

Scheduling time-triggered tasks in multicore real-time systems: a machine learning approach

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Abstract—Background: Previous research and/or rationale for performing the study.

Aims: Hypotheses/propositions to be tested, or goal of the study.

Method: Description of the type of study, treatments, number and nature of experimental units (people, teams, algorithms, programs, tasks etc.), experimental design, outcome being measured.

Results: Treatment outcome values, level of significance.

Conclusions: Limitations of the study, implications of the results, and further work

Index Terms—real-time system, scheduling, time-triggered tasks, DAG, multicore

I. INTRODUCTION

Real-time systems are utilized in various domains such as air traffic control, public transportation, and automated vehicles. Unlike non-real-time systems, tasks in real-time systems must be both functionally correct and meet strict execution time constraints, known as deadlines. Failure to meet these deadlines can lead to severe consequences. The critical nature of these systems necessitates the design of a system architecture that focuses on time and incorporating fault tolerance to ensure high reliability.

One example of such architecture is the time-triggered architecture (TTA)[1][2], which offers a fault-tolerant communication protocol and a precise timing system to synchronize different electronic control units. Increasingly, these real-time system architectures are enhancing their computational resources by transitioning to multiprocessor systems. This shift from uniprocessor to multiprocessor systems addresses the growing complexity and computational demands of tasks executed on these systems (e.g., autonomous cars, computer vision systems), aiming to reduce both the execution time of these tasks and the required resources to run them[3].

Hence, an increasing number of real-time systems are utilizing multi-core hardware to parallelize their tasks and convert sequential programs into parallelized ones using frameworks such as OpenMP¹ to do so. Unfortunately, in most real-life scenarios, the number of available processors/cores is fewer than the number of tasks/subtasks that can be executed in parallel (i.e., independent tasks). This means that not all independent tasks can be executed simultaneously on the

system, raising the question: which task should be executed first?

This question is particularly important in a real-time context because having the wrong execution order, or schedule, could lead to, at best, a slow system, and at worst, deadline misses, which can have fatal repercussions[4]. In the case of a self-driving car system, for instance, a slight delay of 500 ms in detecting a pedestrian crossing the road can, in some cases, be enough to drive over the pedestrian or cause a car accident. Note that the resources of real-time systems are scarce and limited, which is why using as little processing power as possible while ensuring that tasks meet their deadlines is of crucial importance.

The extreme case of this scheduling problem arises when only one processor is available to execute tasks. This is known as task scheduling on a uniprocessor, and [5] provided two major priority policies: Rate Monotonic (RM) and Earliest Deadline First (EDF) for scheduling independent periodic tasks. However, when considering multiple processors, the scheduling problem becomes much more complex, and different task models must be considered.

A prevalent task model when considering periodic tasks that can be parallelized is the Directed Acyclic Graph (DAG) task model which arises when a time-triggered task can be parallelized into subtasks which are the nodes of the graph, thus reducing the worst-case execution time of the recurrent task when executed on a designated set of cores. Those nodes have dependency constraints which are modeled by the directed edges between the nodes. The DAG task model is used to model tasks that are parallelizable[6], fitting the ever-increasing multicore architectures found in today's real-time system architectures.

Given that the problem of scheduling independent tasks or dependency-constrained groups of jobs (i.e., DAGs) is NP-hard²[7] [8], people have resorted to either heuristics to partially solve the problem, or the optimal but not scalable Integer Linear Programming (ILP) method.

Consequently, machine learning will be considered here as it can better approximate the unattainable perfect solution while being scalable in terms of computing time after the training

¹OpenMP (2011) OpenMP Application Program Interface v3.1. <http://www.openmp.org/mp-documents/OpenMP3.1.pdf>

²If a problem is NP-hard, it means that it is impossible to find a solution in polynomial time complexity, i.e., solutions are not scalable

phase[9][10]. More specifically, the research questions are the following:

RQ1 What is the current state-of-the-Art for DAG tasks scheduling ?

RQ2 What machine learning techniques are used for DAG task scheduling ?

RQ3 Can machine learning be a better solution to schedule DAG tasks ?

RQ3.1 Can a machine learning solution compare to state-of-the-art heuristics for scheduling Directed Acyclic Graph tasks ?

RQ3.2 Can a machine learning solution compare to an ILP solution while being more scalable ?

To achieve this, the background section will introduce various technical terms, concepts, and fundamental algorithms. Following this, a systematic literature review will be conducted to address RQ1 and RQ2, and finally, the artifact and experimental design, results, and conclusion will be presented to answer RQ3.

The solution we propose has the following features..

The primary contributions of this paper are:

II. BACKGROUND

DAG task scheduling introduces several fundamental concepts.

A. DAG task model

A Directed Acyclic Graph (DAG) task $\tau = (G, D, T)$ is comprised of a directed acyclic graph $G = (V, E)$, a relative deadline $D > 0$ and a period $T > 0$. The graph G has a set of vertices V and a set of edges $E \subseteq V \times V$ that models the precedence constraints of the vertices, i.e., for all $(v_i, v_j) \in V^2$, with $i \neq j$, $(v_i, v_j) \in E$ if and only if v_j must wait the end of v_i 's execution to start executing (i.e., v_i is a precedence constraint for v_j). The nodes of the graph G are characterized by their own worst-case execution time C_{v_i} and $vol(G) = \sum_{v_i \in V} C_{v_i}$ is the worst-case execution time of the DAG task τ , also called the total workload of the DAG task. In this paper, the words nodes, vertices and subtasks will be used to address the same thing, that is the vertices of the graph of a DAG task.

An example of a DAG task is shown in Figure 1, where the DAG task has a wcet of 24 time units.

This concept will be the task model used in to conduct part of the systematic literature review (see Section III) and it also will be the task model used for designing the machine learning model (see Section IV).

B. Makespan

The makespan or end-to-end response time of a DAG task is the amount of time it takes for all the subtasks in the DAG task to finish executing when given a schedule. For instance, for the task τ shown in Figure 1, the makespan of τ for the first schedule (from top to bottom) shown in Figure 2 is 17.

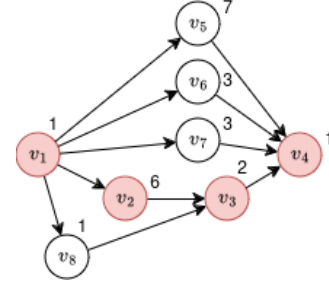


Fig. 1. a) DAG task τ . The worst-case execution time (wcet) of each subtask written as an exponent and the nodes highlighted in red are the nodes in the critical path, the path of maximum length in terms of wcets.

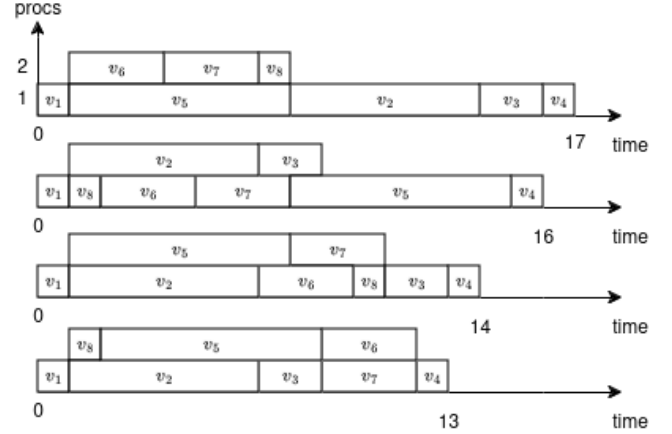


Fig. 2. b) Execution schedules for the DAG task above. Heavily inspired from Zhao et al. [11].

Notice that Figure 2 shows multiple ways of scheduling the DAG task, the bottom one yielding a makespan of 13.

This is a key measurement when scheduling the nodes of a single DAG task, also called intra-task scheduling (see Section III), and it will be the main efficacy criteria when comparing the machine learning model with state-of-the-art heuristics and ILP (see Section IV).

C. Intra-task and inter-task scheduling

When considering the DAG task model, two concepts arise : intra-task scheduling and inter-task scheduling.

Intra-task scheduling of DAG tasks is when only the execution order of the nodes in a single DAG task is considered. The goal of such a problem being to minimize the makespan of a single DAG task.

Inter-task scheduling, on the other hand, is when multiple DAG tasks are considered and the goal then becomes to maximize the acceptance ratio (see below) of the scheduling algorithm.

D. NP-hardness intuition and problem motivation

The problem of intra-task scheduling of DAG tasks, that is, scheduling the nodes of a single DAG task so that the

makespan is minimized, is a NP-hard problem[8][7] but can also be intuitively seen as a NP-difficult problem when looking at the schedules shown in Figure 2. Indeed, when looking at a single DAG task, a simple yet efficient way of scheduling the nodes is looking at a critical-path-first execution order(CPFE). The critical path, highlighted in red in Figure 1, is the longest path of the graph in terms of wcets. The CPFE principle is applied in the third schedule (from top to bottom) in Figure 2 and achieves a makespan of 14. But this is not the minimum makespan as the fourth schedule yields a makespan of 13.

This is due to the fact that, although executing the critical path first is the best strategy[11], one needs to take into account the dependency constraints and thus the global structure of the graph. The fourth schedule in Figure 2 achieves a makespan of 13 by prioritizing the execution of node v_8 before node v_5 which is crucial to enable v_3 to execute sooner than in the third schedule. Typically in graph theory, when the global structure needs to be known in advance in order to find the best solution, it often means that the problem is NP-hard (e.g., the problem of coloring a graph[12] or coloring a path of a graph[13]). Therefore, researchers have resorted to heuristics to solve the problem(see Section III).

E. Utilization factor

The utilization factor represents the percentage of processing time that a taskset (τ_1, \dots, τ_n) will utilize. Formally, it is defined as

$$U = \sum_{k=1}^n \frac{vol(G_k)}{T_k} \quad (1)$$

where U is the utilization factor. This concept is significant because, when evaluating a scheduling algorithm S , we desire S to effectively schedule tasksets that maximize the utilization factor U . Consequently, the higher the utilization factor bound for S , the more efficient the scheduling algorithm. Additionally, this concept is valuable in real-time systems where processing resources are often limited and expensive, making it crucial to maximize their usage.

This concept is also used either as a measurement when comparing two scheduling algorithms and considering their utilization bound(see Section III), or used as a parameter to generate tasksets or DAG tasks with a fixed utilization (see Section IV).

F. Capacity augmentation bound

Another measurement used when scheduling event-chains, or DAG, tasks is the capacity bounds, or capacity augmentation bound, which compares resource use to a theoretically optimal scheduling algorithm. It can also be used as a simple schedulability test. It is often refer to as a β coefficient and the lower β is, the better the scheduling algorithm. This metric is used for DAG tasks or event-chains of tasks.

G. Acceptance ratio

When dealing with several independent DAG tasks or tasksets, the acceptance ratio is often used to measure the

performance of a scheduling algorithm (see Section III). It consists of looking at a number of generated tasksets (or DAG tasks) and calculating the amount of schedulable (i.e., the schedule produced doesn't lead to a deadline miss) tasksets compared to the total amount of tasksets. The resulting percentage is the acceptance ratio and the closer it gets to 100% for a scheduling algorithm, the better the scheduling algorithm.

This concept is also used as a metric, to assert the efficiency of scheduling algorithms when considering inter-task scheduling (see Section III).

While the acceptance ratio, also called system schedulability, is used to measure the performance of scheduling algorithms for inter-DAG task scheduling (i.e., scheduling multiple DAG tasks), the makespan and the capacity bound are only used for DAG tasks and tasksets representing chain of events.

III. RELATED WORKS

A. Systematic Literature Review process

This SLR aims at tackling RQ1 and RQ2. More precisely, the following research questions will be answered:

- RQ1 What is the current state-of-the-Art for DAG tasks scheduling ?
- RQ2 What machine learning techniques are used for DAG task scheduling ?

It will also be shown how the literature doesn't provide a complete answer to RQ3, hence the contributions of this paper.

From these research questions, several concepts have been isolated, namely, time-triggered or DAG tasks, the nature of the system (real-time multicore system), the scheduling of tasks, and machine learning. The recording of the search results were done using the BibTeX LaTeX plugin combine with the google scholar "cite" feature.

Searching was conducted using the IEEE and ACM databases. According to the concepts identified above, the keyword chain used for searching was "(("real-time" OR "real time") AND "system" AND ("time-triggered" OR "time triggered" OR "DAG" OR "Directed Acyclic Graph" OR "event chain" OR "event-chain") AND "task" AND ("scheduling" OR "scheduler" OR "schedule")) AND ("multi-processors" OR "multi-cores" OR "multi processors" OR "multi cores" OR "multi-processor" OR "multi processor" OR "multi-core" OR "multi core")". The search produced 1,259 results on the IEEE database which was reduced to 515 papers when considering only articles published in the past 5 years.

Then the following exclusion criterias were used to filter out the rest of the articles, bringing the number of papers down to 19 (see Figure 3).

- EC1 Not focusing on homogeneous multicores and hard RTS "Heterogeneous" not in the title nor the abstract. "mixed critical*" not in the title nor the abstract
- EC2 Not focusing on scheduling "scheduling" or "scheduler" or "schedule" in the title

”energy” not in the title

Focus on conference and journal papers

EC3 Not focusing on real-time systems, not proposing a scheduling algorithm, not using DAG or event-chain tasks.

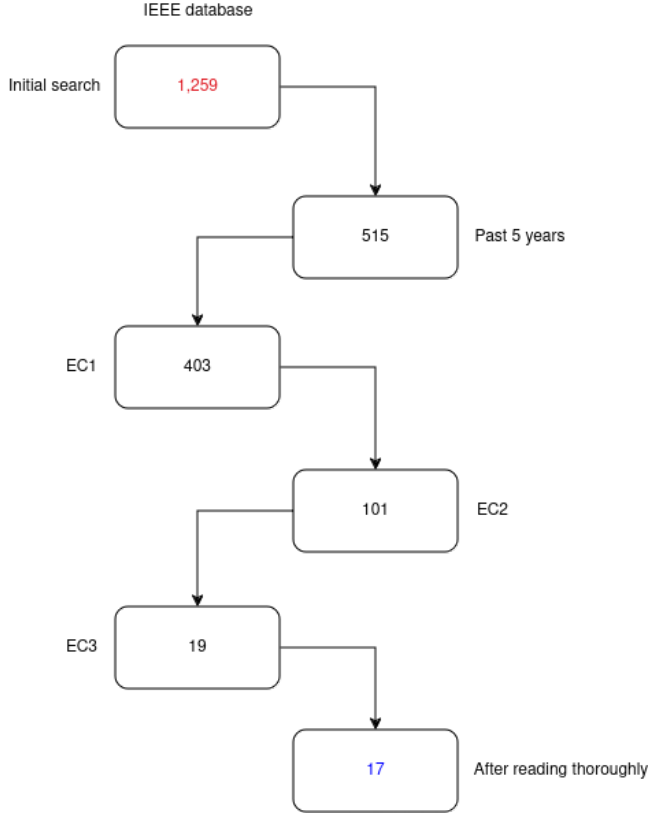


Fig. 3. SLR process diagram. EC stands for Exclusion Criteria, which are listed above.

B. Findings of the Literature Review

1) Non-Machine Learning techniques:

Guan et al. [14] use fluid scheduling to schedule multiple DAG tasks on a multicore system. Fluid scheduling has been used in previous work for independent time-triggered task scheduling[15][16] but very few consider DAG tasks. Fluid-scheduling is known for producing optimal scheduling algorithms. Their method decomposes a DAG task into several sequential segments in which the subtasks will execute according to the fluid scheduling model. Although their algorithm significantly outperforms existing algorithms, the main limitation that is common to all fluid-based scheduling algorithm is the runtime overhead induced by the fluid-scheduling model. Although authors in [14] briefly explain how to transform their scheduling algorithm to a non-fluid one for practical implementation, they do not evaluate the overhead caused by the frequent task migrations and preemptions. This overhead can lead to deadline misses on systems where the migration cost is high which is why it is important, especially with fluid-based algorithms, to consider this overhead[17]. Also, their

algorithm only considers DAG task with implicit deadlines ($D = T$) which makes the response-time analysis simpler but to the cost of not covering all types of tasks that can execute on real-time systems.

As a follow up, Guan et al. [18] extend the fluid scheduling algorithm in [14] to constrained and arbitrary deadline tasks, especially focusing on DAG tasks with a deadline greater than their period, thus generalizing their previous fluid algorithm to all types of periodic tasks. Their main contributions are their new scheduling algorithm that performs better than existing methods in terms of acceptance ratio, and producing the first theoretical capacity bound for DAG tasks with deadlines greater than their periods. However, the authors still don't provide any evaluation on the amount of runtime overhead their scheduling algorithm implementation produces which generally lowers the actual acceptance ratio of the algorithm.

Instead of considering fluid-scheduling, a popular scheduling method is federated scheduling. Federated scheduling is based on the idea of assigning heavy tasks ($U > 1$) to multiple cores for the whole duration of the tasks' executions, and assigning light tasks ($U \leq 1$) to execute on cores that have not been assigned a heavy task. Although it is popular, it suffers from a resource wasting problem, especially when the difference between the critical path's length and the deadline is small, which many papers aim at solving [19] [20] [21] [22] [23] [24].

Jiang et al. [20], for instance, consider federated scheduling and GEDF and introduces a better metric called the util-tensity bound that extends the concept of capacity bound to have a better schedulability test. Based on this newly derived bound, the authors propose an extension to the classic federated algorithm, with very low tensity tasks being scheduled with GEDF, tasks with high-utilization and relatively high tencies are scheduled using the classic federated scheduling and low utilization tasks with relatively high tencies are scheduled using partitioned-EDF. Their algorithm, based on their newly derived bound, effectively improves the system schedulability of DAG tasks and reduces the resource wasting problem of federated scheduling. The main limitation of this paper is that they only consider GEDF for their util-tensity bound and also only consider implicit deadline DAG tasks which doesn't represent tasks that need to have a deadline lower than their period, for example.

This problem of resource wasting in federated scheduling is also tackled by Kobayashi and Azumi [23] where they propose a federated and bundled-based scheduling algorithm which enhances the schedulability of DAG tasks compared to existing federated scheduling algorithms. Their method consists of using federated scheduling for tasks with high critical path to deadline ratio and bundled scheduling for tasks with low critical path to deadline ratio. Unfortunately, this paper only looks at 3 DAG tasks to evaluate their algorithm which is a really small amount and is not representative of the different DAG tasks that can exist and leaves space for observational bias.

Jiang et al. [21] take another approach by proposing a

virtually-federated scheduling algorithm that leverages the advantages of federated scheduling while improving the acceptance ratio for DAG tasks, outperforming existing algorithms. Their approach consists of adding a virtual layer of processors, on top of physical processors, and apply their federated-based scheduling algorithm on those virtual processors, thus enabling tasks to share a physical processor even though they are assigned to different virtual processors. The main drawback in [21] is that the authors only consider the heavy tasks (i.e., $U > 1$) and do not take the light tasks into account, meaning it doesn't consider tasks that only need one processor to execute.

To fix this limitation, Jiang et al. [22] extend their previous work[21] so that it considers both heavy and light tasks. The resulting virtually federated scheduling algorithm clearly outperforms any other federated-based scheduling algorithms in terms of acceptance ratio. However, they still only consider implicit or constrained deadline tasks and they don't provide any evaluation of the run time overhead their algorithm might induce, to compare with algorithms currently used in real-time systems, such as GEDF.

Guan et al. [19] consider arbitrary deadline tasks and especially DAG tasks that have a deadline that is greater than their period. They introduce a new federated scheduling algorithm that takes those type of tasks into account and compare it to existing global or federated scheduling approaches for arbitrary deadline tasks, significantly outperforming most of them in terms of acceptance ratio. Their approach consists of using this new proposed algorithm for heavy tasks that have a deadline bigger than their period, then using classic federated scheduling for the heavy tasks with a constrained deadline, and finally using EDF-First-Fit (EDF-FF) for the light tasks. Although the fluid-based method in [18] outperforms this new federated scheduling algorithm, the impracticality of fluid-based algorithm makes this algorithm the current best, in terms of acceptance ratio, for dealing with arbitrary deadlines. The main limitation of this work is that it doesn't tackle the resource wasting problem that classical federated scheduling, or their new algorithm, has or can potentially have, but only focuses on providing an algorithm for arbitrary deadline tasks.

For constrained deadline DAG tasks, He et al. [24] propose a federated-based scheduling algorithm that outperforms on average by more than 18% previous SOTA[22] in terms of acceptance ratio, making this work the current SOTA for constrained deadline multi-DAG scheduling. Their approach uses the notion of degree of parallelism, which they define rigorously, to improve the classic federated scheduling way of choosing the number of cores to assign each heavy tasks. They also propose a new response-time bound for constrained deadline DAG tasks based on this defined notion. Although their method clearly stands out, they don't consider intra-task scheduling at all when their motivation came from the notion of degree of parallelism being used but wrongly defined in previous intra-task scheduling work[25][11].

Federated scheduling isn't the only method used, Jiang et al. [26], for instance, propose a decomposition-based approach to

schedule multi-DAG tasks as well as a metric for testing the schedulability of tasks. Their decomposition strategy proves to be the most efficient, according to the defined metric, and the scheduling algorithm derived from it shows promising results in terms of acceptance ratio. Their decomposition strategy basically works by first defining execution segments and then then assigning subtasks to those segments using the laxity³ of those subtasks so that no segments are overloaded with workload. The main limitation of this work is that they only look at GEDF variants for priority assignment and do not evaluate their decomposition method using other scheduling heuristics for multi-DAGs. Most of the articles presented up to now tackle inter-task scheduling, not considering the intra-task execution schedule.

Indeed, intra-task scheduling[27][28] [29][9][10] [30] is often tackled as a separate problem due to the dependency constraints.

Xiao et al. [28], for instance, introduce a scheduling algorithm, 'MAS', that shortens the makespan of periodic DAG tasks compared to the classic EDF dynamic priority scheduling technique. Their algorithm is based on a clustering approach, combined with a technique called task duplication, and evaluate their results on an actual simulation object for real-time scheduling. Unfortunately, their evaluation is only based on a single DAG task and they only compare their algorithm with EDF. Their algorithm also shows a scalability problem compared to other existing algorithm with comparable results.

A scalable way of scheduling sub-tasks of a DAG is looking at priority-list scheduling which He et al. [27] use to propose an algorithm that effectively outperforms other intra-task DAG scheduling algorithms in terms of makespan. Their priority assignment algorithm is based on the length of the paths passing through each vertex. The longer the maximum length, the higher the priority. This effectively takes advantage of the inner graph structure to optimize the intra-task execution order, which is something that hasn't been done before this work. Although the authors compare their results with existing scheduling heuristics, they do not consider the, mathematically optimal, ILP method to compare their makespan results with the mathematically minimum makespan.

This priority-list scheduling approach is also used by [25], extending their previous work[11] which develop a priority assignment based on the critical-path execution first (CPEF) concept, effectively outperforming He et al. [27] in terms of makespan and providing a federated-based multi-DAG scheduling algorithm, compatible with this new priority-list scheduling algorithm. Their multi-DAG scheduling algorithms also outperforms the multi-DAG algorithm used in [27]. Their method uses the vertices in the critical path as producers of workload for the parallelizable vertices to consume. For multi-DAG they look at assigning processors to DAG tasks, like in federated scheduling, using a parallelism-aware workload distribution model that uses their Concurrent Producer

³Laxity is the gap between the total execution time of a task (potentially comprising the I/O delays) and its deadline.

Consumer (CPC) model to assign cores while minimizing the inter-task workload interference. One limitation of their work is that, although they consider constrained deadlines for the response-time analysis, they only use implicit deadline DAG tasks for evaluating the system schedulability of their multi-DAG scheduling algorithm.

Those intra-task scheduling papers only consider the theoretical makespan when task migration and preemption is instantaneous, but they don't take the runtime overhead into account. One major factor in the runtime overhead is the communication delays between each subtasks of a DAG task, which are rarely considered. To that end, Shi et al. [29] propose an extension of the DAG task model to add execution groups that bind groups of subtasks to a single physical core, thus reducing inter-core communication which can cause major communication delays depending on the topology of the system. They also introduce a scheduling algorithm and compare the makespan of their approach to existing methods such as federated scheduling and critical path-based scheduling. Their method shows comparable results while minimizing the communication overheads. However, the evaluation is only done on 100 generated DAG tasks which is a small sample size compared to the other papers[25][27], exposing the experiment to observational biases. Also, although they introduce a way to extend their approach to schedule multiple DAGs, they do not provide any evaluation of that.

2) Machine Learning techniques:

Only a few papers consider machine learning to solve the scheduling problem.

Lee et al. [10], for instance, design a deep reinforcement learning (DRL) model called GoSu which takes a DAG task as input and outputs a priority list of the DAG's subtasks. The makespan resulting from this priority-list is then compared to the results in [25] and [27] and the DRL model proposed in [10] outperforms them by up to 3%. The model is comprised of a graph convolutional network layer to encode the graph structure information, and a sequential decoder layer based on the attention-mechanism, which produces a priority list of the vertices. The reinforcement learning uses the makespan as the reward to minimize and the REINFORCE algorithm is used to find the best policy. Although the time it takes for the model to run is measured, no comparison with the ILP method is done and there is no evaluation of the scalability of the model when increasing the amount of cores in the system or the amount of subtasks in a DAG task. But Lee et al. [10] isn't the only work considering DRL as a method for DAG intra-task scheduling.

Indeed, Zhao et al. [9] also use the DRL approach to tackle the intra-task scheduling problem and compare their results to the makespan obtained by solving the equivalent ILP problem. Their model achieves up to 75% of makespan reduction compared to ILP, that is, the makespan produced by the ILP method is 25% smaller than the makespan produced by their DRL model, which is a relatively good performance as the ILP approach gives the mathematically minimum makespan. The more important result, however, is that when you increase the

subtasks in the DAG tasks, the ILP method explodes in terms of computing time when the DRL approach gives a result in a relatively short time, making it scalable, unlike ILP. The model uses a combination of a graph neural network with attention layers to better capture the structure and dependency information of the DAG task. The makespan is also used for the reward function but Soft Actor Critic algorithm is used for training the model. Unfortunately, the paper doesn't provide an evaluation when increasing the number of cores in the system and also doesn't compare their model to SOTA heuristics, which also aim to approximate the optimal solution given by the ILP method.

Guan et al. [30] focus more on optimizing communication delays by looking at the real-time simulation system FRTDS and using the I/O usage and ram allocation to construct a cost function, which is then used as a reward for their proposed DRL model to schedule DAG's subtasks. The cost is divided into a current cost, what we know, and the future cost which is predicted using the subtask's successors. The model performs better, in terms of makespan, than existing scheduling algorithms implemented on the FRTDS platform but because of the RL process accumulating the previous subtask's execution as experience to learn, the method uses a lot of memory which affects the speed of execution.

Table I gives a summary of the findings.

According to these findings, the current state-of-the-Art for DAG task scheduling (RQ1) seems to be a federated-based scheduling approach for inter-task scheduling and a global priority-list approach for intra-task scheduling [24][25].

In terms of machine learning techniques (RQ2), every article found uses deep reinforcement learning for scheduling DAG tasks. More specifically, the model proposed is often a combination of a kind of graph neural network and attention layers to produce a priority-list of the subtasks of the DAG task.

Multiple limitations were found for each paper. Notably, the type of task that is considered which mostly is constrained or implicit deadline tasks and arbitrary is rarely considered due to the complexity it adds to the scheduling analysis. Also, there hasn't been any use of supervise machine learning for real-time task scheduling and only one paper looked at comparing a machine learning solution to the optimal schedule provided by the ILP methodology.

IV. RESEARCH METHODOLOGY

To answer the research questions defined in section I, the right research methodology needs to be selected to conduct systematic research. Multiple such methodologies exists but the following four will be evaluated and the ones which fit best to this research will be selected.

A. Systematic Literature Review

The systematic literature review (SLR) methodology aims at looking at the current state-of-the art in a specific domain by selecting a range of articles in the scientific literature[32]. The main difference between a simple literature review is that the

TABLE I
SLR SUMMARY TABLE

Ref.	Motivation	Contribution(s)	Limitation(s)	Methodology Summary
[14]	DAG tasks scheduling is getting more popular and fluid scheduling performs great theoretically	Provide a DAG-fluid scheduling algorithm that performs way better in terms of acceptance ratio than previous algorithms	Fluid scheduling is impractical and introduces a lot of overhead and task migrations, also only for implicit deadlines tasks	fluid-based algorithm where it decomposes a DAG's subtasks into multiple sequential segments
[27]	DAGs are popular but no one looked at the intra-task execution order to leverage the graph structure	proposes a priority list scheduling algorithm for a single DAG task which performs better than SOTA in terms of makespan	no comparison with optimal priority assignment algorithms / optimal schedules.	uses the length (in terms of wcets) of each paths passing through the current vertex to assign the priority to the current vertex, the higher the length, the higher priority
[23]	Federated scheduling for DAG tasks is has proved efficient but for tasks where the difference between the critical path and the deadline is small, it can lead to over-allocating cores.	proposed a federated and bundled-based scheduling algorithm to avoid this problem and enhanced the schedulability of DAG tasks using their algorithms	They only compare their method with an example of a dag task set comprised of 3 dag tasks.	Uses federated scheduling for tasks with high critical path to deadline ratio and bundled scheduling for tasks with low critical path to deadline ratio.
[28]	DAG task scheduling is NP-hard so one can only approximate the optimal algorithm (when considering polynomial timed algorithms) and not a lot has been done on scheduling parallel recurring tasks	Introduces a scheduling algorithm 'MAS' that shortens the makespan of recurring DAG tasks compared to EDF	only compares EDF and MAS using one example of a DAG task for makespans and also only compares with EDF. Even though MAS shortens the makespan, it is less scalable than comparable algorithms.	The MAS algorithm integrates clustering, scheduling, and task duplication techniques and is evaluated using a TMS320C6678 simulation for measurements closely aligned with real-world results.
[20]	The capacity-bound measures performance and tests schedulability for DAG scheduling, but it may exclude schedulable tasks by using the same bound for normalized utilization and tensity.	Introduces a new bound called the util-tensity bound which proves to be a better schedulability test for GEDF with federated scheduling.	only looks at GEDF with federated scheduling and not other scheduling algorithms.	Uses GEDF for low-tensity tasks, federated scheduling for high-utilization, high-tensity tasks, and partitioned EDF for low-utilization, high-tensity tasks.
[26]	Decomposition-based scheduling can improve schedulability for DAG task scheduling but can also worsen it. It is, along with global scheduling, one of the main method to schedule DAG tasks.	Developed an efficient decomposition strategy and schedulability test. The resulting GEDF-based scheduling algorithm shows promising acceptance ratios.	Only looks at GEDF variants which is based on the EDF heuristics for priority assignments.	The decomposition works by first defining execution segments and then assigning subtasks to those segments based on their laxity so that there are no segments overloaded with workload.
[24]	The notion of degree of parallelism has been used for DAG task scheduling but lacks a clear definition in the research community.	Proposes a new response-time bound for DAG tasks as well as a new scheduling algorithm based on federated scheduling that outperforms the SOTA by more than 18% on average	They don't say which intra-task scheduling algorithm is used (just that it's work-conserving) and they don't consider intra-task scheduling.	They modify federated scheduling by optimizing core allocation for heavy tasks based on the degree of parallelism.
[29]	Many DAG intra-task scheduling algorithms overlook inter-core communication delays. In robotics and automotive applications, grouping subtasks on a single processor can reduce these delays by using the L1 cache.	Extend DAG to EG-DAG to bind subtasks to a single core, reducing communication delays. Their new scheduling algorithm shows similar performance to existing methods with lower overhead.	The evaluation has been done using only 100 DAG tasks which is quite low to cover all different types of DAG tasks. They propose a way to schedule multiple DAGs but do not offer evaluation results for that.	They use list scheduling with one list per execution group and use worst-fit heuristic to map the execution groups to the processors.
[19]	Federated scheduling works well for constrained deadlines but struggles with arbitrary deadline DAG tasks, especially with long WCET. Allowing job migration leads to pessimistic schedulability analysis.	Propose a new federated scheduling algorithm for arbitrary deadline DAG tasks with long WCETs. It outperforms other algorithms in acceptance ratio.	Doesn't tackle the problem of resource wasting when using federated scheduling or their new version of it.	The new federated algorithm addresses tasks with deadlines longer than periods and high densities, using standard federated scheduling for tasks with shorter deadlines and EDF-FF for low-density tasks.
[9]	The NP-hard nature of DAG multi-core scheduling makes ILP solutions time-consuming, leading researchers to explore scalable heuristics.	Uses Deep Reinforcement Learning to learn an optimal scheduling policy for DAG tasks, comparing it to the ILP method.	Doesn't compare the machine learning method with SOTA heuristics, but only compares with ILP.	They use a Graph Neural Network with attention layers to capture structure and dependencies, maximizing the negative makespan as the reward function.
[31]	Current methods for allocating shared resources in multi-core real-time systems use static analysis or heuristics, which may not cover all scenarios, leading to higher WCETs and reduced schedulability.	They use Deep Reinforcement learning to propose a holistic scheduling and allocation framework and their model shows better schedulability than existing methods.	Only considers independent periodic tasks and also only considers even-EDF and even-RM when comparing schedulability performance.	The platform has an LLC architecture with a shared memory bus. The DRL model uses MLP and proximal policy optimization to generate time-triggered schedules and memory allocations.
[25]	A previous work done by Zhao et al. [11] introduced a fixed-priority scheduling algorithm for DAG intra-task scheduling which performed better than SOTA but didn't extend the method to multi-DAG scheduling.	"Extends the CPC model from Zhao et al. [11] to multi-DAG scheduling with a Parallelism-aware workload distribution algorithm, improving system schedulability and outperforming existing methods.	Considers constrained deadlines DAG tasks for the analysis but only consider implicit deadlines DAG tasks for the experiment evaluation.	Uses a critical path first model, prioritizing nodes on the critical path and allocating parallel execution time to subtasks. For multi-DAG scheduling, they use a federated-like approach based on the degree of parallelism of the DAG tasks.

[10]	Several heuristics for DAG intra-task scheduling have been used but no scalable optimal scheduling algorithm exists.	Propose a DRL-based model for computing intra-task priorities in DAG scheduling, outperforming SOTA by up to 3% in makespan.	No ILP method comparison for minimum makespan is made, and scalability of the GoSu DRL model with more cores/subtasks isn't shown.	The network uses a Graph Convolutional Network and an attention-based decoder to generate a priority list, trained with REINFORCE using negative makespan as the reward.
[22]	Virtual scheduling, using threads as virtual processors, has been considered in the past but never for DAG task scheduling. The similar federated scheduling method suffers from resource wasting.	Use the concept of virtual processors to provide a virtually-federated scheduling algorithm which significantly outperforms other federated scheduling methods in terms of acceptance ratio.	Only considers implicit and constrained deadline DAG tasks and doesn't consider the running time overhead that the proposed method induces.	Introduce active and passive virtual processors (VPs) per core. The active VP executes high-priority tasks, while unused active VP time is treated as a passive VP for low or high-priority tasks.
[18]	Most DAG studies use implicit deadlines, with few focusing on arbitrary deadlines, especially when deadlines exceed the task period. Fluid scheduling shows promise but is only applied to implicit deadlines.	Propose a fluid scheduling algorithm for constrained and arbitrary deadline DAG tasks, introducing the first capacity bound for deadlines longer than periods. It outperforms SOTA in acceptance ratio (as of 2022).	As for every fluid scheduling based algorithm the issue of runtime overhead is not entirely considered as they don't evaluate this metric.	They first decompose each DAG task into segments of sequential tasks and then assign execution rates to each tasks or threads. Those two steps aim at producing a fluid schedule so that it appears as though each DAG task is continuously running on the cores.
[30]	Most scheduling algorithm that consider resource use consider it as constraints rather than considering them as part of the scheduling decision process.	Propose a DRL-based algorithm for task scheduling on the FRTDS simulation system, outperforming existing algorithms in makespan for single DAG tasks.	The reinforcement learning algorithm uses the previous tasks' execution as experience which implies a lot of memory usage, thus affecting the speed of execution.	It uses I/O and RAM allocation to create a cost function as the RL reward, combining current costs with future costs predicted from successor subtasks.
[21]	Federated scheduling has shown great potential for scheduling DAG tasks but suffers from a resource wasting problem which has been addressed but to a limited extent.	Propose a virtually-federated scheduling algorithm that reduces resource wastage while maintaining federated scheduling's benefits, and outperforms existing algorithms in acceptance ratio.	Only considers heavy tasks and constrained deadline DAG tasks.	Introduce Active and Passive VPs per core. Active VPs handle primary tasks and use excess capacity for Passive VPs. Allocation is based on deadlines, critical path length, and task usefulness.

results need to be reproducible, that is, one can get the exact same results by simply following the different steps described by the one writing the SLR. This is done by first defining a set of keywords to search for, i.e., a search string, and then identifying the databases to search on. The resulting articles are then filtered out using exclusion and/or inclusion criteria to narrow down the number of papers to review. Examples of such criterias are restricting the publication year-range, excluding certain types of articles (i.e., conferences, early-access, etc.), etc. The remaining articles are then screened by first reading their abstract and then, from the resulting filtered articles, their entire content, which further filters the articles found through the initial search. This process gives a final list of papers to review and compare against each other to correctly answer the research questions. It is especially useful to answer research questions such as RQ1 and RQ2 and to have a good representation of the state-of-the-Art but often will show the research gaps that exists in the literature, thus not fully answering a specific research question. To address these gaps, other research methods need to be considered.

B. Design Science

The design science methodology is focused on the creation and evaluation of artifacts intended to solve practical problems. It emphasizes the development of knowledge through the design and implementation of innovative solutions, such as algorithms, methods, tools, and frameworks, particularly in fields like software engineering[33]. For instance, one might design a new machine learning architecture or a new algorithm to better answer a specific problem, while rigorously detailing the design and evaluation aspect of this new technology or

system. Indeed, in this methodology, the designed artifact(s) need(s) to answer a precise problem, defined beforehand, and choices in the design must be clearly justified. The evaluation of the artifact(s) needs not only to answer research questions, but also demonstrate practical applications, thus balancing methodological rigor and practical utility. In our case, the problem of scheduling DAG tasks has important practical applications and according to the SLR, no one looked at supervised learning as a solution to generating priority-lists for global fixed-priority scheduling. The non-existence of a supervised learning model implies it needs to be created, or designed, which is exactly the purpose of the design science methodology. Hence, RQ3 will be answered by designing a supervised learning model and evaluating this potential solution to the fixed-priority DAG task scheduling problem.

C. Case study

A case study is useful at providing a great understanding of a real-life scenario that happened or that is currently happening, illustrating a specific issue with a real-life context. In a case study, you look closely at real-life observations to evaluate or investigate a design in the context of a real-life scenario[34]. It is especially used in the medical field to study and investigate a group of people and their eating habits or look at the effect of placebo in a control group compared to a medical substance to be tested on a test group. One can also use a case study methodology to study a specific phenomena and how an application react to it which can lead, in the case of a software application, to finding limitations or missing elements. Another use of the case study methodology is to address one or more real-life issues by analyzing a system

using multiple datasets. For instance, a case study might design a benchmark for testing certain types of applications. In this research, no real-life scenario will be considered as the data collected will be via a DAG task generator because real-life data collection is very time-consuming and isn't the focus of this study. Indeed, the focus will be on designing an artifact, rather than investigating an existing one, simply because there aren't any supervised learning model that has been found in the literature (see Section III). Therefore, the case study approach will not be used in this research.

D. Experiment

The experiment, or controlled experiment, methodology aims at identifying cause-effect chains by defining hypotheses and control variables on a specific system, and running multiple tests or experiments while having fixed and varying variables to assert their role in the system's behaviour[35]. The controlled experiment approach can provide insights on relationships between the controlled variables and the system which contributes to the body of knowledge of the specific system. This can be used, for instance, to observe and explain the impact of hyperparameters of a machine learning model on its performance. This approach has its drawbacks, the main one being that the experiment always has biases and doesn't fully reflect the reality of the matter. This drawback can be exacerbated when considering a small sample size or forgetting to take into account controlled variables that impact the results of the experiment, which is why great care needs to be taken for the design phase of the experiment(s). Nonetheless, the controlled experiment approach will be used in this research to validate or invalidate hypotheses about the designed AI model performances, especially when compared to the ILP method. It will answer RQ3 by not only evaluating the model designed using the design science methodology, but also experimenting with different values and parameters that are not part of the evaluation, to better grasp the behaviour and performances of the designed model. The drawback mentioned previously will be tackled using a random dag generator as well as a large DAG task set, to keep the observational bias to a minimum. Cross-validation of the model will also be used to minimize the impact of this drawback.

The SLR can answer research questions 1 and 2, by first collecting and comparing the different papers in the literature and then identifying not only the state-of-the-Art for scheduling DAG tasks on real-time systems, but also the machine learning techniques that are currently used in the literature as well as their drawbacks and limitations. The fact that only very few papers use machine learning to tackle the problem of real-time DAG task scheduling motivates the design of a new machine learning model to better answer RQ3 which implies applying the design science methodology to provide a more complete answer as to how a supervised machine learning model can compare to reinforcement learning models, heuristics, and also the ILP method. In addition, the controlled experiment ap-

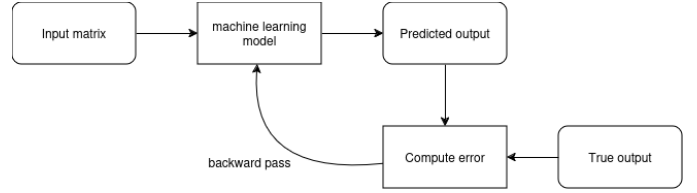


Fig. 4. The supervised learning method.

proach can help interpret the evaluation results of the designed model by playing with different hyperparameter sets and also providing an answer to the scalability aspect in RQ3.2. The time limitations of this study as well as the fact that the identified SOTA papers use a dag task generation script and not real-life dag tasks datasets, makes the use of the case study methodology not relevant in this research's context and not able to correctly compare the results with the SOTA papers.

V. SYSTEM DESIGN

No supervised learning model has been designed to tackle the non-preemptive, global fixed-priority scheduling problem for DAG tasks. Therefore, we must first design a supervised learning model.

In supervised learning, the machine learning model predicts an output (forward pass) and then computes the error between the predicted output and a known true output. The gradient of the error function is then propagated through the network to tweak the model's trainable parameters, which is also called the backward pass (see Figure 4).

A. Supervised design

1) Input DAGs:

Each input DAG task will be represented using a matrix of numbers with each row being a node and each column being a raw feature of a node. The list of raw features is similar to what is proposed by Lee et al. [10], that is :

- the normalized wcet of the node, i.e., C_i/L for node i with L being the total workload ;
- the number of incoming neighbours ;
- the number of outgoing neighbours ;
- a boolean value of whether the node is the source or sink node ;
- a boolean value of whether the node is part of the critical path of the DAG.

The wcet is widely used as a criteria for priority-list scheduling algorithm (RM, EDF[36], etc.) but it needs to be normalized to have the context information of the whole graph. The number of incoming and outgoing neighbours makes it possible to take into account the inner structure of the graph to compute the execution order. The source and sink nodes are particular nodes in that their priority is not important because they will respectively execute first and last due to their dependency constraints. Finally, the critical path plays

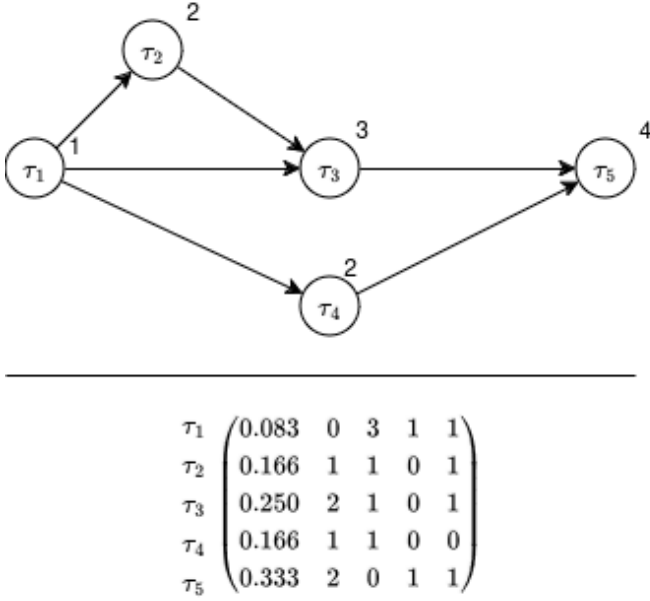


Fig. 5. Example dag task with 5 nodes a total workload of 12 and the matrix representation of each node with the column respectively being the above list of features.

	0	1	2	3	4
τ_1	0.25	0.15	0.40	0.10	0.10
τ_2	0.04	0.06	0.01	0.09	0.80
τ_3	0.50	0.35	0.08	0.02	0.05
τ_4	0.10	0.23	0.07	0.55	0.05
τ_5	0.30	0.52	0.08	0.04	0.06

\Rightarrow
 $\begin{matrix} \tau_1 \tau_2 & \tau_3 & \tau_4 \tau_5 \\ [2, 4, 0, 3, 1] \end{matrix}$

Fig. 6. Example of an matrix output from the model, the predicted list of priorities (on the right) is retrieved from the probabilities.

a huge role in state-of-the-art heuristics[27][11], with nodes in the critical path often having higher priorities than those that aren't. An example of such a DAG task representation is shown in Figure 5.

2) Output labels:

An Integer Linear Programming (ILP) solver will be used to compute the optimal (minimum makespan) schedule for each DAG task and then ordering the nodes according to their release time in the ILP schedule.

The output of the model will be a matrix of probabilities, with each row being the index of a node and each column being the index of the priority. There are as many priorities as there are nodes and the priority list of each DAG is then retrieved using the column index of the maximum probability as the assigned probability, for each row. Matrix output example for the DAG task shown in Figure 5 is shown in Figure 6.

The ILP output matrix to compare the predicted output to is of the same shape as the predicted output matrix with the probabilities being 1 on the optimal priority for each row, and 0 otherwise.

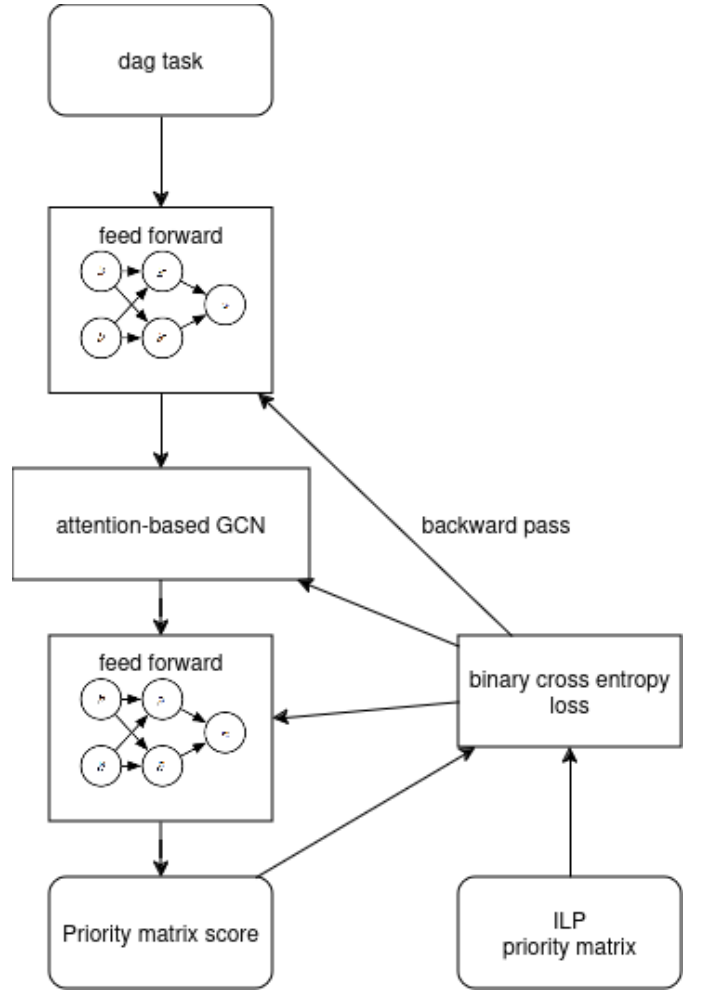


Fig. 7. The architecture diagram of the proposed supervised machine learning model.

3) Loss function:

The problem is being treated as a classification problem, hence the binary cross-entropy loss function will be used. This function is defined as follows :

$$loss(x, y) = \sum_{i=1}^n -y_i \log(x_i) \quad (2)$$

where x is the flattened matrix representing the predicted output, y is the flattened matrix representing the true output (ILP output), and n is the number of element in x and y .

B. Model design

The model's architecture is very similar to the proposed encoder in Lee et al. [10], that is, the model is comprised of three modules. Two feed forward networks and one attention-based graph convolutional network (see Figure 7).

1) Feed forward networks:

The two feed forward networks have 3 layers with each layer n producing the following output, where $W_n \in \mathbb{R}^{5 \times 5}$ is the matrix of trainable weights at layer n , $b_n \in \mathbb{R}^5$ is the bias

and X_n is either a node's vector representation or the output of the previous layer, and $ReLU(x) = \max(0, x)$:

$$o_n = ReLU(W_n X_n + b_n), n \in \{1, 2, 3\} \quad (3)$$

There is an exception for the second feed forward network where the last layer's output is computed using the following equation:

$$o_3 = \tanh(W_3 X_3 + b_3) \quad (4)$$

where $W_3 \in \mathbb{R}^{nbPriorities \times 5}$, $b_3 \in \mathbb{R}^{nbPriorities}$ and \tanh is the hyperbolic tangent activation function. Also, $nbPriorities$ corresponds to the number of different priorities that can be assigned to each node.

2) Graph Convolutional Network:

For each gc layer, the input vector X_k goes through an aggregation phase where, given the set of incoming neighbours of node v_i , $\mathcal{N}_{in}(v_i)$, which includes v_i , and the set of outgoing neighbours $\mathcal{N}_{out}(v_i)$, which also includes v_i , the next vector representation X_{k+1} is calculated by the following equation:

$$GCN(X) = AttentionModule(X, \mathcal{N}_{in}(v_i), \mathcal{N}_{out}(v_i)) \quad (5)$$

where *AttentionModule* is defined by the Equations 6–9:

$$AttentionModule(X, \mathcal{N}_{in}(v_i), \mathcal{N}_{out}(v_i)) = ELU(W(Att(X, \mathcal{N}_{in}(v_i)) \oplus Att(X, \mathcal{N}_{out}(v_i))) + b) \quad (6)$$

$$Att(X, \mathcal{N}(v_i)) = W \sum_{j \in \mathcal{N}(v_i)} \alpha_{ij} X_j \quad (7)$$

Where

$$\alpha_{ij} = \frac{\exp(a^T W X_i + b^T W X_j)}{\sum_{k \in \mathcal{N}(v_i)} \exp(a^T W X_i + b^T W X_k)} \quad (8)$$

are the attention coefficients which evaluates how important is v_j to v_i 's vector representation, similar to what is done in Lee et al. [10].

Every W , a , and b represent a different matrix of trainable parameters, and ELU is the exponential linear unit activation function (Equation 9).

$$ELU(x) = \begin{cases} x, & \text{if } x > 0 \\ \exp(x) - 1, & \text{if } x \leq 0 \end{cases} \quad (9)$$

The idea behind using attention is to make the model take into account the inner structure of the graph by looking at the importance of each node compared to its neighbour nodes. The GCN layer can be repeated several times to improve the model's capacity to better capture the complexity of the graph structure. Unfortunately, when testing with 3 GCN layers, we ran into an oversmoothing problem[37], which lead us to restrict the number of GCN layers to just one layer.

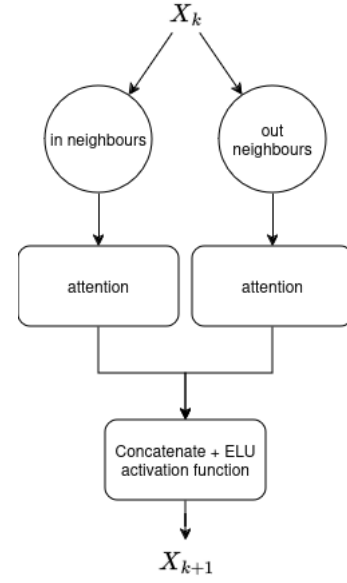


Fig. 8. Diagram of the graph convolution network layer. X_k is the transformed node vector representation and ELU is the exponential linear unit function (see Equation 9).

C. Computing the labels

Yip and Kuo [38] proposed an ILP-based scheduling solver for event-chains of time-triggered tasks using the Logical Execution Time paradigm[39]. Their work aimed at minimizing the sum of dependency delays between the job instances of each task and they have recently added support for multicore architectures⁴. It is this solver that will be slightly modified and used for computing the labels. The main modification is to replace the objective function, which initially was the sum of dependency delays (see the paper [38] for more details), by the end execution time of the sink node (i.e., the makespan) of the graph. This effectively makes the program minimize the makespan for an input graph which is precisely what we want. The other modifications involve setting the configuration parameters *useOffset*, *useHeterogeneousCores* and *restrictTaskInstancesToSameCore* to *False*.

To convert the input DAG task to an event-chain of LET task, each node of the graph is considered as a LET task with the LET interval being the wcet of the node and every node of a DAG task have the same period which is two times the total workload of the DAG.

VI. CONTRIBUTION 1

Oh by the way, [?] did some great work.
Give an overall summary of the steps involved.

VII. CONTRIBUTION 2

Give an overall summary of the steps involved.

⁴<https://github.com/mkuo005/LET-LP-Scheduler>

VIII. EXPERIMENTAL RESULTS

Set up: what experiments/benchmarks were chosen?

Execution of results: how were the experiments conducted?

Data: what was found to have happened?

Synthesis: what does the data mean?

Relevance: how does this work compare to others, and to what extent does it answer the RQs

Limitations:

IX. CONCLUSIONS AND FUTURE WORKS

ACKNOWLEDGEMENT

For referencing in LaTeX, check out: <https://texblog.org/2014/04/22/using-google-scholar-to-download-bibtex-citations/>

REFERENCES

- [1] H. Kopetz and G. Bauer, "The time-triggered architecture," *Proceedings of the IEEE*, vol. 91, no. 1, pp. 112–126, 2003.
- [2] H. Kopetz, "The time-triggered model of computation," in *Proceedings 19th IEEE Real-Time Systems Symposium (Cat. No. 98CB36279)*. IEEE, 1998, pp. 168–177.
- [3] C. Maiza, H. Rihani, J. M. Rivas, J. Goossens, S. Altmeyer, and R. I. Davis, "A survey of timing verification techniques for multi-core real-time systems," *ACM Computing Surveys (CSUR)*, vol. 52, no. 3, pp. 1–38, 2019.
- [4] D. Abbott, "Chapter 17 - linux and real-time," in *Linux for Embedded and Real-Time Applications (Fourth Edition)*, fourth edition ed., D. Abbott, Ed. Newnes, 2018, pp. 257–270.
- [5] C. L. Liu and J. W. Layland, "Scheduling algorithms for multiprogramming in a hard-real-time environment," *Journal of the ACM (JACM)*, vol. 20, no. 1, pp. 46–61, 1973.
- [6] S. Baruah, V. Bonifaci, A. Marchetti-Spaccamela, L. Stougie, and A. Wiese, "A generalized parallel task model for recurrent real-time processes," in *2012 IEEE 33rd Real-Time Systems Symposium*, 2012, pp. 63–72.
- [7] J. Du and J. Y.-T. Leung, "Complexity of scheduling parallel task systems," *SIAM Journal on Discrete Mathematics*, vol. 2, no. 4, pp. 473–487, 1989.
- [8] J. Ullman, "Np-complete scheduling problems," *Journal of Computer and System Sciences*, vol. 10, no. 3, pp. 384–393, 1975.
- [9] M. Zhao, L. Mo, J. Liu, J. Han, and D. Niu, "Gat-based deep reinforcement learning algorithm for real-time task scheduling on multicore platform," in *2024 36th Chinese Control and Decision Conference (CCDC)*, 2024, pp. 5674–5679.
- [10] H. Lee, S. Cho, Y. Jang, J. Lee, and H. Woo, "A global dag task scheduler using deep reinforcement learning and graph convolution network," *IEEE Access*, vol. 9, pp. 158 548–158 561, 2021.
- [11] S. Zhao, X. Dai, I. Bate, A. Burns, and W. Chang, "Dag scheduling and analysis on multiprocessor systems: Exploitation of parallelism and dependency," in *2020 IEEE Real-Time Systems Symposium (RTSS)*, 2020, pp. 128–140.
- [12] R. V. Book, "Richard m. karp. reducibility among combinatorial problems. complexity of computer computations, proceedings of a symposium on the complexity of computer computations, held march 20-22, 1972, at the ibm thomas j. watson center, yorktown heights, new york, edited by raymond e. miller and james w. thatcher, plenum press, new york and london 1972, pp. 85–103." *The Journal of Symbolic Logic*, vol. 40, no. 4, pp. 618–619, 1975.
- [13] T. Erlebach and K. Jansen, "The complexity of path coloring and call scheduling," *Theoretical Computer Science*, vol. 255, no. 1, pp. 33–50, 2001. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0304397599001528>
- [14] F. Guan, J. Qiao, and Y. Han, "Dag-fluid: A real-time scheduling algorithm for dags," *IEEE Transactions on Computers*, vol. 70, no. 3, pp. 471–482, 2021.
- [15] S. K. Baruah, N. K. Cohen, C. G. Plaxton, and D. A. Varvel, "Proportionate progress: A notion of fairness in resource allocation," in *Proceedings of the twenty-fifth annual ACM symposium on Theory of computing*, 1993, pp. 345–354.
- [16] H. Cho, B. Ravindran, and E. D. Jensen, "An optimal real-time scheduling algorithm for multiprocessors," in *2006 27th IEEE International Real-Time Systems Symposium (RTSS'06)*. IEEE, 2006, pp. 101–110.
- [17] A. Block and J. Anderson, "Accuracy versus migration overhead in real-time multiprocessor reweighting algorithms," in *12th International Conference on Parallel and Distributed Systems - (ICPADS'06)*, vol. 1, 2006, pp. 10 pp.–.
- [18] F. Guan, L. Peng, and J. Qiao, "A fluid scheduling algorithm for dag tasks with constrained or arbitrary deadlines," *IEEE Transactions on Computers*, vol. 71, no. 8, pp. 1860–1873, 2022.
- [19] —, "A new federated scheduling algorithm for arbitrary-deadline dag tasks," *IEEE Transactions on Computers*, vol. 72, no. 8, pp. 2264–2277, 2023.
- [20] X. Jiang, J. Sun, Y. Tang, and N. Guan, "Utilization-tensity bound for real-time dag tasks under global edf scheduling," *IEEE Transactions on Computers*, vol. 69, no. 1, pp. 39–50, 2020.
- [21] X. Jiang, N. Guan, H. Liang, Y. Tang, L. Qiao, and Y. Wang, "Virtually-federated scheduling of parallel real-time tasks," in *2021 IEEE Real-Time Systems Symposium (RTSS)*, 2021, pp. 482–494.
- [22] X. Jiang, H. Liang, N. Guan, Y. Tang, L. Qiao, and Y. Wang, "Scheduling parallel real-time tasks on virtual processors," *IEEE Transactions on Parallel and Distributed Systems*, vol. 34, no. 1, pp. 33–47, 2023.
- [23] T. Kobayashi and T. Azumi, "Work-in-progress: Federated and bundled-based dag scheduling," in *2023 IEEE Real-Time Systems Symposium (RTSS)*, 2023, pp. 443–446.

- [24] Q. He, N. Guan, M. Lv, and Z. Gu, "On the degree of parallelism in real-time scheduling of dag tasks," in *2023 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, 2023, pp. 1–6.
- [25] S. Zhao, X. Dai, and I. Bate, "Dag scheduling and analysis on multi-core systems by modelling parallelism and dependency," *IEEE Transactions on Parallel and Distributed Systems*, vol. 33, no. 12, pp. 4019–4038, 2022.
- [26] X. Jiang, N. Guan, X. Long, and H. Wan, "Decomposition-based real-time scheduling of parallel tasks on multicore platforms," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 39, no. 10, pp. 2319–2332, 2020.
- [27] Q. He, x. jiang, N. Guan, and Z. Guo, "Intra-task priority assignment in real-time scheduling of dag tasks on multi-cores," *IEEE Transactions on Parallel and Distributed Systems*, vol. 30, no. 10, pp. 2283–2295, 2019.
- [28] S. Xiao, D. Li, and S. Wang, "Periodic task scheduling algorithm for homogeneous multi-core parallel processing system," in *2019 IEEE International Conference on Unmanned Systems (ICUS)*, 2019, pp. 710–713.
- [29] J. Shi, M. Gtintel, N. Ueter, G. v. der Bruggen, and J.-J. Chen, "Dag scheduling with execution groups," in *2024 IEEE 30th Real-Time and Embedded Technology and Applications Symposium (RTAS)*, 2024, pp. 149–160.
- [30] Y. Guan, B. Zhang, and Z. Jin, "An frtfs real-time simulation optimized task scheduling algorithm based on reinforcement learning," *IEEE Access*, vol. 8, pp. 155 797–155 810, 2020.
- [31] Z. Xu, Y. Zhang, S. Zhao, G. Chen, H. Luo, and K. Huang, "Drl-based task scheduling and shared resource allocation for multi-core real-time systems," in *2023 IEEE 3rd International Conference on Intelligent Technology and Embedded Systems (ICITES)*, 2023, pp. 144–150.
- [32] B. Kitchenham, O. Pearl Brereton, D. Budgen, M. Turner, J. Bailey, and S. Linkman, "Systematic literature reviews in software engineering – a systematic literature review," *Information and Software Technology*, vol. 51, no. 1, pp. 7–15, 2009, special Section - Most Cited Articles in 2002 and Regular Research Papers. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0950584908001390>
- [33] R. Wieringa, "Design science methodology: principles and practice." New York, NY, USA: Association for Computing Machinery, 2010.
- [34] C. Sarah, C. Kathrin, R. Ann, H. Guro, A. Anthony, and S. Aziz, "The case study approach," *BMC Research Medical Methodology*, vol. 11, no. 1, p. 100, 2011.
- [35] V. R. Basili, "The role of controlled experiments in software engineering research," in *Empirical Software Engineering Issues. Critical Assessment and Future Directions: International Workshop, Dagstuhl Castle, Germany, June 26-30, 2006. Revised Papers*. Springer, 2007, pp. 33–37.
- [36] G. C. Buttazzo, "Rate monotonic vs. edf: Judgment day," *Real-Time Systems*, vol. 29, pp. 5–26, 2005.
- [37] D. Chen, Y. Lin, W. Li, P. Li, J. Zhou, and X. Sun, "Measuring and relieving the over-smoothing problem for graph neural networks from the topological view," in *Proceedings of the AAAI conference on artificial intelligence*, vol. 34, no. 04, 2020, pp. 3438–3445.
- [38] E. Yip and M. M. Kuo, "Letsynchronise: An open-source framework for analysing and optimising logical execution time systems," in *Proceedings of Cyber-Physical Systems and Internet of Things Week 2023*, 2023, pp. 349–354.
- [39] C. M. Kirsch and A. Sokolova, "The logical execution time paradigm," *Advances in Real-Time Systems*, pp. 103–120, 2012.