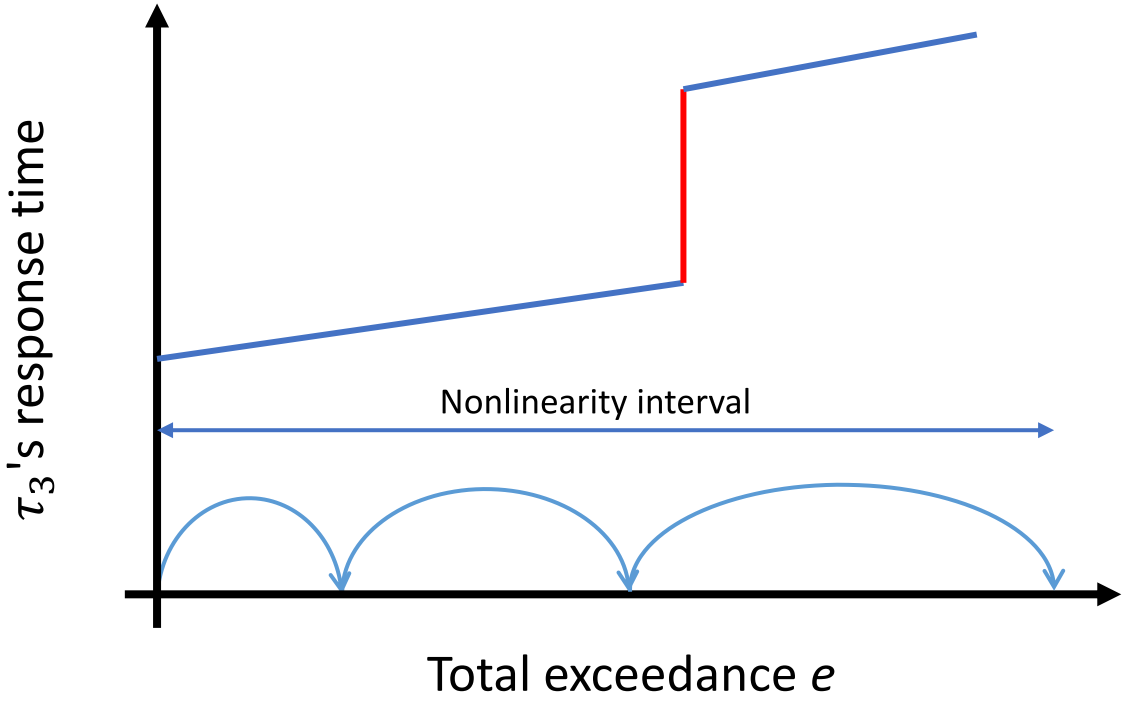

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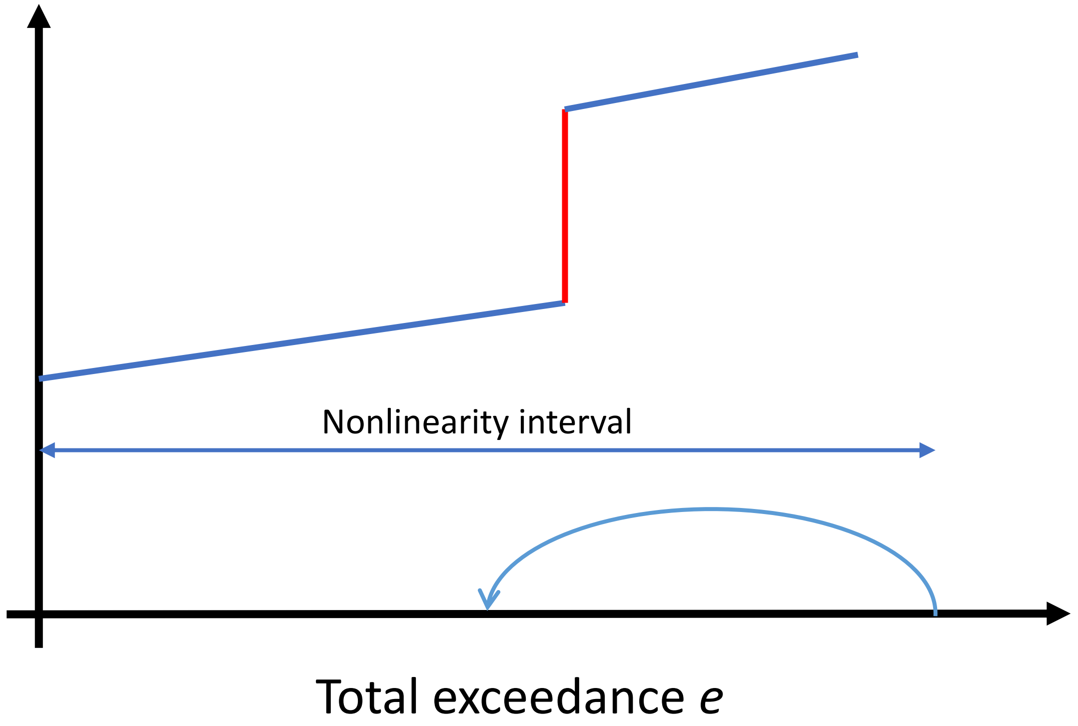

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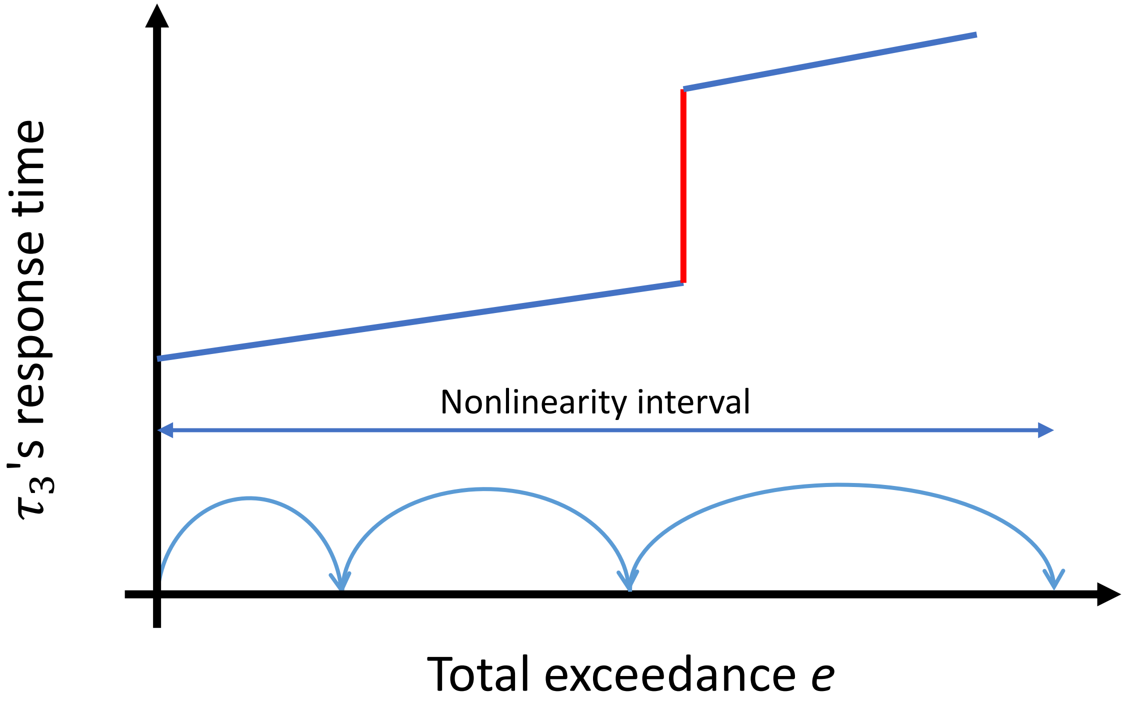

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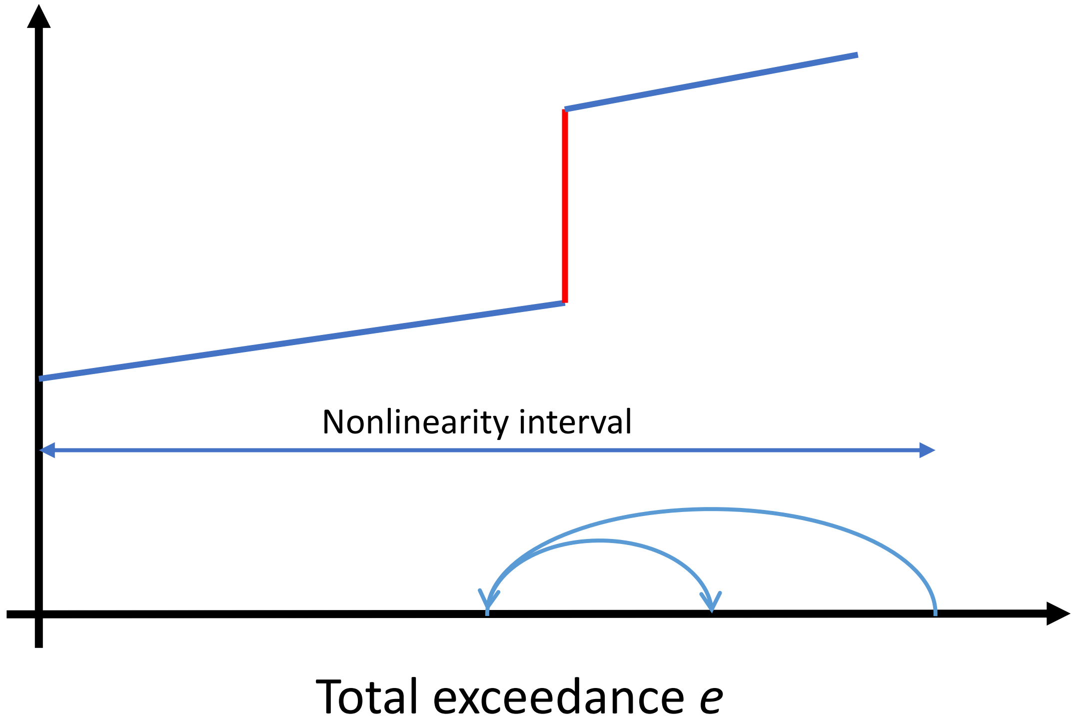

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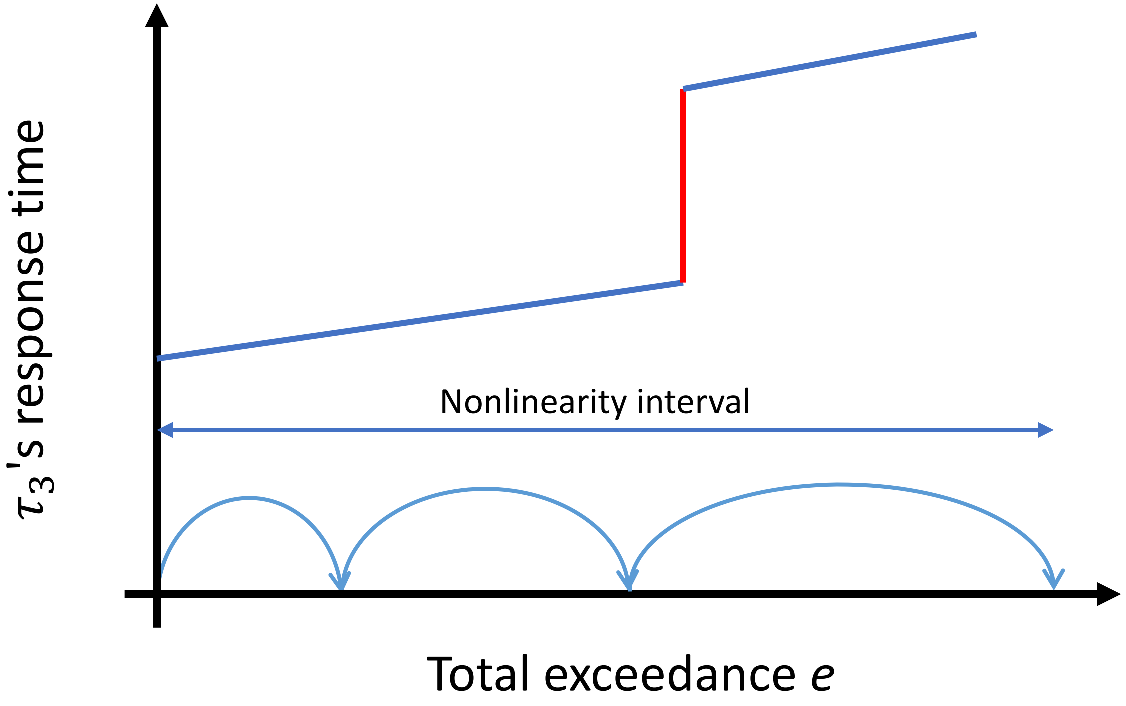

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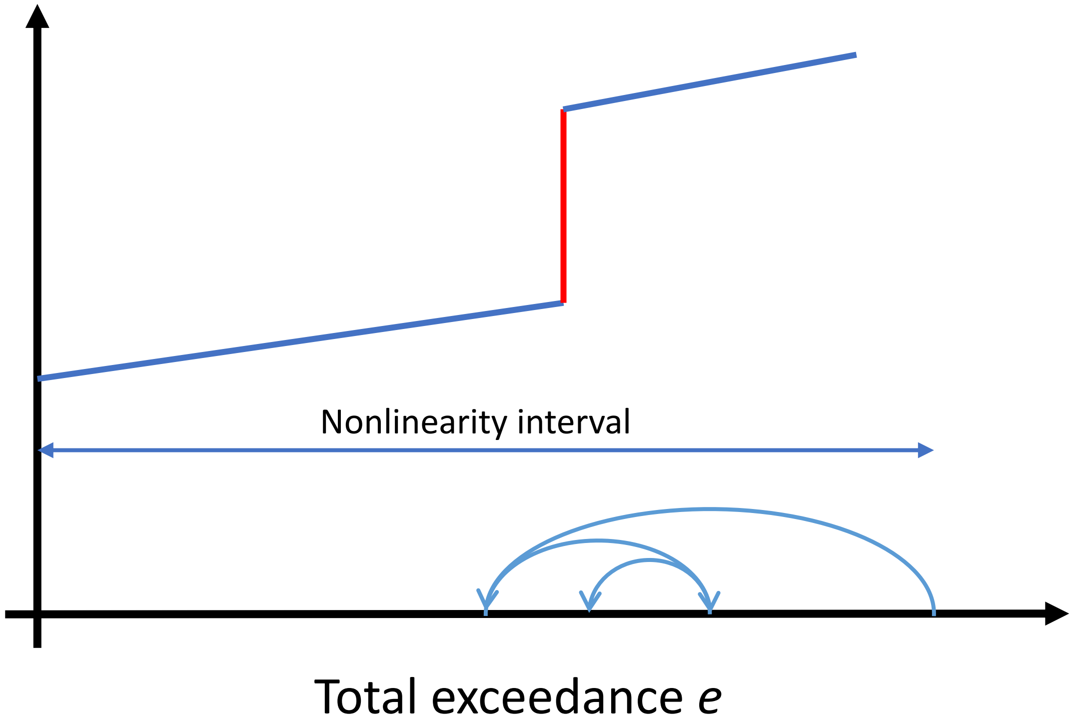

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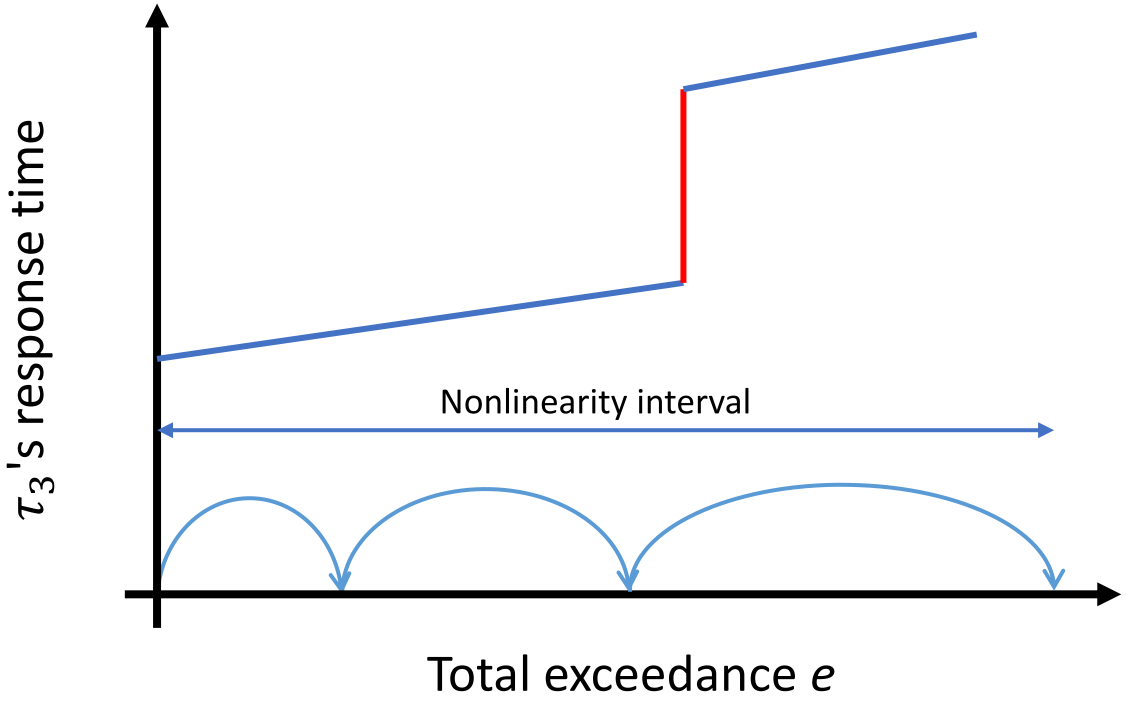

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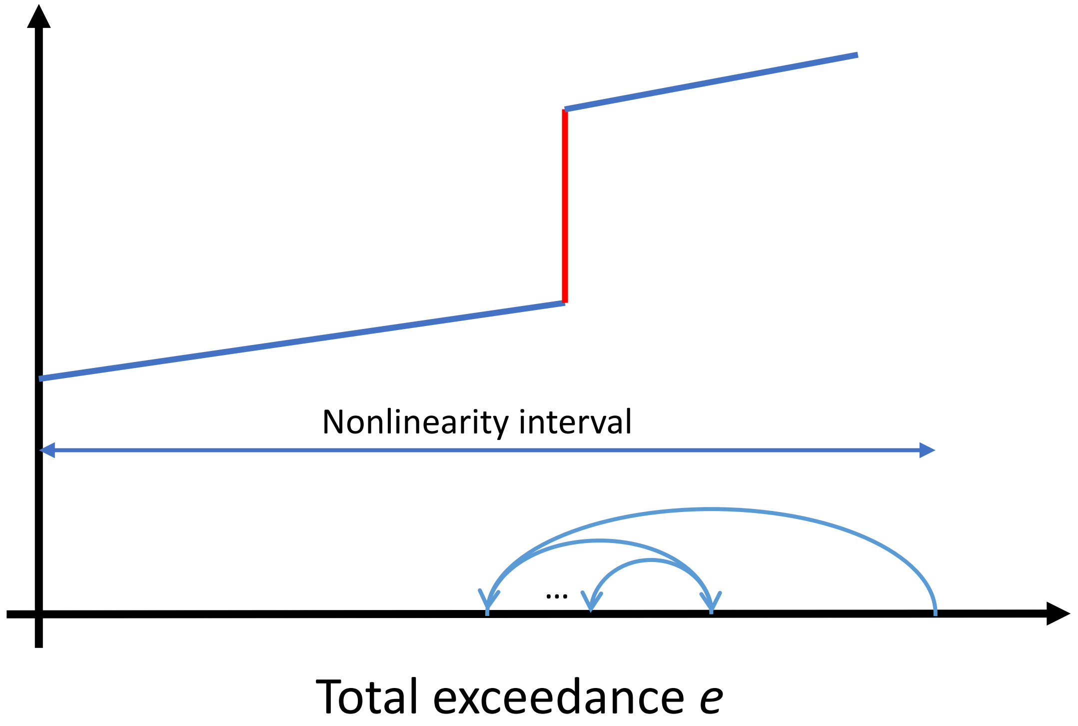

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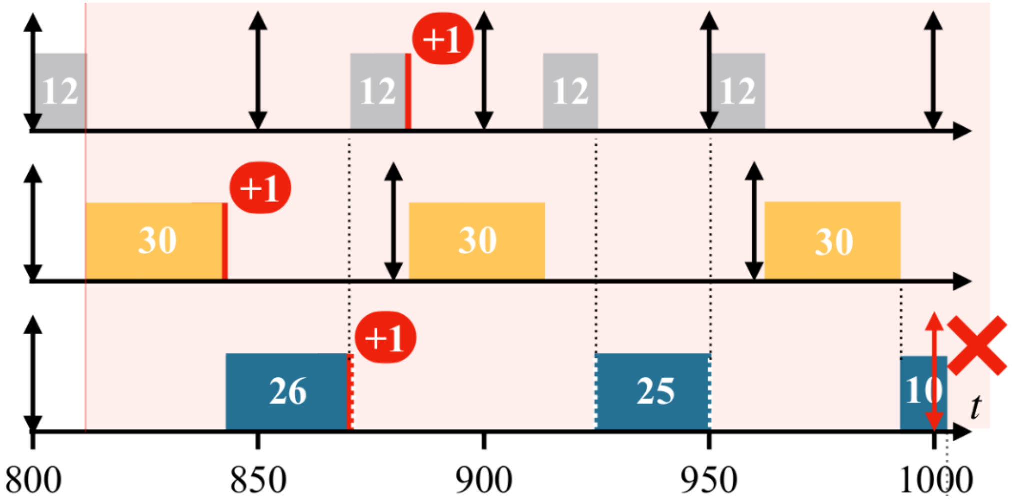

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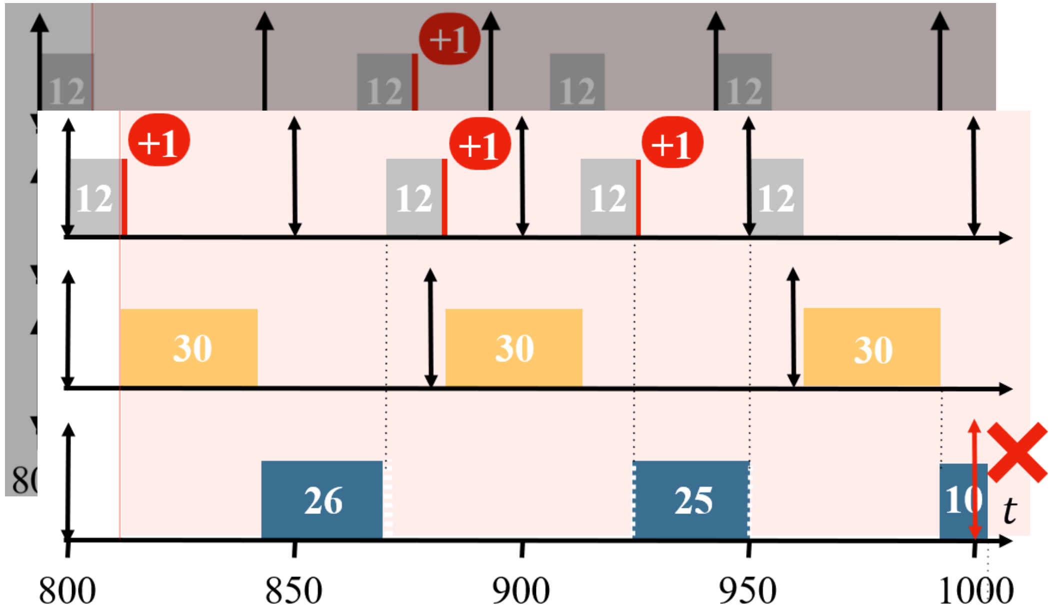

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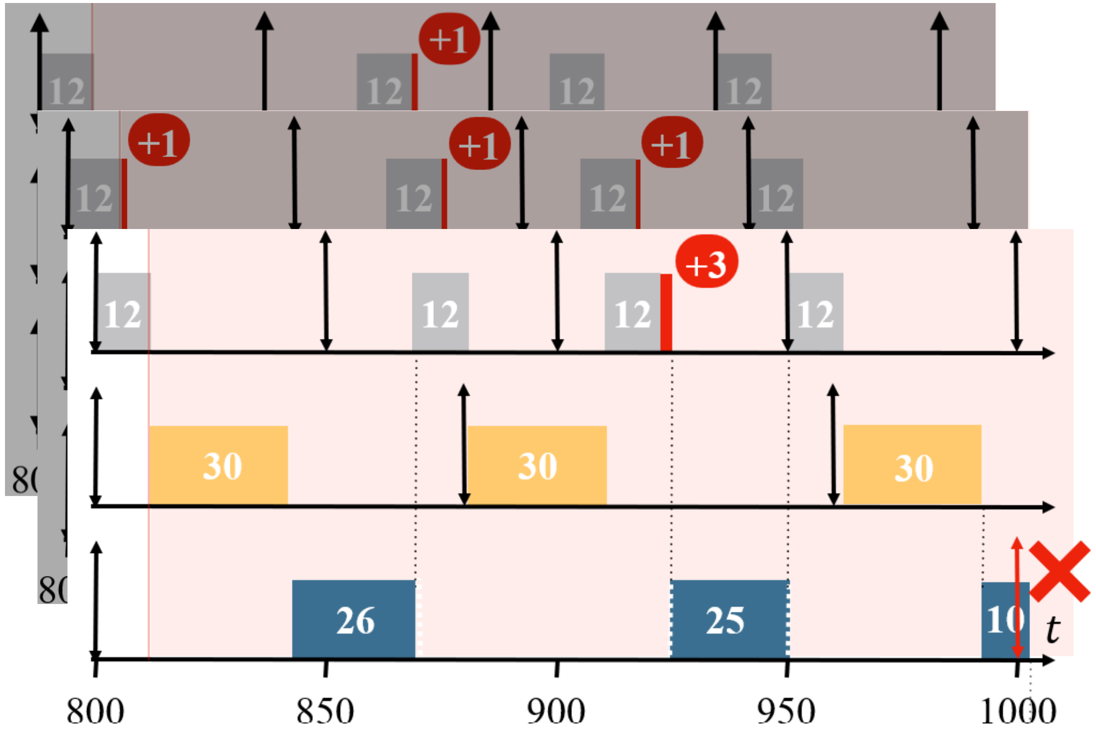

Solution-Space Analysis

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QUESTION

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This may vary based on:

- The specific system
- The workload
- The designer’s preferences
- …

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Exeedance balancer

A few jobs exceed a lot
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- Case study
  - WATERS 2017 industrial challenge

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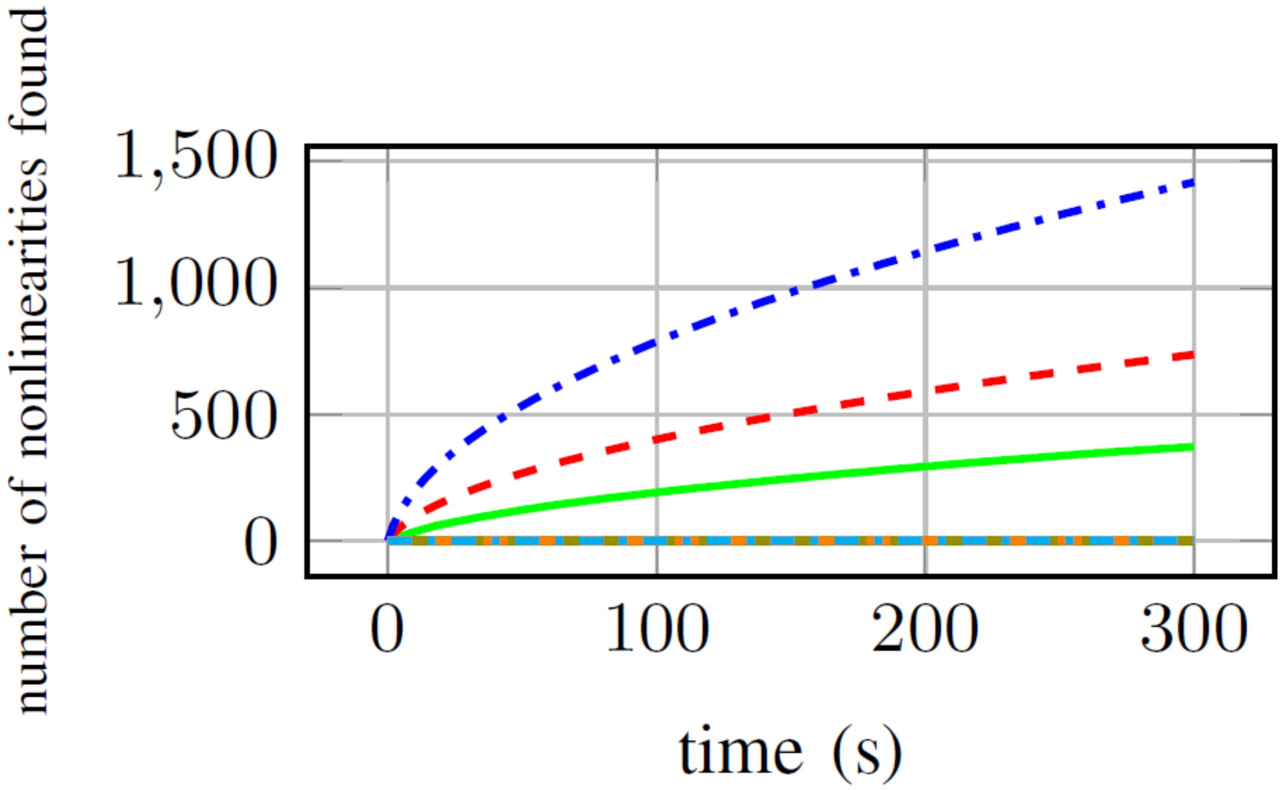
The **nonlinearities search algorithm** was compared with a brute-force solution

DRS-based, fully non-preemtpive workload – 3600 tasksets



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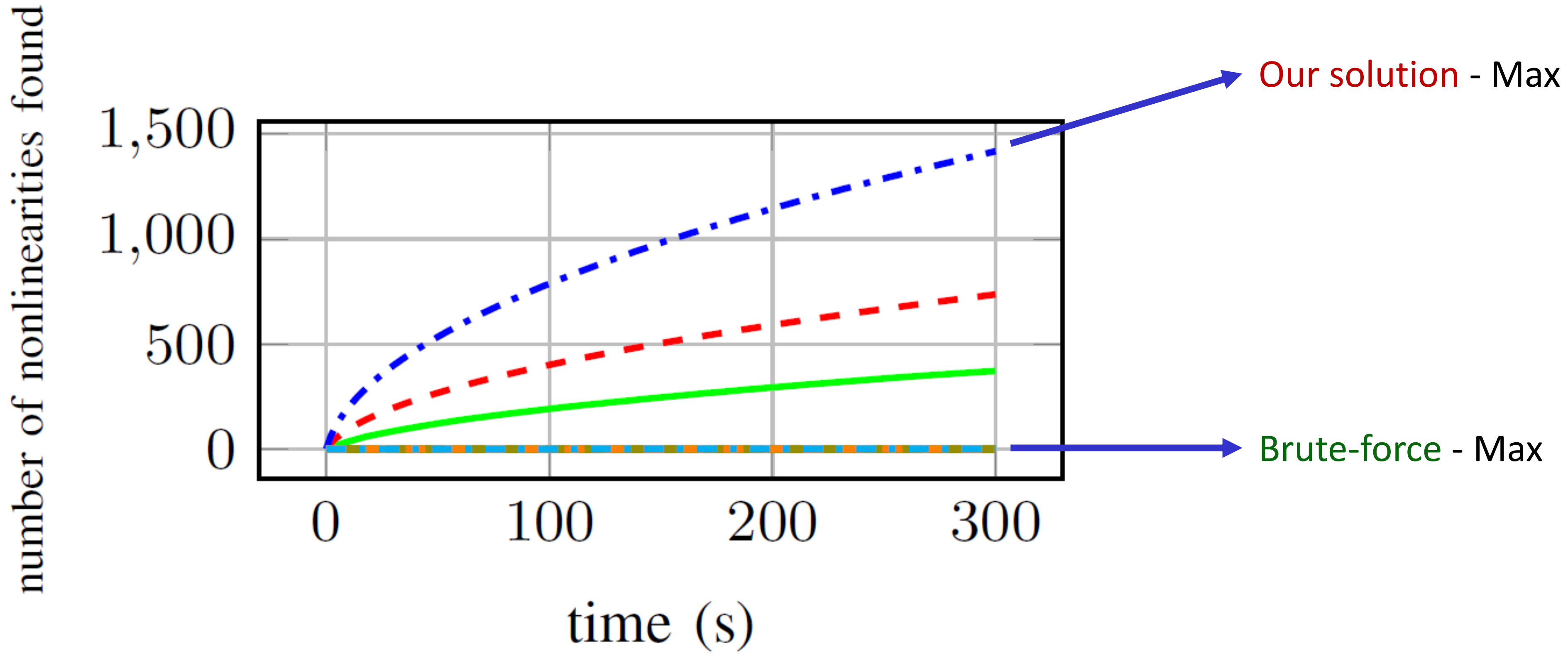

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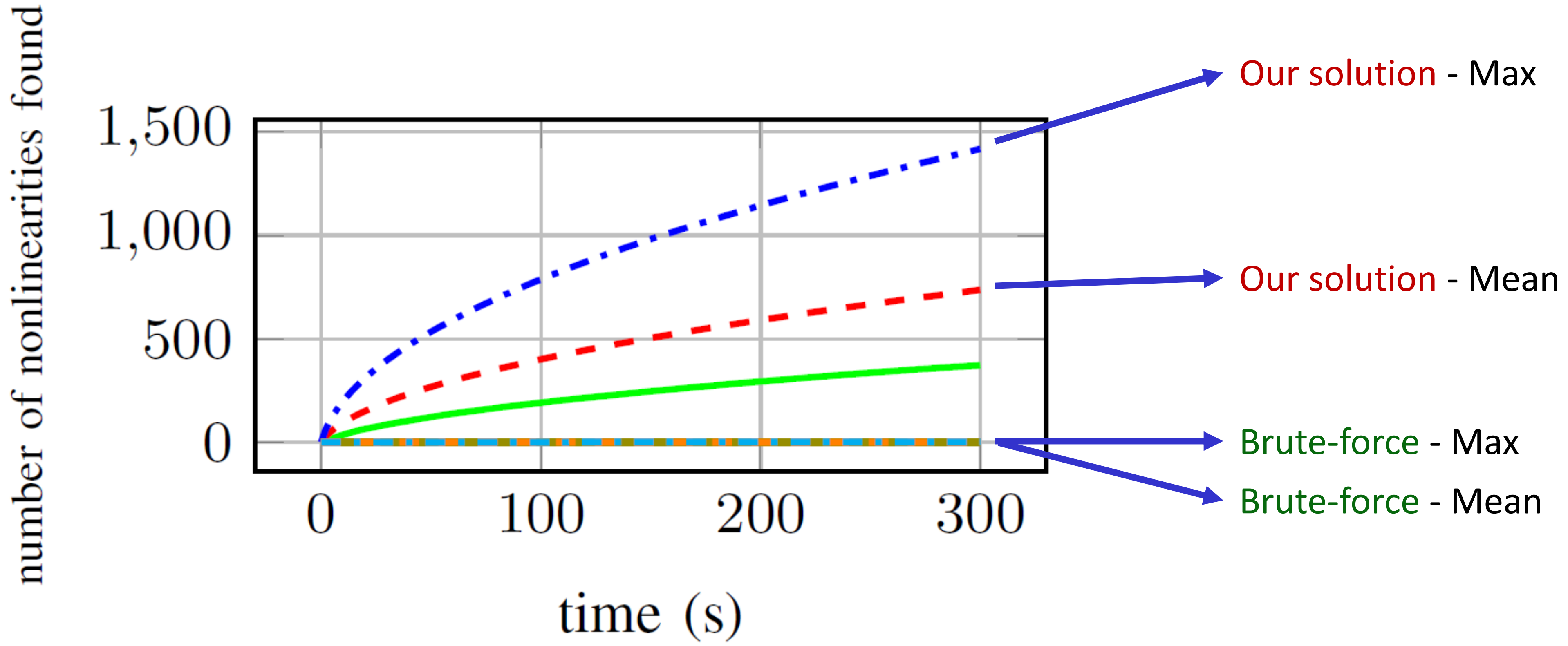

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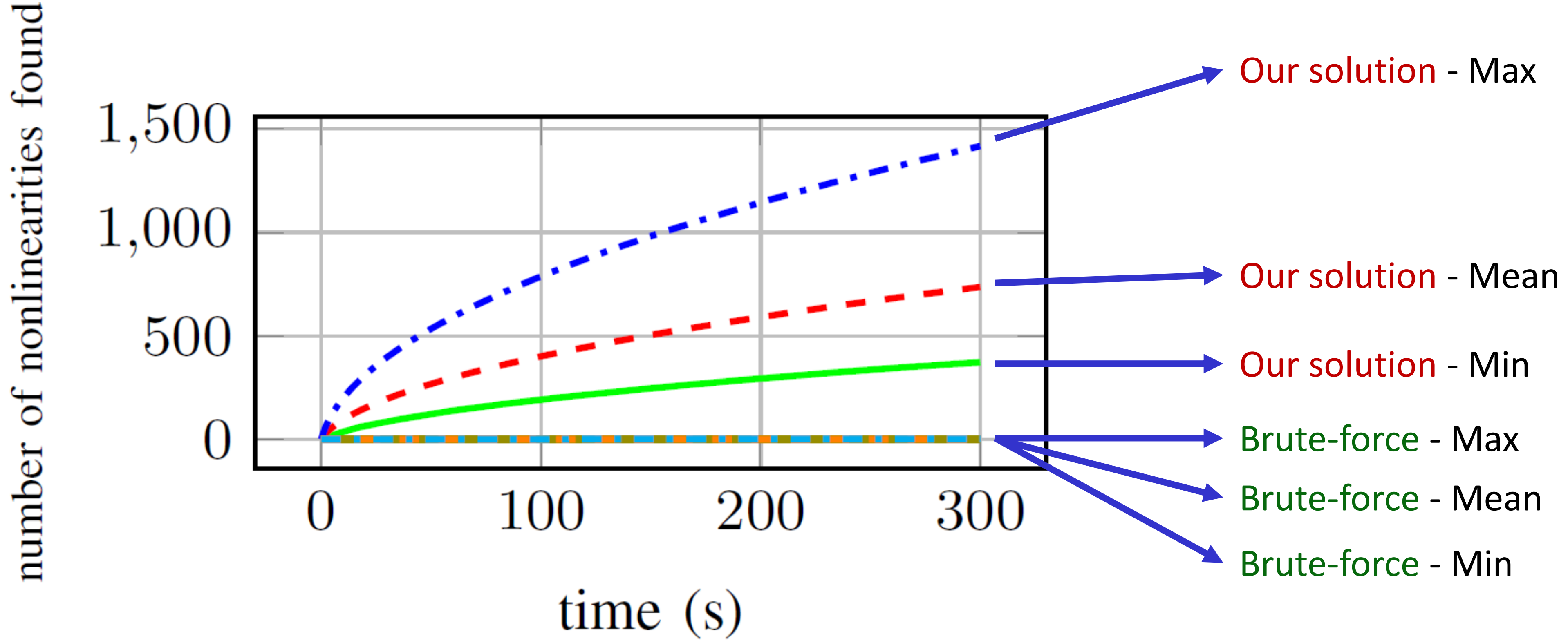

NET Trustworthiness

The **NET trustworthiness** parameter affects the amount of exceedance assigned to a task

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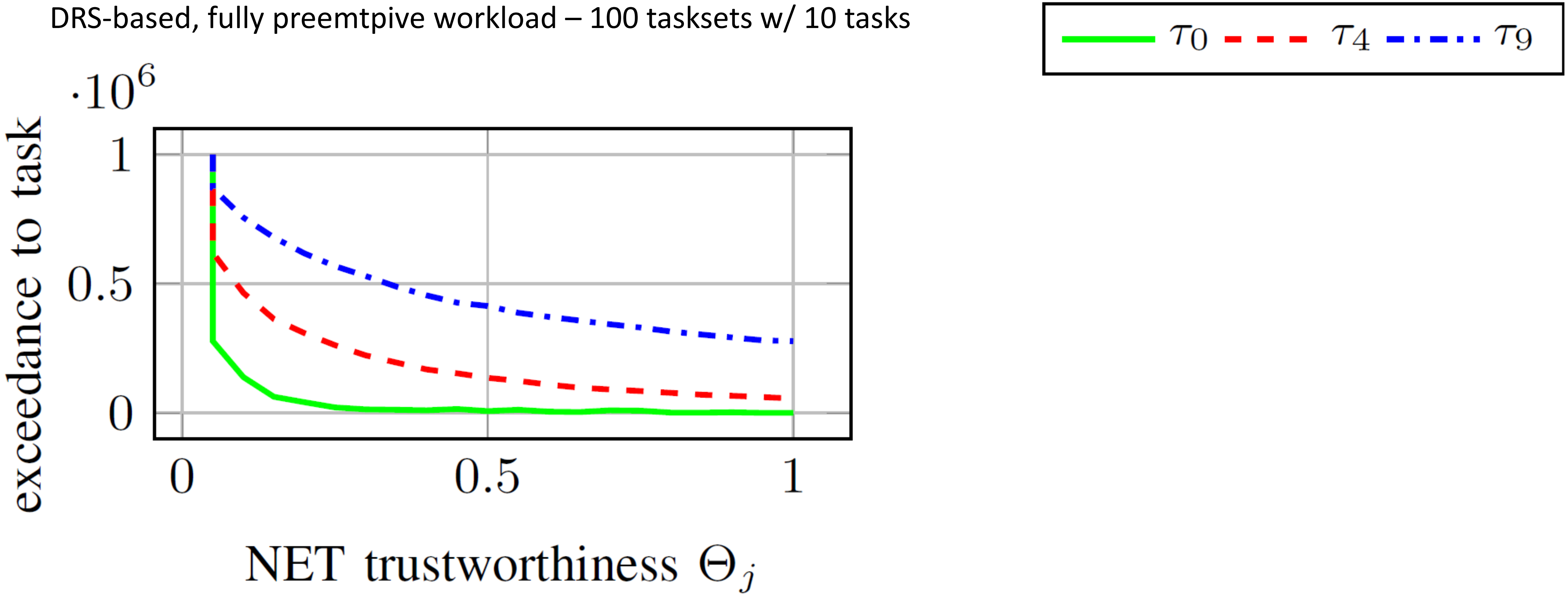

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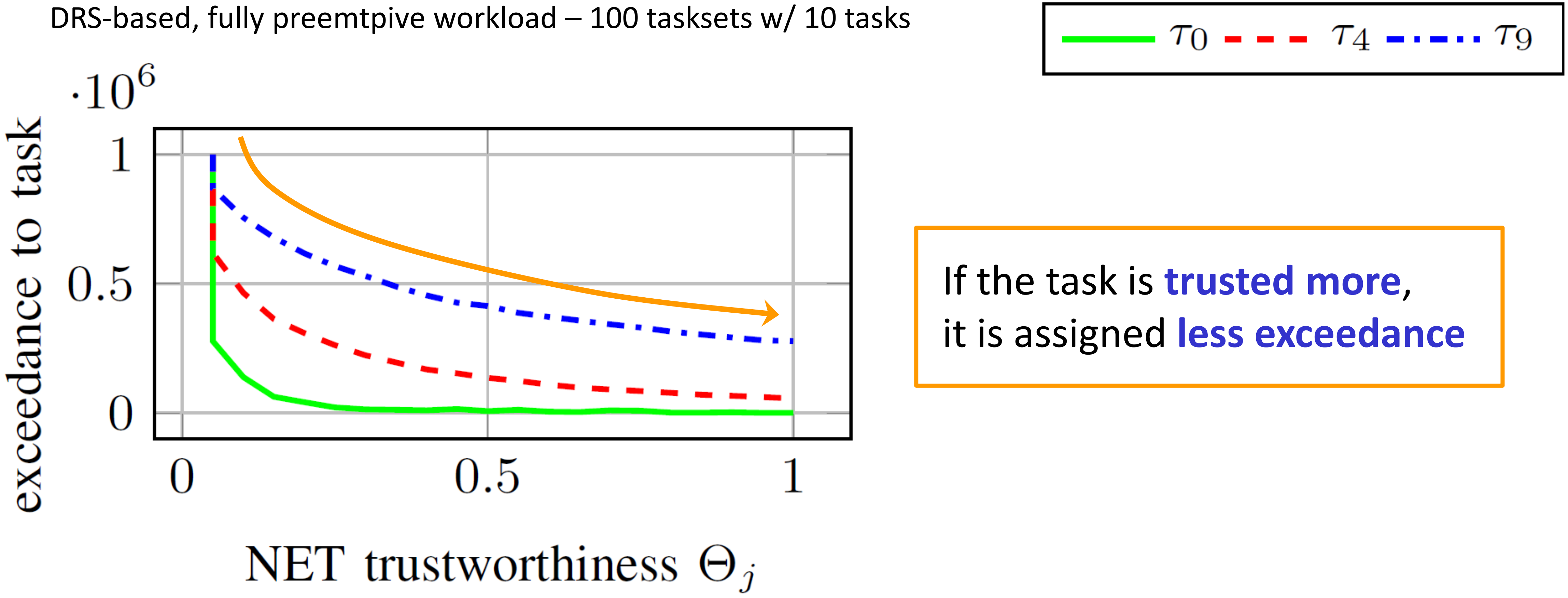

If the task is **trusted more**,
it is assigned **less exceedance**

Balancer Effects

The **exceedance balancer** parameter affects the number of jobs that are assigned exceedance

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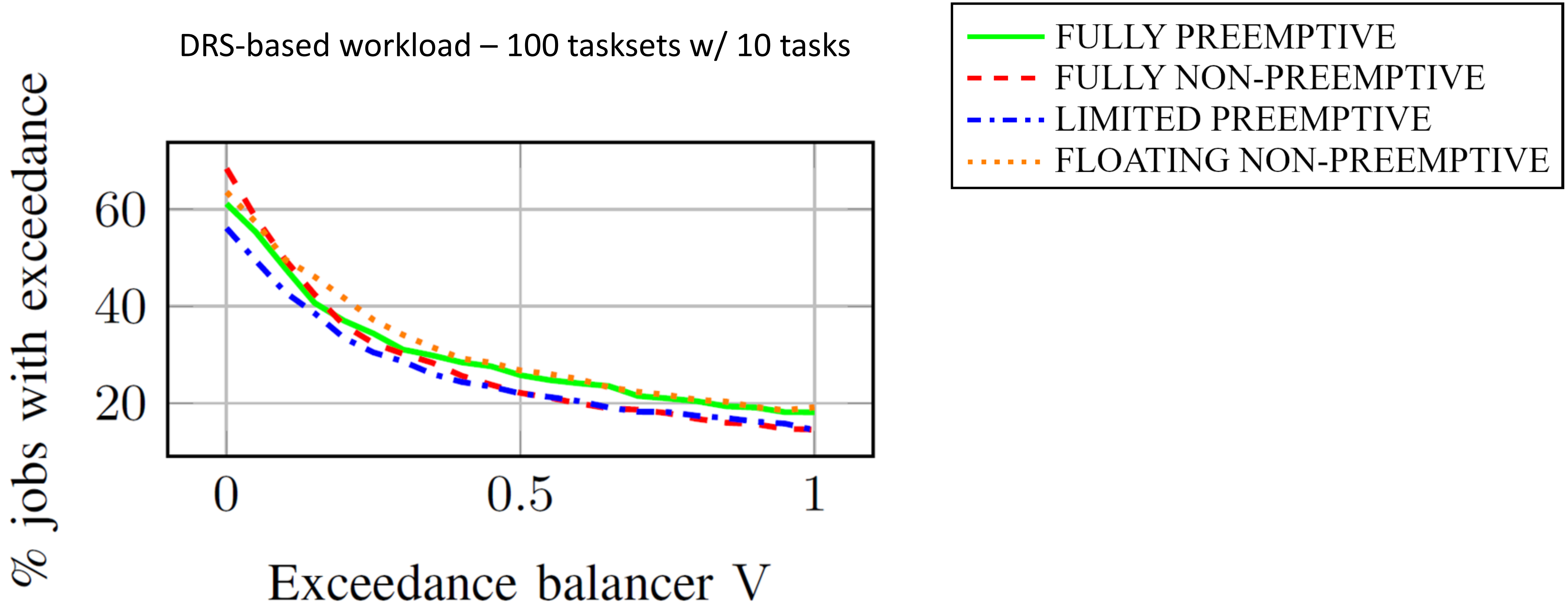

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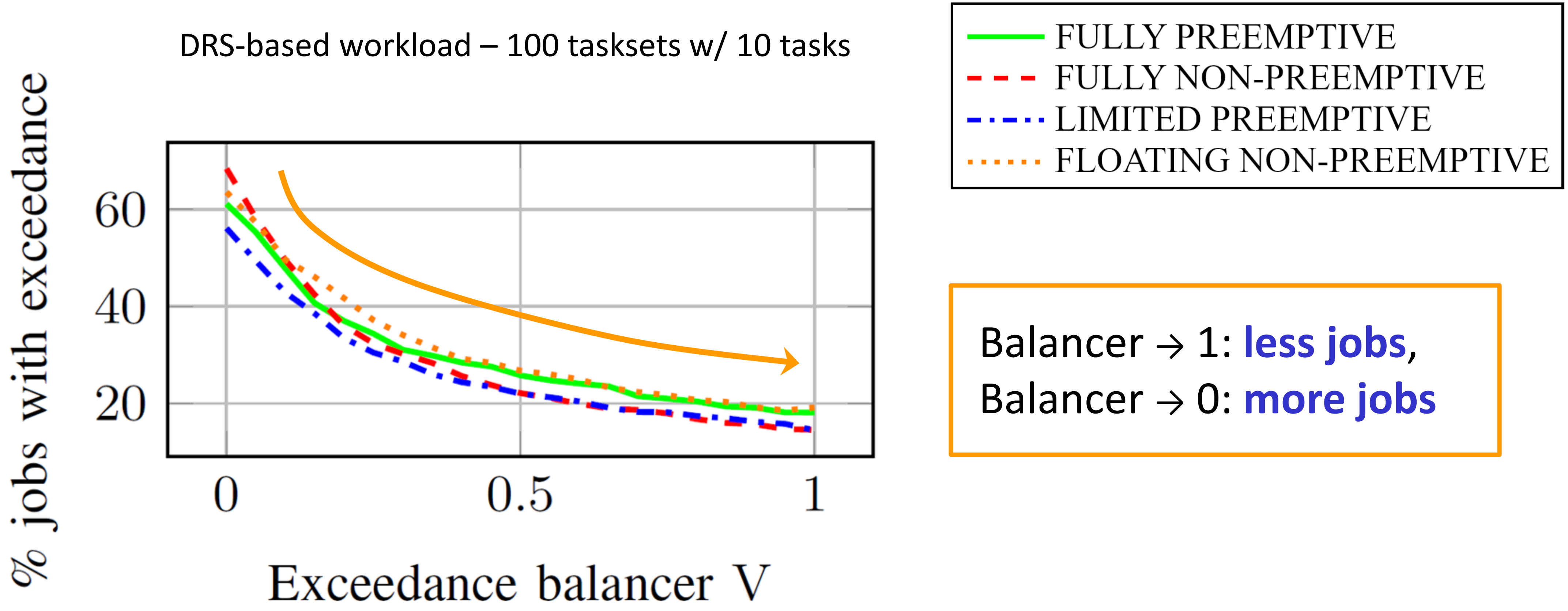

Balancer → 1: **less jobs**,
Balancer → 0: **more jobs**

Case Study

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Slowdown = exceedance / NET

The MILP was modified to look for the slowdown that makes the taskset unschedulable.

Task	Period	NET	e	$\min\max x_h^s$	$L_7(e)$
τ_1	2 ms	0.364 ms	1.636 ms	450.06%	97.59 ms
τ_2	5 ms	0.838 ms	3.071 ms	159.24%	99.39 ms
τ_3	20 ms	9.421 ms	3.591 ms	21.89%	99.91 ms
τ_4	50 ms	2.776 ms	14.407 ms	16.99%	399.06 ms
τ_5	100 ms	8.476 ms	3.929 ms	4.09%	179.91 ms
τ_6	200 ms	0.124 ms	7.733 ms	4.02%	279.91 ms
τ_7	1000 ms	0.123 ms	38.542 ms	4.01%	1079.91 ms

Case Study

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The optimization problem can be **easily extended** to consider additional metrics.

Case study: WATERS 2017 challenge - NET = 0.9 · WCET

NOTE:
Original taskset not schedulable with WCETs!

Slowdown = exceedance / NET

The MILP was modified to look for the slowdown that makes the taskset unschedulable.

Exceedance to deadline miss

Task	Period	NET	e	$\min\max x_h^s$	$L_7(e)$
τ_1	2 ms	0.364 ms	1.636 ms	450.06%	97.59 ms
τ_2	5 ms	0.838 ms	3.071 ms	159.24%	99.39 ms
τ_3	20 ms	9.421 ms	3.591 ms	21.89%	99.91 ms
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Exceedance to deadline miss

Slowdown necessary for a deadline miss to occur

Task	Period	NET	e	$\min \max x_h^s$	$L_7(e)$
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Exceedance to deadline miss — Slowdown necessary for a deadline miss to occur — Bound on the recovery time

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Slowdown necessary for a deadline miss to occur

Bound on the recovery time

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High-priority tasks have a big safety margin

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High-priority tasks have a big safety margin

Low-priority tasks have a very small safety margin!

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- Exceedance analysis helps to **efficiently explore** the space of exceedance effects in order to:
  - Explore hypothetical scenarios;
  - Assess the system's safety margin w.r.t. transient execution-time fluctuations.

- The results of the analysis can be presented visually and **easily understood** by the system's designer.

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Future work

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  - Self-suspending tasks
  - …

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  - Support for locking protocols
  - Self-suspending tasks
  - …

- The approach can be extended to **other task parameters:**
  - Release jitter
  - Critical-section length
  - Supply-bound functions
  - …

Thank you!