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► **To cite this version:**

Sonia Ben Mokhtar, Louis-Claude Canon, Anthony Dugois, Loris Marchal, Etienne Rivière. Taming Tail Latency in Key-Value Stores: a Scheduling Perspective (extended version). 2021. hal-03144818v1

**HAL Id: hal-03144818**

**<https://inria.hal.science/hal-03144818v1>**

Preprint submitted on 17 Feb 2021 (v1), last revised 12 Mar 2021 (v2)

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# Taming Tail Latency in Key-Value Stores: a Scheduling Perspective (extended version)

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**Abstract.** Distributed key-value stores employ replication for high availability. Yet, they do not always efficiently take advantage of the availability of multiple replicas for each value, and read operations often exhibit high tail latencies. Various replica selection strategies have been proposed to address this problem, together with local request scheduling policies. It is difficult, however, to determine what is the absolute performance gain each of these strategies can achieve. We present a formal framework allowing the systematic study of request scheduling strategies in key-value stores. We contribute a definition of the optimization problem related to reducing tail latency in a replicated key-value store as a minimization problem with respect to the maximum weighted flow criterion. By using scheduling theory, we show the difficulty of this problem, and therefore the need to develop performance guarantees. We also study the behavior of heuristic methods using simulations, which highlight which properties are useful for limiting tail latency: for instance, the EFT strategy—which uses the earliest available time of servers—exhibits a tail latency that is less than half that of state-of-the-art strategies, often matching the lower bound. Our study also emphasizes the importance of metrics such as the stretch to properly evaluate replica selection and local execution policies.

**Keywords:** Online Scheduling · Key-Value Store · Replica Selection · Tail Latency · Lower Bound

## 1 Introduction

Online services are used by a large number of users accessing ever-increasing amounts of data. One major constraint is the high expectation of these users in terms of service responsiveness. Studies have shown that an increase in the average latency has direct effects on the use frequency of an online service, e.g., experiments at Google have shown that an additional latency of 400 ms per request for 6 weeks reduced the number of daily searches by 0.6 % [18].

In modern cloud applications, data storage systems are important actors in the evolution of overall user-perceived latency. Considerable attention has been given, therefore, to the performance predictability of such systems. Serving a single user request usually requires fetching multiple data items from the storage system. The overall latency is often that of the slowest request. As a result, a very small fraction of slow requests may result in overall service latency degradation for many users. This problem is known as the *tail latency problem*. In large-scale deployments of cloud applications, it has been observed that the 95<sup>th</sup> and 99<sup>th</sup> percentiles in the query distribution show latency values that can be several orders of magnitude higher than the median [3, 24].

In this study, we focus on the popular class of storage systems that are key-value stores, where each value is simply bound to a specific key [25, 41]. These systems scale horizontally by distributing responsibility for

fractions of the key space across a large number of storage servers. They ensure disjoint-access parallelism, high availability and durability by relying on data *replication* over several servers. As such, read requests may be served by any of these replica.

Replica selection strategies [33, 35, 56] dynamically schedule requests to different replicas in order to reduce tail latency. When the request reaches the selected replica, it is inserted into a queue and a local queue scheduling strategy may decide to prioritize certain requests over others. These combinations of global and local strategies are well adapted to the distributed nature of key-value stores, as they assume no omniscient or real-time knowledge of the status of each replica, or of concurrently-scheduled requests. It remains difficult, however, to systematically assess their potential. On the one hand, there is no clear upper bound on the performance that a global, omniscient strategy could theoretically achieve. On the other hand, it is difficult to determine what is the impact of using only local or partial information on achievable performance. Our goal in this paper is to bridge this gap, and equip designers of replica selection and local scheduling strategies with tools enabling their formal evaluation. By modeling a corresponding scheduling problem, we develop a number of guarantees that apply to a variety of designs.

*Outline.* We make the following contributions:

- a formal model to describe replicated key-value stores and the scheduling problem associated to the minimization of tail latency (Section 3);
- a polynomial-time offline algorithm, a  $(2 - \frac{1}{m})$ -approximation guarantee and a NP-completeness result for related scheduling problems (Section 4);
- online heuristics to solve the online optimization of maximum weighted flow, representing compromises in locally available information at the different servers of the key-value store (Section 6);
- the comparison of these heuristics in extensive simulations (Section 7).

The algorithms, the related code, data and analysis are available online<sup>5</sup>.

## 2 Related Work

We review related work on key-value stores and system contributions for reducing latency, and on latency minimization work in scheduling theory.

### 2.1 Dealing with Tail-Latency in Key-Value Stores

The principles of key-value stores were first documented by Amazon with Dynamo [25]. Cassandra [41] is a widely-used open-source key-value store, following principles similar to that of Dynamo; other popular key-value stores include Redis [19], memcached [36], and document stores such as MongoDB [22].

Key-value stores implement data partitioning for horizontal scalability. Typically, data is spread over a cluster of servers using consistent hashing. This consists of treating the output of a hashing function as a ring; each server is then assigned a position on this circular space and becomes responsible of all data between it and its predecessor (the position of a data item is decided by hashing the corresponding key) [25, 41]. Replication is implemented on top of data partitioning, by duplicating each data item on the successors of its assigned server. Fig. 1 shows an example of a cluster with a replication factor of 3: value whose keys' hash values fall in the range of  $M_2$  can also be requested from servers  $M_3$  and  $M_4$ .

Design and implementation improvements have been proposed to improve response time and in particular reduce tail-latency in key-value stores. They include the use of redundant requests [57, 58], performing smart resource allocation [28], or employing hybrid scheduling [26, 27]. We are interested in this paper in replica selection strategies [33, 35, 56]. The server receiving a request (or coordinator) is generally not the one in charge of the corresponding key. All servers know, however, the partitioning and replication plan. Coordinators can therefore associate a key with a list of replicas, and select the most appropriate to query. Cassandra uses

<sup>5</sup> <https://doi.org/10.6084/m9.figshare.13114196>

Dynamic Snitching [41], a strategy based on load histories for the different servers. It selects the replica with the lowest average load over a time window. This strategy is prone to instabilities, as lowly-loaded servers tend to receive swarm of requests. C3 [56] is an adaptive replica selection strategy that can quickly react to heterogeneous service times and mediate this instability and resulting load unbalance. Dynamic snitching and C3 both assume that values are served with the same latency. This does not reflect the reality of storage workloads, where values may be highly heterogeneous in size [3]. Requests for small values may be scheduled behind requests for large values, creating a head-of-line blocking problem and increasing tail latency. Coordinator servers do not have, however, directly access to the size of data items, and only know the requested key. Héron [33] addresses this problem by propagating across the cluster the identity of values whose size is over a threshold, together with load information and pending requests to such large values. This information is stored at each coordinator using a Bloom filter, and Héron avoids scheduling requests for small values behind pending requests for large values. While the above solutions empirically improve tail latency there is no evidence that better solutions do not exist as the proposed heuristics are not based on any formal ground. On the other side of the spectrum, scheduling theory has studied related problems as discussed in the following section.

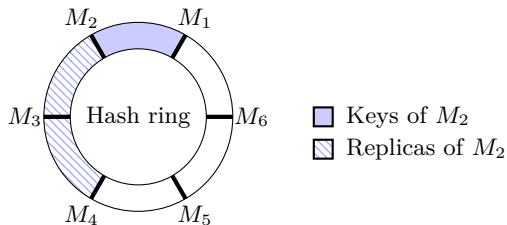


Fig. 1. Data partitioning and replication on a cluster of 6 servers.

## 2.2 Latency Minimization in Scheduling Theory

Minimization of latency under a set of constraints in online systems is the subject of a rich literature in scheduling theory. This property—the time a request spends in the system—is more commonly called “flow time” in theoretical works, and a great diversity of scheduling problems deal with the optimization of this criterion. The traditional functions that constitute the objective to minimize are the max-flow ( $F_{\max}$ ) and the sum-flow ( $\sum F_i$ ).

*Minimizing maximum (weighted) flow* It is well-known that the maximum flow criterion is minimized by the FIFO (First In First Out) strategy on a single-machine [14]. This scheme is also  $(3 - \frac{2}{m})$ -competitive on  $m$  machines when preemption is allowed or not [14], and Ambühl et al. gave a  $(2 - \frac{1}{m})$ -competitive algorithm for the preemptive case, which is optimal [1]. Sometimes the maximum weighted flow is considered  $\max w_i F_i$  in order to give more importance to some requests. For example Bender et al. introduced the stretch, where the weight is the inverse of the request serving time ( $w_i = 1/p_i$ ), to express and study the notion of fairness for scheduling HTTP requests in web servers [14]. For single-machine problems, they proved that no polynomial-time algorithm can approximate the offline non-preemptive problem of optimizing the max-stretch criterion within a factor  $\Omega(n^{1-\varepsilon})$ , for any  $\varepsilon > 0$ , unless  $P = NP$ . They also exhibit an FPTAS for the preemptive case, and they derive an  $O(\sqrt{\Delta})$ -competitive algorithm from the EDF (Earliest Deadline First) strategy, with  $\Delta$  being the ratio between the largest processing time to the smallest one ( $\Delta = \frac{\max p_i}{\min p_i}$ ). Later, Legrand et al. presented a polynomial-time algorithm to solve the offline minimization of max weighted flow time on unrelated machines when preemption is allowed [43]. The FIFO strategy is also shown to be  $\Delta$ -competitive for the online problem of minimizing the max-stretch on one machine, and a lower bound of  $\frac{1}{2}\Delta^{\sqrt{2}-1}$  is derived. Saule et al. improved this result by showing a lower bound of  $\frac{1}{2}(1 + \Delta)$  on a single server and

$\frac{1}{2}(1 + \frac{\Delta}{m+1})$  on  $m$  servers [52]. Finally, Dutot et al. closed the online problem of minimizing the stretch on a single machine by proving a lower bound of  $\frac{1}{2}\Delta(\sqrt{5} - 1)$ , which is tight [29]. Some additional works deal with the minimization of maximum weighted flow time under different assumptions and models [2, 7, 47].

Table 4 provides a more exhaustive summary of results on max-flow minimization.

*Minimizing sum (weighted) flow* Optimizing the average performance is obtained through minimizing the sum flow time criterion. It is well known that this problem is hard without preemption, while the preemptive version can be polynomially solved by the SRPT (Shortest Remaining Processing Time) strategy [5]. Kellerer et al. gave an  $O(\sqrt{n})$ -approximation algorithm for the non-preemptive case, and proved that no polynomial-time algorithm can approximate the offline non-preemptive problem of minimizing the sum-flow within a factor  $\Omega(n^{\frac{1}{2}-\varepsilon})$ , for any  $\varepsilon > 0$ , unless  $P = NP$  [38]. On  $m$  servers, Leonardi et al. analyzed SRPT and showed a competitive ratio of  $O(\min(\log \Delta, \log \frac{n}{m}))$  [45]. They provide a lower bound of  $\Omega(n^{\frac{1}{3}-\varepsilon})$  on the approximability of this problem, unless  $P = NP$ . For the weighted sum flow, SRPT has been proven 2-competitive on a single server, and 14-competitive on parallel machines [50]. Note that one must be careful when using the (weighted) sum flow time criterion, as it may lead to starvation: some requests may be infinitely delayed in an optimal solution [14]. This is one reason why we discard this criterion in our study.

There also exists a number of results about weighted sum-flow. For the sum-stretch criterion, one such result is that SRPT is 2-competitive on a single server and 14-competitive on parallel machines [50]. Chekuri et al. improved this last competitiveness result by providing a 9.82-competitive algorithm on  $m$  machines, and a 17.32-competitive algorithm for non-migratory version of the problem [21]. They also present a  $(2 + \varepsilon)$ -approximation for the offline optimization of weighted sum-flow on one machine.

For a more detailed survey about sum-flow optimization, see Table 5.

*Replication in scheduling* An important consequence of replication is that a given request cannot be executed by any server; it must be processed by a server in the subset of replicas able to handle it. In scheduling literature, this constraint is known as “multipurpose machines”, “processing set restrictions” or even “eligibility constraints”. Brucker et al. proposed a formalization and analyzed the complexity of some of these problems [15], by introducing the  $\mathcal{M}_i$  term in the classical  $\alpha|\beta|\gamma$  notation. They also used a routine based on solving the minimum cost matching problem to polynomially solve  $Q|\mathcal{M}_i, p_i = 1|\sum w_i U_i$  and  $P|\mathcal{M}_i, r_i, p_i = 1|\sum w_i U_i$ . Another notable result is that  $P|\mathcal{M}_i, pmtn|\sum C_i$  can be solved in polynomial time by transforming any preemptive schedule in a non-preemptive one without worsening the objective. A more recent survey is also proposed by Leung et al. [46], and Shabtay et al. treated a similar problem where there are two job types that can be processed by a specific subset of machines [53].

To the best of our knowledge, there exists no work considering replication for the minimization of the maximum (weighted) flow.

### 3 Formal Model

We propose a formal model of a distributed and replicated key-value store. This section describes the theoretical framework and states the optimization problem related to the minimization of tail latency.

#### 3.1 Application and Platform Models

We start by defining a key-value map  $(K, V)$  as a set of associations between keys and values. We associate  $c$  keys  $K = \{K_1, \dots, K_c\}$  to  $c$  values  $V = \{V_1, \dots, V_c\}$ : each unique key  $K_l$  refers to a unique value  $V_l$  whose size is  $z_l > 0$ .

The considered problem is to schedule a set of  $n$  requests  $T = \{T_1, \dots, T_n\}$  on  $m$  parallel servers  $M = \{M_1, \dots, M_m\}$  in a replicated key-value store. The set  $K$  is spread over these servers. For one server  $M_j$ , the function  $\Psi$  gives the subset of keys  $\Psi(M_j) \subseteq K$  that is owned by  $M_j$ . Each request  $T_i$  carries a key that will be used to retrieve a specific value in the store. For one request  $T_i$ , the function  $\varphi$  gives this key  $\varphi(T_i) = K_l$ . The same key can be carried by different requests. Fig. 2 shows the relationship between requests, keys and

values. A server  $M_j$  may execute a request  $T_i$  if and only if  $\varphi(T_i) \in \Psi(M_j)$ , i.e.,  $M_j$  holds the value for the carried key of  $T_i$ .

All requests are independent: no request has to wait for the completion of another request, and no communication occurs between requests. We limit ourselves to the non-preemptive problem, as real implementations of key-value stores generally do not interrupt requests.

In addition, each request  $T_i$  has a processing time  $p_i = \alpha z_i + \beta$ , where  $\alpha, \beta > 0$  (with  $\varphi(T_i) = K_l$ ). Processing time is equal to the average network latency  $\beta$  plus data sending time, which is proportional to the size of the value this request is looking for (factor  $\alpha$  represents the inverse of the bandwidth). A request is also unavailable before time  $r_i \geq 0$  and its properties are unknown as well.

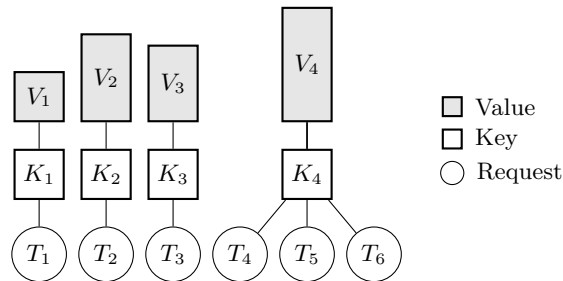
As a server  $M_j$  may execute a request  $T_i$  only if it holds the key  $\varphi(T_i)$ , we treat the multipurpose machines scheduling problem where the set  $\mathcal{M}_i \subseteq M$  represents the set of machines able to execute the request  $T_i$ , i.e.,  $\mathcal{M}_i = \{M_j \mid \varphi(T_i) \in \Psi(M_j)\}$ . In the Graham  $\alpha|\beta|\gamma$  notation of scheduling problems, this constraint is commonly denoted by  $\mathcal{M}_i$  in the  $\beta$ -part. This aspect of the problem models data replication on the cluster. Key-value stores tend to express the replication factor, i.e., the number of times the same data is duplicated, as a parameter  $k$  of the system. Therefore, we have  $|\mathcal{M}_i| = k$ .

### 3.2 Problem Statement

There is no objective criterion that can straightforwardly represent the formal optimization of tail latency, as there is no formal definition of this system concept. Different works consider the 95<sup>th</sup> percentile, the 99<sup>th</sup> percentile, or the maximum, and it should be highlighted that we do not want to degrade average performance too much. We propose to approach the tail latency optimization by minimizing a well-known criterion in online scheduling theory: the maximum time spent by requests in the system, also known as the maximum flow time  $\max F_i$ , where  $F_i = C_i - r_i$  expresses the difference between the completion time  $C_i$  and the release time  $r_i$  of a request  $T_i$ .

However, it seems unfair to wait longer for a request for a small value to complete than for a large one: for example, we know that a user’s tolerance for the response time of a real system is greater when a process considered to be heavy is in progress. Hence, the latency should be weighted to emphasize the relative importance of a given request; we are looking for a “fairness” property. To formalize this idea, we associate a weight  $w_i$  to each  $T_i$ . The definition of this weight is flexible, in order to allow the key-value store system designer to consider different kinds of metrics. We focus on three weighting strategies in our simulations. First, the flow time ( $w_i = 1$ ) gives an importance to each request that is proportional to its cost, which favors requests for large values. Second, the stretch ( $w_i = \frac{1}{p_i}$ ) gives the same importance to each request, but this favors requests for small values because they are more sensitive to scheduling decisions. Third, the square root of the processing time inverse ( $w_i = \frac{1}{\sqrt{p_i}}$ ) constitutes a compromise between the two previous cases.

In summary, our optimization problem consists in finding a schedule minimizing the maximum weighted flow time  $\max w_i F_i$  under the following constraints:



**Fig. 2.** A bipartite graph showing relations between requests, keys and values. Different requests may hold the same key (e.g.  $K_4$ ).

- $P$ : there are  $m$  parallel identical servers.
- $\mathcal{M}_i$ : each request  $T_i$  is executable by a subset of servers.
- online- $r_i$ : each request  $T_i$  has a release time  $r_i \geq 0$  and request characteristics  $(r_i, p_i$  and  $w_i)$  are not known before  $r_i$ .

A solution to this problem ( $P|\mathcal{M}_i, \text{online-}r_i|\max w_i F_i$ ) is to find a schedule  $\Pi$ , which, for a request  $T_i$ , gives its executing server and starting time. Then we define a pair  $\Pi(T_i) = (M_j, \sigma_i)$ , where the server  $M_j$  executes  $T_i$  at time  $\sigma_i \geq r_i$ . Server  $M_j$  must hold the required value ( $M_j \in \mathcal{M}_i$ ), and there are no simultaneous executions: two different requests cannot be executed at the same time on the same server.

As mentioned earlier, we are also interested in minimizing the average latency ( $\sum w_i F_i$ ) as a secondary objective; even if the main goal is to reduce tail latency, it would not be reasonable to degrade average performance doing so. This bi-objective problem could be approached by the optimization of the more general  $\ell_p$ -norm function of flow times [10], but it is left for future work.

## 4 Maximum Weighted Flow Optimization

In order to evaluate the performance of replica selection heuristics, it would be interesting to derive optimal or guaranteed algorithms for the offline version of our problem, namely the minimization of the maximum weighted flow time of requests, or even for restricted variants. We show here that we can derive optimal or approximation algorithms when tasks are all released at time 0, but as soon as we introduce release dates, the problem gets harder to tackle. Nevertheless, a lower bound can be computed.

### 4.1 Without Release Times

We first focus on the non-preemptive problem of minimizing the maximum weighted flow time on a single server when there is no release times, i.e., all requests are available at time 0. Remark that in this case, the more common completion times equivalently replace flow times (i.e.,  $C_i = F_i$ ). We consider a simple algorithm named SINGLE-SIMPLE (Algorithm 1) which schedules requests by non-increasing order of weights  $w_i$ , to solve this scheduling problem.

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#### Algorithm 1 SINGLE-SIMPLE

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**Input:**  $w_i$

**Output:** a schedule

- 1: schedule requests by non-increasing order of  $w_i$
  - 2: **return** schedule
- 

**Theorem 1.** SINGLE-SIMPLE (Algorithm 1) solves  $1||\max w_i C_i$  in polynomial time.

*Proof.* Let  $OPT$  be an optimal schedule. If all requests are ordered by non-increasing weight, then SINGLE-SIMPLE is optimal. If they are not, we can find two consecutive requests  $T_j$  and  $T_k$  in  $OPT$  such that  $w_j \leq w_k$ . Then, their contribution to the objective is  $\mathcal{C} = \max(w_j C_j, w_k(C_j + p_k)) = w_k(C_j + p_k)$  because  $w_j C_j \leq w_j(C_j + p_k) \leq w_k(C_j + p_k)$ . If we swap the requests, then the contribution becomes  $\mathcal{C}' = \max(w_k C'_k, w_j(C'_k + p_j))$  where  $C'_k$  is the completion time of request  $T_k$  in this new schedule. By construction,  $C_j + p_k = C'_k + p_j$ . We have  $w_k C'_k \leq w_k(C'_k + p_j)$ ,  $w_j(C'_k + p_j) \leq w_k(C'_k + p_j)$  and  $w_k(C'_k + p_j) = w_k(C_j + p_k) = \mathcal{C}$ . Therefore,  $\max(w_k C'_k, w_j(C'_k + p_j)) = \mathcal{C}' \leq \mathcal{C}$ .

It follows that if two consecutive requests are not ordered by non-increasing weight in  $OPT$ , we can switch them without increasing the objective. By repeating the operation request by request, we transform  $OPT$  in another optimal schedule where requests are sorted by non-increasing  $w_i$ . Hence, SINGLE-SIMPLE is optimal.  $\square$

SINGLE-SIMPLE does not extend to  $m$  parallel machines in the general case. However, it solves the case where all requests have homogeneous size  $p$ .

**Theorem 2.** SINGLE-SIMPLE (Algorithm 1) solves  $P|p_i = p|\max w_i C_i$  in polynomial time.

*Proof.* We use the same kind of argument than for the single-machine case. Let  $OPT$  be an optimal schedule. If all requests are ordered by non-increasing weight, then SINGLE-SIMPLE is optimal. If they are not, let  $T_j$  and  $T_k$  be two requests in  $OPT$  such that  $w_j \leq w_k$ . By definition,  $p_j = p_k = p$ . Without loss of generality, we consider that there is no idle time intervals in  $OPT$ , and  $T_j$  starts at time  $t$ , whereas  $T_k$  starts at time  $t + cp$  with  $c \geq 0$  (on any server).

Their contribution is  $\mathcal{C} = \max(w_j C_j, w_k(C_j + cp)) = w_k(C_j + cp)$  because  $w_j C_j \leq w_k C_j \leq w_k(C_j + cp)$ . If we switch  $T_j$  and  $T_k$ , then the contribution is  $\mathcal{C}' = \max(w_k C'_k, w_j(C'_k + cp))$ . By construction,  $C'_k + cp = C_j + cp$ , i.e.,  $C'_k = C_j$ . We have  $w_k C'_k = w_k C_j \leq w_k(C_j + cp)$  and  $w_j(C'_k + cp) = w_j(C_j + cp) \leq w_k(C'_k + cp)$ . Hence,  $\mathcal{C}' \leq \mathcal{C}$ .

It follows that we can transform  $OPT$  in another optimal schedule by switching repeatedly non-sorted requests. Then, SINGLE-SIMPLE is optimal.  $\square$

For  $m$  machines when processing times are not identical, the problem is trivially NP-hard even with unit weights because  $P||C_{\max}$  is NP-hard [44]. We prove that SINGLE-SIMPLE is an approximation algorithm.

**Theorem 3.** SINGLE-SIMPLE (Algorithm 1) computes a  $(2 - \frac{1}{m})$ -approximation for the problem  $P||\max w_i C_i$ , and this ratio is tight.

*Proof.* Let us consider a schedule  $S$  built by SINGLE-SIMPLE and an optimal schedule  $OPT$ . We denote by  $T_j$  the request for which  $w_j C_j = \max w_i C_i^S$ , i.e., the request that reaches the objective in  $S$ . Then we remove from  $S$  and  $OPT$  all  $T_i$  such that  $w_i < w_j$  (it does not change the objective  $\max w_i C_i^S$  in  $S$  and can only decrease  $\max w_i C_i^{OPT}$  in  $OPT$ ). Let  $C_{\max}^*$  denote the optimal makespan when scheduling only the remaining requests. As  $S$  is a list-scheduling (in the sense of Graham), we have  $C_{\max}^S \leq (2 - \frac{1}{m}) \cdot C_{\max}^*$  [32], where  $C_{\max}^S$  is the completion time of the last request in  $S$  (i.e.,  $C_j = C_{\max}^S$ ). Let  $T_k$  be the last completed request in  $OPT$ , such that  $C_k = C_{\max}^{OPT}$ . This makespan is bounded by the optimal one (i.e.,  $C_{\max}^* \leq C_k^{OPT}$ ). Therefore,

$$\begin{aligned} \max w_i C_i^S &= w_j C_j^S = w_j C_{\max}^S \leq \left(2 - \frac{1}{m}\right) \cdot w_j C_{\max}^* \\ &\leq \left(2 - \frac{1}{m}\right) \cdot w_j C_k^{OPT} = \left(2 - \frac{1}{m}\right) \cdot \frac{w_j}{w_k} \cdot w_k C_k^{OPT} \\ &\leq \left(2 - \frac{1}{m}\right) \cdot \frac{w_j}{w_k} \cdot \max w_i C_i^{OPT}. \end{aligned}$$

As we removed all requests weighted by a smaller value than  $w_j$ , we have  $\frac{w_j}{w_k} \leq 1$  and it follows that  $\max w_i C_i^S \leq (2 - \frac{1}{m}) \cdot \max w_i C_i^{OPT}$ . We now prove that this bound is asymptotically tight, by considering the instance with  $m$  machines and  $n = m(m - 1) + 1$  requests  $T_{1 \leq i \leq n}$  with the following weights and processing times:

- $w_i = W + 1, p_i = 1$  for all  $1 \leq i < n$ ;
- $w_n = W, p_n = m$ .

Request  $T_n$  will be scheduled last in  $S$ , which gives an objective of  $\max w_i C_i^S = (2m - 1)W$ , whereas an optimal schedule starts this request at time 0 and has an objective of  $\max w_i C_i^{OPT} = m(W + 1)$ . On this instance, the approximation ratio  $(2 - \frac{1}{m}) \cdot \frac{W}{W+1}$  tends to  $2 - \frac{1}{m}$  as  $W \rightarrow \infty$ .  $\square$



## 4.2 Offline Problem With Release Times

Legrand *et al.* solved the scheduling problem  $R|r_i, pmtn|\max w_i F_i$  in polynomial time using a linear formulation of the model [43]. This offline problem is very similar to the one we are interested in, as the platform relies on unrelated machines, which generalizes our parallel multipurpose machines environment ( $P|\mathcal{M}_i|\max w_i F_i$  is a special case of  $R|\max w_i F_i$  [46]). In fact, it only differs on one specific aspect: it allows preempting and migrating jobs, which we do not permit in our model.

We establish below the complexity of the problem  $P|r_i, pmtn^*|\max w_i F_i$ , where non-migratory<sup>6</sup> preemption is allowed. Interestingly, preventing migration makes the problem NP-complete. The proof of this result (available in the report [13]) consists in a reduction from the NP-complete problem  $P||C_{\max}$  [44].

**Definition 1 (NonMigratory-Dec( $T, M, B$ )).** *Given a set of requests  $T$ , a set of machines  $M$  and a bound  $B$ , if we define the deadline  $d_i = r_i + \frac{B}{w_i}$  for all  $T_i$ , is it possible to build a non-migratory preemptive schedule where each request meets its deadline?*

**Theorem 4.** *The problem NONMIGRATORY-DEC( $T, M, B$ ) is NP-complete.*

*Proof.* We prove the NP-completeness of this problem by reduction from  $P||C_{\max}$ , which is NP-complete [44]. Obviously, NONMIGRATORY-DEC( $T, M, B$ ) belongs to NP.

**Building instance.** We consider an instance  $I_1$  of the decision problem associated to  $P||C_{\max}$ : given a set of requests  $T'$ , a set of servers  $M'$  and a bound  $B'$ , is it possible to schedule each request  $T'_i$  non-preemptively on  $M'$  such that  $C_{\max} = B'$ ? We construct the following instance  $I_2$  of NONMIGRATORY-DEC( $T, M, B$ ) from  $I_1$ . We first set  $M = M'$  and  $B = B'$ . For each request  $T'_i$  we define a request  $T_i$  to which we associate a release time  $r_i = 0$  and a weight  $w_i = 1$ ; hence,  $d_i = B$ .  $I_2$  can clearly be constructed in polynomial time in the size of  $I_1$ .

**Equivalence of problems.** A solution to  $I_1$  trivially constitutes a non-preemptive (thus non-migratory) solution to  $I_2$ .

Assume now that  $I_2$  has a solution  $S$ . It means that for each server  $M_j$ , we know a set  $A_j \subseteq T$  of requests that are preemptively scheduled on  $M_j$  exclusively (recall migration is not allowed), and  $\max_{T_i \in A_j} C_i^S$  is the makespan of  $M_j$  in  $S$ . For each request  $T_i$ , we denote the associated set of  $n_i$  processing intervals by  $\Lambda_i = \{(\sigma_{i,k}, \delta_{i,k}) \mid 1 \leq k \leq n_i\}$ , where  $\sigma_{i,k}$  is the start time of the  $k$ -th processing interval of  $T_i$  and  $\delta_{i,k}$  is its duration. For all  $i, k$ ,  $\sigma_{i,k} + \delta_{i,k} \leq \sigma_{i,k+1}$ , and for all  $j$ ,

$$\begin{aligned} \max_{T_i \in A_j} C_i^S &= \sum_{T_i \in A_j} \sum_{k=1}^{n_i} \delta_{i,k} \\ &\leq C_{\max}^S = B. \end{aligned}$$

We can build a solution  $S'$  to  $I_1$  by removing preemptions from  $S$ , i.e., for each request  $T_i$ , we rearrange its  $n_i$  intervals (without migrating them) such that for all  $k$ ,  $\sigma_{i,k} + \delta_{i,k} = \sigma_{i,k+1}$ . As we only switch processing intervals of requests, it does not change the makespan values of servers, therefore,

$$\begin{aligned} \max_{T_i \in A_j} C_i^{S'} &= \sum_{T_i \in A_j} \sum_{k=1}^{n_i} \delta_{i,k} \\ &= \max_{T_i \in A_j} C_i^S \\ &\leq C_{\max}^S = B = B'. \end{aligned}$$

□

<sup>6</sup> We express non-migratory preemption as  $pmtn^*$  in the  $\beta$ -part, not to be confused with the classic  $pmtn$  constraint.

### 4.3 Online Problem

We now study problems in an online context, where properties of requests are not known before their respective release time. We prove that there exists no optimal online algorithm for the minimization of maximum weighted flow even on the very simple case of a single machine and unit request sizes, as outlined in the following theorem.

**Theorem 5.** *No online algorithm can be optimal for the scheduling problem  $1|\text{online-}r_i, p_i = 1|\max w_i F_i$ .*

*Proof.* Let us prove this by building an example instance. We consider 10 requests  $T_{1 \leq i \leq 10}$  with the following weights and release times:

- $w_i = 3, r_i = i - 1$  for all  $1 \leq i \leq 8$ ;
- $w_9 = 1, r_9 = 0$ ;
- $w_{10} = 1, r_{10} = 0$ .

We can construct an optimal schedule  $OPT$  by starting  $T_9$  and  $T_{10}$  before  $T_8$ , which gives an objective of  $\max w_i F_i^{OPT} = 9$ . Now let  $T_{11}$  be a request released at  $r_{11} = 9$  with a weight  $w_{11} = 11$ . The new optimal schedule  $OPT'$  has to schedule  $T_8$  before  $T_{11}$ , i.e.,  $T_9$  or  $T_{10}$  will start last, to obtain an objective of  $\max w_i F_i^{OPT'} = 11$ .  $OPT'$  cannot be built from  $OPT$ ; adding a new request may lead to reconsider our previous scheduling choices. Hence, the competitive ratio is always strictly greater than 1.  $\square$

We now present an adaptation of SINGLE-SIMPLE to the online case, restricted to unit tasks, SINGLE-UNIT (Algorithm 2): at each time step, we consider all submitted requests at this time and schedule the one whose flow (if processed now) is the largest. This gives priority to the currently most impacting requests.

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#### Algorithm 2 SINGLE-UNIT

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**Input:**  $w_i, r_i$

**Output:** a schedule

- 1: **for** each time  $t$  with at least one available request **do**
  - 2:   execute request with highest  $w_i(t + 1 - r_i)$
  - 3: **end for**
  - 4: **return** schedule
- 

Unfortunately, even on unit size tasks, this strategy does not lead to an approximation algorithm, as outlined by the following theorem.

**Theorem 6.** *The competitive ratio of SINGLE-UNIT (Algorithm 2) is arbitrarily large for the scheduling problem  $1|\text{online-}r_i, p_i = 1|\max w_i F_i$ .*

*Proof.* First, we build an instance designed to reach an arbitrary large ratio. Then, we determine a lower bound on the objective achieved with SINGLE-UNIT and finally, an upper bound on the optimal one.

*Instance characteristics.* For an arbitrary competitive ratio  $k \geq 1$ , we build the following instance with  $n$  requests. The first  $k$  requests have a processing cost of  $w_i = k$  and release time  $r_i = 0$ . Then, a new request arrives at each new time step with a processing cost that is the highest integer lower than or equal to  $1 + \frac{1}{k}$  times the previous submitted request (i.e.,  $w_i = \lfloor (1 + \frac{1}{k})w_{i-1} \rfloor$  and  $r_i = i - k$  for  $k < i \leq n$ ). In total,  $n = k^2 + 11$  requests are submitted.

*SINGLE-UNIT lower bound.* At time  $t = 0$ , SINGLE-UNIT starts one of the first  $k$  requests because they are the only ones that are ready. We now prove that at any time  $t$  such that  $1 \leq t < k$ , SINGLE-UNIT starts one of the remaining first  $k$  requests, which delays all arriving requests (any request  $T_i$  such that  $k < i < 2k$ ). On one hand,  $w_i(t+1-r_i) = k(t+1)$  for any of the first  $k$  requests ( $1 \leq i \leq k$ ). On the other hand, for  $k < i \leq n$ ,  $w_i \leq (1 + \frac{1}{k})w_{i-1}$  and thus,  $w_i \leq (1 + \frac{1}{k})^{i-k}k$ . Therefore,  $w_i(t+1-r_i) \leq (1 + \frac{1}{k})^{i-k}k(t+1-i+k)$ . It remains to prove that at any time  $t$  such that  $1 \leq t < k$ , any of the first requests has the highest value, that is  $k(t+1) \geq (1 + \frac{1}{k})^{i-k}k(t+1-i+k)$  for all  $k < i \leq t+k$ . By changing variables ( $j = i - k$  and  $t' = t + 1$ ), this corresponds to proving  $(1 + \frac{1}{k})^j(t' - j) \leq t'$  for all  $1 \leq j < t' \leq k$ . We show by induction that  $(1 + \frac{1}{k})^j(t' - j) \leq t'$  for all  $0 \leq j$  and for a given  $t' \geq 2$  and  $k \geq t'$ . The induction basis with  $j = 0$  is direct ( $t' \leq t'$ ). The induction step assumes  $(1 + \frac{1}{k})^j(t' - j) \leq t'$  to be true for a given  $j \geq 0$ .

$$\begin{aligned} (1 + \frac{1}{k})^{\frac{t'-j-1}{t'-j}} &= (1 + \frac{1}{k})(1 - \frac{1}{t'-j}) \\ &= 1 + \frac{1}{k} - \frac{1}{t'-j} - \frac{1}{k(t'-j)} \leq 1 \end{aligned}$$

The last line is obtained by remarking that  $t' \leq k$  and  $j \geq 0$ . Thus,  $\frac{1}{k} \leq \frac{1}{t'-j}$ . Therefore,  $(1 + \frac{1}{k})^{j+1}(t' - (j + 1)) = (1 + \frac{1}{k})^j(t' - j)(1 + \frac{1}{k})^{\frac{t'-j-1}{t'-j}} \leq t'$ , which concludes the induction proof.

At time  $t = k$ , all of the first  $k$  requests have been completed. We now prove that at any time  $t$  such that  $k \leq t < n$ , SINGLE-UNIT starts request  $T_{t+1}$ . This would mean that at time  $t$ , only requests  $T_i$  such that  $t < i \leq t+k$  are ready and not completed. We prove by induction that at time  $k \leq t < n$ , all requests  $T_i$  with  $i \leq t$  are completed. The induction basis with  $t = k$  is already proved above. Assume the hypothesis is true for a given  $k \leq t < n$ , it remains to prove that at time  $t' = t + 1$ ,  $T_{t+2}$  is started among requests  $T_i$  such that  $t' < i \leq t' + k$ . On one hand,  $w_i(t' + 1 - r_i) = w_{t+2}k$  for request  $T_{t+2}$ . On the other hand, for  $t' + 1 < i \leq t' + k$ ,  $w_i(t' + 1 - r_i) \leq (1 + \frac{1}{k})^{i-t'-1}w_{t+2}(t' + 1 - i + k)$ . It remains to prove that  $(1 + \frac{1}{k})^{i-t'-1}w_{t+2}(t' + 1 - i + k) < w_{t+2}k$  for  $t' + 1 < i \leq t' + k$  and for a given  $k \leq t < n$ . By changing variables ( $j = i - t' - 1$ ), this corresponds to proving  $(1 + \frac{1}{k})^j(k - j) < k$  for all  $0 < j < k$ . We show this again by induction on  $j$  for a given  $k \geq 1$ . For the induction basis,  $(1 + \frac{1}{k})(k - 1) = k + 1 - 1 - \frac{1}{k} < k$ . For the induction step, we can show that  $(1 + \frac{1}{k})^{\frac{k-j+1}{k-j}} \leq 1$  by remarking that  $k > k - j$ , which concludes the induction proof.

To conclude on the performance of SINGLE-UNIT, request  $T_i$  is started at time  $t = i - 1$  and therefore, the objective value is at least  $w_n F_n = w_n(C_i - r_i) = kw_n$ .

*Optimal upper bound.* A better objective value can be obtained by starting all requests as soon as they arrive except for the first  $k$  ones: request  $T_1$  is started at time  $t = 0$ ; then, request  $T_i$  is started at time  $t = i - k$  for  $k < i \leq n$ ; finally, the remaining requests among the first  $k$  ones are started ( $T_i$  is started at time  $t = n - k + i - 1$  for  $1 < i \leq k$ ). We analyse the objective value for request  $T_k$  because it is the last one to be executed among the first  $k$  requests, and  $T_n$  because it is the one with the highest weight among the last  $n - k$  requests. For  $T_k$ ,  $w_k F_k = k(C_k - r_k) = kn$ . For  $T_n$ ,  $w_n F_n = w_n$ .

We prove that  $w_n \geq kn$  by deriving a lower bound on  $w_n$ . The weights increase in multiple stages. At first, each increment is unitary  $w_{i+1} = w_i + 1$  for  $k \leq i < 2k$ . Then, the increment increases at the second stage and  $w_{i+1} = w_i + 2$  for  $2k \leq i < 2k + \lceil k/2 \rceil$ . At the  $k$ th stage,  $w_{i+1} = w_i + k$  for a single request. At a given stage  $j$ , the increment of the weight is  $j$  for at most  $\lceil k/j \rceil$  requests. Let  $n_1 = \sum_{j=1}^k \lceil k/j \rceil$  be the number of such requests (assuming  $n - k \geq n_1$ ). Finally, the remaining  $n_2 = n - k - n_1$  requests are incremented by a value that increases by at least 1 for each new request:  $w_{i+1} \geq w_i + (k + i - n + n_2)$  for  $n - n_2 < i \leq n$ .

The last weight  $w_n$  is at least the sum of the increments of all these stages:  $w_n \geq k + \sum_{j=1}^k j \lceil k/j \rceil + \sum_{j=1}^{n_2} (k+j)$ . Thus,  $w_n \geq k(k+1) + kn_2 + n_2^2/2$ . Our hypothesis is that  $w_n \geq kn$ , which would be verified if

$$\begin{aligned} k(k+1) + kn_2 + n_2^2/2 &\geq kn \\ k(k+1) + k(n-k-n_1) + (n-k-n_1)^2/2 &\geq kn \\ 2k(1-n_1) + (n-k-n_1)^2 &\geq 0 \\ n-k-n_1 &\geq \sqrt{2k(n_1-1)} \\ n &\geq k+n_1 + \sqrt{2k(n_1-1)}. \end{aligned}$$

We bound  $n_1$  using the asymptotic expansion of the harmonic number  $H_k$ :

$$\begin{aligned} n_1 = \sum_{j=1}^k \lceil k/j \rceil &< \sum_{j=1}^k k/j + k \\ &< k(H_k + 1) \\ &< k(\log(k) + \gamma + \frac{1}{2k} + 1) \end{aligned}$$

where  $\gamma \approx 0.577$  is the Euler-Mascheroni constant. What remains to be proved is

$$n \geq k(\log(k) + \gamma + \frac{1}{2k} + 2) + \sqrt{2(\log(k) + \gamma + \frac{1}{2k} + 1)}.$$

Numerical analysis shows this occurs when  $n = k^2 + 11$ , which proves that  $w_n \geq kn$ .

Thus, the optimal objective is at most  $w_n$  and the one achieved with SINGLE-UNIT is at least  $kw_n$ , which concludes the proof.  $\square$

## 5 Lower Bound

We have seen that our initial scheduling problem, with heterogeneous processing times, no preemption and in an online setting is far from being solvable or even approximable. This motivates the search of lower bounds to constitute a formal baseline and derive performance guarantees. One way to do this is to compute an optimal solution to the offline problem (or a relaxed version) and compare it to a solution generated by an online heuristic.

### 5.1 Maximum Weighted Flow with Machines Restrictions

We propose an ILP (Integer Linear Program) to solve the scheduling problem  $P|\mathcal{M}_i, r_i, p_i = 1|\max w_i F_i$ , which we adapt to provide a lower bound to the case with arbitrary processing times  $p_i$ . We denote allocations of requests to servers by  $x_{i,j,t}$ :  $x_{i,j,t} = 1$  if request  $T_i$  is allocated to server  $M_j$  at time  $t$ , and 0 otherwise.  $x_{i,j,t}$  is defined for each request  $T_i \in T$ , for each server  $M_j \in \mathcal{M}_i$ , for all times  $r_i \leq t \leq \tau$  where  $\tau = \max_i r_i + n$ , which yields at most  $nk\tau$  variables. Then solving the Mixed Integer Linear Program (1) provides a solution to the scheduling problem:

- we want to minimize the maximum weighted flow time (Equation (1a));
- each request must be scheduled (Equation (1b),  $n$  constraints);
- each request starts after its release time (Equation (1c),  $n$  constraints);
- there is no simultaneous execution on the same machine (Equation (1d),  $k\tau$  constraints).

$$\mathbf{minimize} \quad \max_i w_i \left[ \left( \sum_{j,t} t \cdot x_{i,j,t} \right) + p_i - r_i \right] \quad (1a)$$

$$\mathbf{subject\ to} \quad \forall i, \sum_{j,t} x_{i,j,t} = 1 \quad (1b)$$

$$\forall i, \sum_{j,t} t \cdot x_{i,j,t} \geq r_i \quad (1c)$$

$$\forall j, \forall t, \sum_i x_{i,j,t} \leq 1 \quad (1d)$$

$$x_{i,j,t} \in \{0, 1\} \quad (1e)$$

In order to constitute a lower bound for the problem with arbitrary processing times, we transform each non-unitary request and we adapt the objective. Each request  $T_i$  arriving at time  $r_i$  with a processing time  $p_i$  is replaced with  $p_i$  requests arriving at times  $r_i, r_i + 1, \dots, r_i + p_i - 1$ . The new objective function to minimize is  $\max_{i'} w_{i'}(C_i - r_{i'})$  where  $i'$  is the index of the original non-unitary request.

Even if this ILP theoretically constitutes a lower bound to the considered problem, its resolution is unfortunately too difficult in practice for non-trivial instances that would be representative ( $n > 1000$  requests). A more practical solution would require to reduce the number of variables and constraints, or relax the model to a pure Linear Program. Alternatively, we tackle these performance issues by focusing on another related problem that is polynomially solvable and provides a lower bound to our scheduling problem.

## 5.2 Maximum Weighted Flow with Preemption

The solution to  $R|r_i, pmtn|\max w_i F_i$  provides such a lower bound, which is found by performing a binary search on a Linear Program [43], followed by the reconstruction scheme from Lawler *et al.* [42]. In order to facilitate the work for the reader, we explain the complete procedure here (refer to the mentioned articles for details about the correctness).

The algorithm of Legrand *et al.* relies on the fact that this problem is equivalent to the deadline scheduling problem: we want to find the minimum objective  $f$  such that, when we fix a deadline  $d_i(f) = r_i + \frac{f}{w_i}$  to each request  $T_i$ , it is possible to find a feasible schedule where all requests are executed during their feasible interval  $[r_i, d_i(f)]$ .

We define the ordered set of epochal times  $E^f = \{r_1, \dots, r_n, d_1(f), \dots, d_n(f)\}$ , for any value  $f$ . Each epochal time  $E_t^f$  has a position  $t$  in the set, and let  $\mathcal{T}_r(i)$  (resp.  $\mathcal{T}_d(i)$ ) give the position of the value  $r_i$  (resp.  $d_i(f)$ ) in  $E^f$ . Adjacent epochal times constitute time intervals  $[E_t^f, E_{t+1}^f]$  (of course, for  $t = 2n$ , the considered interval is  $[E_t^f, +\infty[$ ).

It is critical to observe that the relative ordering of epochal times only changes for specific values  $f$ , i.e., there is an ordered set  $\{\mathcal{F}_k\} \in 2^{\mathbb{Q}}$  such that, for all  $k$  and for any  $f, g \in ]\mathcal{F}_k, \mathcal{F}_{k+1}[$ ,  $f < g$ , the relative ordering of  $E^f$  is the same as the relative ordering of  $E^g$ . Each  $\mathcal{F}_k$  is called a milestone, and corresponds to a value  $f$  for which one deadline is equal to the release time or the deadline of another request.

*Computing milestones.* We first need to get the set of milestones, i.e., all values  $f$  for which the relative ordering of epochal times  $E^f$  changes. This happens when the deadline of a request  $T_i$  coincides with the release time or the deadline of a request  $T_j$ , with  $i \neq j$ . There are two cases to consider:

- $d_i(f) = r_j \implies r_i + \frac{f}{w_i} = r_j \implies f = w_i(r_j - r_i)$ ;
- $d_i(f) = d_j(f) \implies r_i + \frac{f}{w_i} = r_j + \frac{f}{w_j} \implies f = \frac{w_i w_j}{w_j - w_i}(r_j - r_i)$ , where  $w_i \neq w_j$ <sup>7</sup>.

<sup>7</sup> With different release times, two deadlines will never coincide if  $w_i = w_j$ .

*Solving in a milestone interval.* Let  $\mathcal{F}_1$  and  $\mathcal{F}_2$  be two consecutive milestones. We want to know if there exists  $f \in [\mathcal{F}_1, \mathcal{F}_2]$  such that a preemptive deadline scheduling is feasible, and if so, get the minimal one. Let  $x_{i,j,t}$  be the fraction of  $T_i$  processed by  $M_j$  during the time interval  $[E_t^f, E_{t+1}^f]$ . Then the Linear System (2) provides a solution:

- we want to minimize the objective value (Equation (2a));
- each request must be completely processed (Equation (2b));
- the total processing time during a time interval cannot exceed its capacity (Equation (2c));
- the processing time of a request during a time interval cannot exceed its capacity, i.e., a given request cannot be simultaneously executed by several servers (Equation (2d));
- a request cannot be executed before its release time (Equation (2e));
- a request cannot be executed after its deadline (Equation (2f)).

$$\mathbf{minimize} \quad f \tag{2a}$$

$$\mathbf{subject\ to} \quad \forall i, \sum_{j,t} x_{i,j,t} = 1 \tag{2b}$$

$$\forall j, \forall t, \sum_i x_{i,j,t} \cdot p_{i,j} \leq E_{t+1}^f - E_t^f \tag{2c}$$

$$\forall i, \forall t, \sum_j x_{i,j,t} \cdot p_{i,j} \leq E_{t+1}^f - E_t^f \tag{2d}$$

$$\forall i, \forall j, \forall t, \mathcal{T}_r(i) \geq t + 1 \implies x_{i,j,t} = 0 \tag{2e}$$

$$\forall i, \forall j, \forall t, \mathcal{T}_d(i) \leq t \implies x_{i,j,t} = 0 \tag{2f}$$

$$\mathcal{F}_1 \leq f \leq \mathcal{F}_2 \tag{2g}$$

*Optimal solution.* We have the set of milestones and a way to obtain the optimal solution in a milestone interval if there is one, hence we are able to find the globally optimal objective value by performing a binary search on the set of milestones. Let us now build the schedule from the provided solution  $f$ .

*Schedule reconstruction.* Let us assume that we are considering the  $t$ -th time interval  $[E_t^f, E_{t+1}^f]$  (we will repeat the same procedure for all intervals, and concatenate the partial schedules). First, we build the  $m \times n$  cost matrix  $A$  such that  $A_{j,i} = x_{i,j,t} \cdot p_{i,j}$ , which represents the fraction of request that should be executed during the current time interval. The procedure is to build iteratively the schedule by choosing a subset  $\mathcal{D}$  of elements in  $A$ , called the decrementing set (at most one element per row and per column), and a time length  $\delta$  at each step, until all elements of  $A$  are equal to zero. Let us construct the  $(m+n) \times (m+n)$  bistochastic matrix

$$B = \left( \begin{array}{c|c} A & D_m \\ \hline D_n & A^T \end{array} \right),$$

where  $A^T$  is the transpose of  $A$ , and  $D_m$  (resp.  $D_n$ ) is an  $m \times m$  (resp.  $n \times n$ ) diagonal matrix whose elements are such that each row sum and column sum of  $B$  is equal to  $E_{t+1}^f - E_t^f$ . As stated by the Birkhoff-von Neumann theorem, each bistochastic matrix is a convex combination of permutation matrices, i.e.,  $B = \sum_k c_k \mathcal{P}_k$ , where each  $c_k$  is a coefficient and  $\mathcal{P}_k$  is a  $(m+n) \times (m+n)$  permutation matrix. The top-left  $m \times n$  block of any  $\mathcal{P}_k$  gives a decrementing set  $\mathcal{D}$  to schedule in the current iteration: if  $\mathcal{P}_{k_j,i} = 1$ , then  $A_{j,i} \in \mathcal{D}$ , which means the request  $T_i$  may be executed by the server  $M_j$ .

We now compute the maximum processing time  $\delta$  allowed during the current iteration. We denote a row  $j$  in  $A$  as tight if its sum is equal to  $E_{t+1}^f - E_t^f$ , and slack otherwise. The same terminology is used for a column  $i$ .  $\delta$  is chosen to be maximum subject to the following constraints:

- if  $A_{j,i} \in \mathcal{D}$  and is in a tight row or column, then  $\delta \leq A_{j,i}$ ;
- if  $A_{j,i} \in \mathcal{D}$  and is in a slack row, then  $\delta \leq A_{j,i} + (E_{t+1}^f - E_t^f) - \sum_k A_{j,k}$ ;

- if  $A_{j,i} \in \mathcal{D}$  and is in a slack column, then  $\delta \leq A_{j,i} + (E_{t+1}^f - E_t^f) - \sum_k A_{k,i}$ ;
- if row  $j$  contains no element of  $\mathcal{D}$ , then  $\delta \leq (E_{t+1}^f - E_t^f) - \sum_k A_{j,k}$ ;
- if column  $i$  contains no element of  $\mathcal{D}$ , then  $\delta \leq (E_{t+1}^f - E_t^f) - \sum_k A_{k,i}$ .

Finally, for each  $A_{j,i} \in \mathcal{D}$ ,  $T_i$  is scheduled on  $M_j$  as soon as possible for  $\min(\delta, p_{i,j})$  time units, and  $A_{j,i}$  is replaced by  $\max(0, A_{j,i} - \delta)$  in  $A$ .

## 6 Online Heuristics

We recall that a solution to our problem consists, for each request, in choosing a server among the ones holding a replica of the requested data as well as a starting time for each request. These two decisions appear at different places in a real key-value store: the selection strategy  $R$  used by the coordinator gives a replica  $R(T_i) = M_r$ , whose execution policy  $E_r$  defines the request starting time  $E_r(T_i) = \sigma_i$ . This section describes several online replica selection heuristics and execution policies that we then compare by simulation.

### 6.1 Replica Selection

We consider several replica selection heuristics with different levels of knowledge about the cluster state. Some of these levels are hard to achieve in a real system; for instance, the information about the load of a given server will often be slightly out of date. Similarly, the information about the processing time can only be partial, as the size of the requested value cannot be known by the coordinator for large scale data sets, and practical systems generally employ an approximation of this metric, e.g., by keeping track of size *categories* of values using Bloom filters [33]. However, we exploit this exact knowledge in our simulations to estimate the maximal performance gain that a given type of information allows. We now describe selection heuristics.

**RANDOM.** The replica is chosen uniformly at random among compatible servers:  $M_r = \text{rand } \mathcal{M}_i$ . This strategy has no particular knowledge.

**LEASTOUTSTANDINGREQUESTS (LOR).** Let  $\mathcal{R}(M_j)$  be the number of outstanding requests sent to  $M_j$ , i.e., the number of sent requests that received no response yet. The chosen replica minimizes  $\mathcal{R}(M_j)$ :

$$M_r = \underset{M_j \in \mathcal{M}_i}{\operatorname{argmin}} \mathcal{R}(M_j).$$

It is easy to implement, as it only requires local information; in fact, it is one of the most commonly used in load-balancing applications [56].

**HÉRON.** We also consider an omniscient version of the replica selection heuristic used by Héron [33]. It identifies requests for values with size larger than a threshold, and avoids scheduling other requests behind such a request for a large value by marking the chosen replica as *busy*. When the request for a large value completes, the replica is marked *available* again. The replica is chosen among compatible servers that are *available* according to the scoring method of C3 [56]. The threshold is chosen according to the wanted proportion of large requests in the workload.

**EARLIESTFINISHTIME (EFT).** Let  $\text{FINISHTIME}(M_j)$  denote the earliest time when the server  $M_j$  becomes available, i.e., the time at which it will have emptied its execution queue. The chosen replica is the one with minimum  $\text{FINISHTIME}(M_j)$  among compatible servers:

$$M_r = \underset{M_j \in \mathcal{M}_i}{\operatorname{argmin}} \text{AVAILTIME}(M_j).$$

Knowing  $\text{FINISHTIME}$  is hard in practice, because it assumes the existence of a mechanism to obtain the exact current load of a server. A real system would use a degraded version of this heuristic.

EARLIESTFINISHTIME-SHARDED (EFT-S). For this heuristic, servers are specialized: we define small servers, which execute only requests for small values, and large servers, which execute all requests for large values and some requests for small values when possible (similarly to size-aware sharding [28]). Each request for a large value is scheduled on large servers using the EFT strategy, while each request for a small value is scheduled on any server (small or large), also using EFT.

For the following experiments, we define large servers as the set of servers  $\{M_b\}_{1 \leq b \leq m}$  such that  $b \bmod k = 0$  (recall  $k$  is the replication factor). This makes sure that one server in each interval  $\mathcal{M}_i$  is capable of treating requests for large values. We define a threshold parameter  $\omega$  to distinguish between requests for small and large values: requests with duration larger than  $\omega$  are treated by large servers only, while others can be processed by all available servers.

We derive the threshold  $\omega$  from the size distribution. In the best case, when all servers in each interval of replicas are perfectly balanced, requests for small values are scheduled on small servers only and requests for large values on large servers only. It means that the total work is  $k$  times larger than the work on large servers on average. Let  $X$  be the random variable that models the size distribution, and  $f_X$  denote its probability density function. We denote by  $p(X) = \alpha X + \beta$  the duration of the corresponding request (where  $\alpha$  is the inverse of the bandwidth and  $\beta$  the latency), and by  $p_\omega(X)$  the duration if it is a large value (and zero otherwise), that is:

$$p_\omega(X) = \begin{cases} p(X) & \text{if } p(X) \geq \omega \\ 0 & \text{otherwise.} \end{cases}$$

Then, the expected work on large servers when any request is submitted is

$$E[p_\omega(X)] = \int_{x=0}^{\frac{\omega-\beta}{\alpha}} 0 f_X(x) dx + \int_{x=\frac{\omega-\beta}{\alpha}}^{\infty} (\alpha x + \beta) f_X(x) dx.$$

It should be equal to the expected work when any request is submitted,  $E[p(X)]$ , divided by  $k$ . This leads to finding  $\omega$  such that:

$$E[p_\omega(X)] = \frac{1}{k} \cdot E[p(X)]. \quad (3)$$

This heuristic has to be able to distinguish requests for small and large values with respect to  $\omega$ ; it could be achieved in practice with combined Bloom filters, in a similar fashion than Héron [33].

STATICWINDOW (*SW*). The requests are no longer scheduled on reception, but every  $q$  time units, where  $q$  is a parameter of the heuristic. The set  $Q$  denotes the requests received during this window of  $q$  time units. Let  $t$  be the time at which requests from  $Q$  must be scheduled (requests with  $t < r_i \leq t + q$  form the next batch and must be scheduled at time  $t + q$ ). We assume here a centralized system, where a unique scheduler receives and schedules all requests. The underlying idea is to be able to make choices based on more exhaustive workload information than previous greedy heuristics. This heuristic must therefore also decide the order in which the requests of  $Q$  are scheduled. We derive two versions.

**StretchSuff-SW (SSSW).** This strategy is inspired from the Sufferage heuristic [48]. Let  $\mathcal{S}$  be the function giving the estimated stretch [14]  $\mathcal{S}(T_i, M_j) = \frac{1}{p_i} (\max(r_i, \text{AVAILTIME}(M_j)) + p_i - r_i)$  of  $T_i$  when scheduled on  $M_j$  as soon as possible. Let  $\rho(T_i) = \operatorname{argmin}_{M_j \in \mathcal{M}_i} \mathcal{S}(T_i, M_j)$  be the “best” server for  $T_i$ , i.e., the one minimizing its stretch value, and  $\rho'(T_i) = \operatorname{argmin}_{M_j \in \mathcal{M}_i \setminus \rho(T_i)} \mathcal{S}(T_i, M_j)$  be the “second best” server for  $T_i$ . Then, we define the stretch sufferage value  $\text{SUFF}(T_i) = \mathcal{S}(T_i, \rho'(T_i)) - \mathcal{S}(T_i, \rho(T_i)) > 0$  as the difference of stretch values on  $\rho'(T_i)$  and  $\rho(T_i)$ . The request we choose to schedule is the one which suffers the most if we schedule it on its second best server:

$$T_s = \operatorname{argmax}_{T_i \in Q} \text{SUFF}(T_i).$$

The chosen replica is  $\rho(T_s)$ :

$$M_r = \rho(T_s) = \operatorname{argmin}_{M_j \in \mathcal{M}_i} \mathcal{S}(T_s, M_j).$$



---

**Algorithm 3** STRETCHSUFF-SW

---

```
1: loop {every  $q$  time units}
2:   for all  $T_i \in Q$  do
3:      $\rho(T_i) \leftarrow \operatorname{argmin}_{M_j \in \mathcal{M}_i} \mathcal{S}(T_i, M_j)$ 
4:      $\rho'(T_i) \leftarrow \operatorname{argmin}_{M_j \in \mathcal{M}_i \setminus \rho(T_i)} \mathcal{S}(T_i, M_j)$ 
5:      $\text{SUFF}(T_i) \leftarrow \mathcal{S}(T_i, \rho'(T_i)) - \mathcal{S}(T_i, \rho(T_i))$ 
6:   end for
7:   while  $Q$  is not empty do
8:      $T_s \leftarrow \operatorname{argmax}_{T_i \in Q} \text{SUFF}(T_i)$ 
9:     schedule  $T_s$  on  $\rho(T_s)$ 
10:     $Q \leftarrow Q \setminus \{T_s\}$ 
11:    update  $\rho$ ,  $\rho'$  and SUFF
12:  end while
13: end loop
```

---

Request  $T_s$  is then removed from  $Q$ , and we update sufferage values of remaining requests. Algorithm 3 describes this procedure. This strategy runs in time  $O(n^2 \cdot m)$  and uses a space  $O(n)$  per time window.

**StretchMaxMin-SW (SMSW)**. This strategy is inspired from the Max-Min heuristic [48]. We build a matrix  $\text{MAT}$  whose rows are requests of set  $Q$  and columns are servers, where

$$\text{MAT}[T_i, M_j] = \begin{cases} \mathcal{S}(T_i, M_j) & \text{if } M_j \in \mathcal{M}_i \\ +\infty & \text{otherwise.} \end{cases}$$

The best stretch of request  $T_i$  is  $\mathcal{S}_{\text{best}}(T_i) = \mathcal{S}(T_i, \rho(T_i)) = \min_{M_j \in M} \text{MAT}[T_i, M_j]$ . Then, we schedule the request  $T_s$  whose “best” objective value is the highest:

$$T_s = \operatorname{argmax}_{T_i \in Q} \mathcal{S}_{\text{best}}(T_i).$$

The chosen replica minimizes the objective value of  $T_s$ :

$$M_r = \operatorname{argmin}_{M_j \in M} \text{MAT}[T_s, M_j].$$

The request  $T_s$  is then removed from the set  $Q$ , as well as the related row in the matrix  $\text{MAT}$ , and the column  $M_r$  is updated with new values. These operations are repeated until  $Q$  is empty (see Algorithm 4). This strategy runs in time  $O(n^2 \cdot m)$  and uses a space  $O(n \cdot m)$  per time window.

Table 1 summarizes the properties of our heuristics.

**Table 1.** Properties of replica selection heuristics. ACK-DONE denotes the need to acknowledge the completion of sent requests. FINISHTIME is the knowledge of available times of each server.  $p_i$  denotes the processing times of local requests and  $r_i$  their release times.  $n$  is the number of requests in  $Q$  and  $m$  is the total number of servers.

Heuristic Knowledge	Type	Complexity
RANDOM None	Distributed	$O(1)$
LOR ACK-DONE	Distributed	$O(m)$
HÉRON ACK-DONE, $p_i \geq \omega$	Distributed	$O(m)$
EFT FINISHTIME	Distributed	$O(m)$
EFT-S FINISHTIME, $p_i \geq \omega$	Distributed	$O(m)$
SSSW FINISHTIME, $p_i, r_i$	Centralized	$O(n^2 \cdot m)$
SMSW FINISHTIME, $p_i, r_i$	Centralized	$O(n^2 \cdot m)$

---

**Algorithm 4** STRETCHMAXMIN-SW

---

```
1: loop {every  $q$  time units}
2:   for all  $T_i \in Q$  do
3:     for all  $M_j \in M$  do
4:       if  $M_j \in \mathcal{M}_i$  then
5:          $\text{MAT}[T_i, M_j] \leftarrow \mathcal{S}(T_i, M_j)$ 
6:       else
7:          $\text{MAT}[T_i, M_j] \leftarrow +\infty$ 
8:       end if
9:     end for
10:  end for
11:  while  $Q$  is not empty do
12:     $T_s \leftarrow \operatorname{argmax}_{T_i \in Q} \mathcal{S}_{\text{best}}(T_i)$ 
13:     $M_r \leftarrow \operatorname{argmin}_{M_j \in M} \text{MAT}[T_s, M_j]$ 
14:    schedule  $T_s$  on  $M_r$ 
15:     $Q \leftarrow Q \setminus \{T_s\}$ 
16:    remove row  $T_s$  from MAT
17:    update column  $M_r$  in MAT
18:  end while
19: end loop
```

---

## 6.2 Local Queue Scheduling Policies

We now present scheduling policies locally enforced by replicas. Each replica handles an execution queue  $Q$  in which coordinators send requests, and then decides of the order of executions. In a real key-value store, these policies should be able to extract exact information on the local values, and in particular their sizes, as a single server is responsible for a limited number of keys. We consider the following local policies.

**FIRSTINFIRSTOUT (FIFO)**. This is a classic strategy, which is commonly used as a local scheduling policy in key-value stores (e.g., Cassandra [41]). The requests in  $Q$  are ordered by non-increasing insertion time, i.e., the first request that entered the queue (the one with the minimum  $r_i$ ) is the first to be executed.

**MAXWEIGHTEDFLOW (MWF)**. We propose another strategy, which locally reorders requests. When the server becomes available at time  $t$ , the next request  $T_s$  to be executed is the one whose weighted flow is the highest:

$$T_s = \operatorname{argmax}_{T_i \in Q} w_i(t + p_i - r_i).$$

This is a general execution policy that considers the request weights as defined by the system designer. Note that in any case, starvation is not a concern: focusing on the maximum weighted flow ensures that all requests will eventually be processed.

**MAXSTRETCH** We also investigate a particular case of MWF where  $w_i = \frac{1}{p_i}$ ; hence the selected request is the one with maximal stretch. This favors requests for small values in front of requests for large ones, and thus is a way to mitigate the problem of head-of-line blocking.

Table 2 summarizes the properties of our heuristics.

## 7 Simulations

We analyse the behavior of previously described strategies and compare them with each other in simulations. We built a discrete-event simulator based on Python 3.8 and `salabim` 21.0.1 for this purpose, which mimics a real key-value store: coordinators receive user requests and send them to replicas in the cluster, which execute these requests. Each request is first headed to the queue of a server holding a replica of the requested

**Table 2.** Properties of local queue scheduling heuristics.  $p_i$  denotes the processing times of local requests and  $r_i$  their release times.  $N$  is the number of local requests in  $\mathcal{Q}$  and  $m$  is the total number of servers.

Heuristic Knowledge Complexity	
FIFO	None $O(1)$
MWF	$p_i, r_i$ $O(N)$
MAXSTRETCH	$p_i, r_i$ $O(N)$

data by the selection heuristic. Then, the queue is reordered by the local execution policy and requests are processed in this order.

## 7.1 Workload and Settings

We designed a synthetic heterogeneous workload to evaluate our strategies: value sizes follow a Weibull distribution with scale  $\eta = 32\,000$  and shape  $\theta = 0.5$ , which gives a mean size equal to  $\eta \cdot \Gamma\left(1 + \frac{1}{\theta}\right) = 64$  kB, where  $\Gamma$  is the gamma function; these parameters yield a long-tailed distribution that is consistent with existing file sizes characterizations [30]. User requests arrive at coordinators according to a Poisson process with arrival rate  $\lambda = m\mathcal{L}/\bar{p}$ , where  $m$  is the number of servers,  $\mathcal{L}$  is the wanted average server load (defined as the average fraction of time spent by servers on serving requests), and  $\bar{p} = \alpha \cdot \eta \cdot \Gamma\left(1 + \frac{1}{\theta}\right) + \beta$  is the mean processing time of requests. Each key has the same probability of being requested, i.e., we do not model skewed popularity. The cluster consists in  $m = 12$  servers and we set the replication factor to  $k = 3$ , which is a common configuration in real implementations [25, 41]. The network bandwidth is set to  $1/\alpha = 100$  Mbps and the average latency is set to  $\beta = 1$  ms. For the threshold between requests for small and large values, we plug the density function of our Weibull distribution in Equation (3) and solve it numerically for  $\omega$ :

$$\int_{x=\frac{\omega-\beta}{\alpha}}^{\infty} (\alpha x + \beta) \cdot \frac{\theta}{\eta} \cdot \left(\frac{x}{\eta}\right)^{\theta-1} \cdot e^{-\left(\frac{x}{\eta}\right)^{\theta}} dx = \frac{1}{k} \cdot \int_{x=0}^{\infty} (\alpha x + \beta) \cdot \frac{\theta}{\eta} \cdot \left(\frac{x}{\eta}\right)^{\theta-1} \cdot e^{-\left(\frac{x}{\eta}\right)^{\theta}}$$

This yields a threshold  $\omega \approx 26.4$  ms (for a size of 318 kB), resulting in a proportion of 5 % of requests for large values in the workload. Each experiment is repeated on 15 different scenarios; a given scenario defines the processing times  $p_i$ , the release times  $r_i$ , and the replication groups  $\mathcal{M}_i$  according to described settings.

## 7.2 Weight Values

We recall that each request in our model is associated to a weight value  $w_i$ . Thus far, we considered these weights to be completely arbitrary. We now describe and explain the values we used in our simulations:

- $w_i = 1$  for all  $T_i \in T$ . This is the classic flow time (or latency) metric.
- $w_i = \frac{1}{p_i}$ . Pure latency tends to favor large requests over the small ones. One way to work around this behavior is to consider the stretch (weighting the latency with the processing time): it measures the slowdown of a request, i.e., the cost for sharing resources with other requests.
- $w_i = \frac{1}{\sqrt{p_i}}$ . Although the stretch metric is more fair than pure latency, we noted in some experiments that it tends to be inappropriate under heterogeneous workloads where the majority of requests are small. Small requests are too favored. For instance, if a small request of 1 ms and a large request of 100 ms have a stretch value of 2, then the large request can tolerate a 100 ms delay ( $F_i = 200$ ), whereas the small one can only tolerate a 1 ms delay ( $F_i = 2$ ). Yet it seems reasonable to delay small requests a little more to avoid impacting the large ones too much. This weighting seems to be a tradeoff between latency and stretch metrics.

### 7.3 Results

Fig. 3(a) shows the 99<sup>th</sup> quantile of read latency (in milliseconds) as a function of average server load for each selection heuristic and for load values ranging from 0.5 to 0.9. In this context, the maximum of the distribution is impacted by rare events of varying amplitude, which makes this criterion unstable. The stability of the 99<sup>th</sup> quantile allows comparing more confidently the performance between scenarios with identical settings. For an average load  $\mathcal{L} = 0.9$ , Fig. 3(b) shows Empirical Cumulative Distribution Functions (ECDF) of read latencies for each selection heuristics. The dashed horizontal lines respectively represent median, 95<sup>th</sup> and 99<sup>th</sup> percentile. The comparison of selection heuristics with the lower bound introduced in Section 4 is shown in Fig. 3(c). We normalize the max-latency obtained by a selection heuristic with this lower bound. Each boxplot represents the distribution of these normalized maximums among the 15 different scenarios. Horizontal red line locates the lower bound. Fig. 3(d) illustrates the effect of different local execution policies on the 99<sup>th</sup> quantile of stretch. Horizontal lines represent median values.

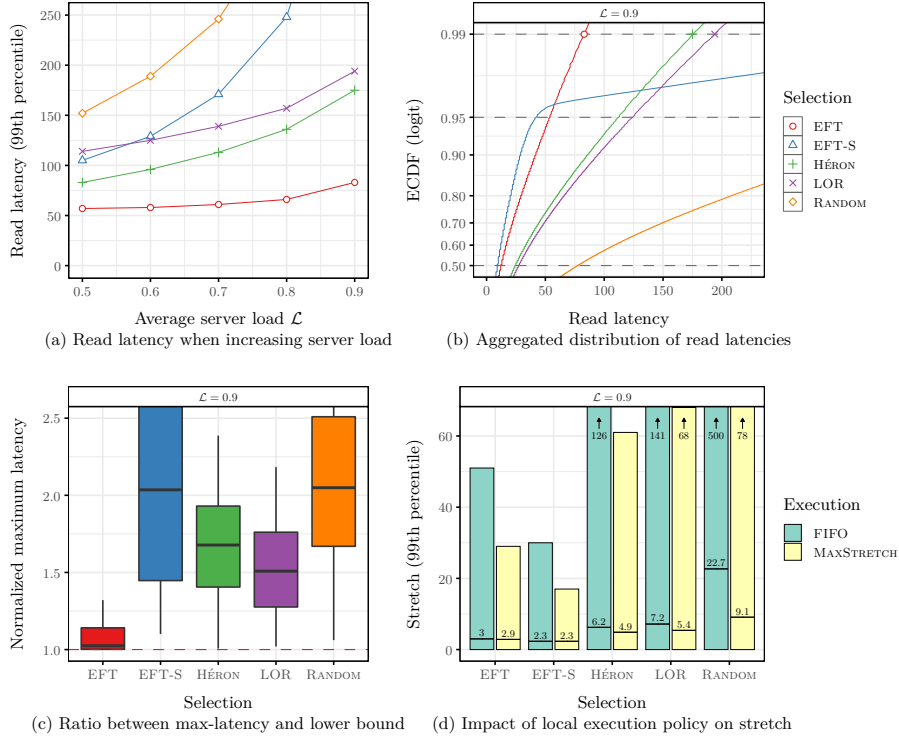
We see in Fig. 3(a) that the choice on selection heuristic is critical for read latency, as the 99<sup>th</sup> quantile can often be improved by a factor 2 compared to state-of-the-art strategies LOR and HÉRON, without increasing median performance as confirmed in Fig. 3(b). This highlights the fact that some properties of the cluster and the workload are more suitable to taming tail latency; in particular, knowing the current load of a server, and thus its earliest available time, allows implementing the EFT strategy and getting very close to the lower bound. Fig. 3(c) also shows that EFT yields the most stable maximums between scenarios, as more than 50 % of normalized values range from 1.0 to 1.15. This improves the confidence that this strategy will perform well in a majority of cases. For the stretch metric, where latencies are weighted by processing times, EFT-S performs even better than EFT (Fig. 3(d)), yielding a 99<sup>th</sup> quantile of 30 (resp. 18) when coupled with FIFO (resp. MAXSTRETCH). This is due to the nature of EFT-S that favors requests for small values, which are in majority in the workload. However, EFT-S does not perform well for the last quantiles in the latency distribution; this corresponds to the 5 % of requests for large values that are delayed in order to avoid head-of-line blocking situations. Fig. 3(d) also illustrates the significant impact of local execution policies on the stretch metric: local reordering according to MAXSTRETCH favors requests for small values, which results in an improvement for all selection strategies, even on the median values. Note that this does not necessarily improve latency, as FIFO is well-known to be the optimal strategy for max-flow on a single machine [14].

## 8 Conclusion

This study defines a formal model of a key-value store in order to derive maximal performance achievable by a real online system, and states the associated optimization problem. We also provide theoretical results on various problems related to our main scheduling problem. After showing the difficulty of this problem, we describe some investigations on a lower bound. We develop online heuristics and compare them with state-of-the-art strategies such as LOR, HÉRON [33] or size-aware sharding [28] using simulations. This allows understanding more finely the impact of replica selection and local execution on performance metrics. We hope that our work will help practitioners draw new scheduling strategies. We plan to continue to improve on a lower bound, for example by using resource augmentation models [23, 37], and we propose to formally analyze EFT with various techniques such as competitive analysis. We wish to study the effect of various assumptions on scheduling, e.g., the impact of skewed key popularity, and to extend the model with multi-get operations [34, 51].

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**Fig. 3.** Distributions of the objective functions for 5 replica selection heuristics. For Fig. (a), (b) and (d), simulations run over 120 s. For Fig. (c), simulations are launched over 1000 requests.

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## 9 Notations

Table 3 provides a list of the most used notations in this document.

## 10 Competitive Analysis

We provide a comprehensive summary of results related to competitive analysis of online scheduling problems which address the minimization of flow time. Tables are organized in the following way: the results are classified into two general columns, where the first one deals with offline optimization and the second one deals with online aspects, and more particularly with competitiveness.

We specify the modalities for each competitive analysis, where the symbol C indicates a clairvoyant problem (i.e., all request properties are known) and S stands for a speed augmentation characteristic (i.e., the online solution is allowed to use an increased fraction of resources compared to offline). Table 4 (resp. Table 5) presents competitive analysis results which are related to maximum (resp. sum) weighted flow. The more general objective  $\ell_p$ -norm is described in Table 6.

## 11 Problems Complexity

To complete our survey on scheduling problems related to our study, we present a summary on complexity results in Table 7.

**Table 3.** List of notations.

Symbol	Definition
$i$	index of requests
$j$	index of machines
$l$	index of keys/values
$n$	number of requests
$m$	number of machines
$c$	number of keys/values
$k$	replication factor
$T_i \in T$	request $i$
$M_j \in M$	machine $j$
$\mathcal{M}_i \subseteq M$	machines able to process $T_i$
$K_l \in K$	key $l$
$V_l \in V$	value $l$
$w_i$	weight of $T_i$
$r_i$	release time of $T_i$
$p_i$	processing time of $T_i$
$\sigma_i$	start time of $T_i$
$C_i$	completion time of $T_i$
$C_i^S$	completion time of $T_i$ in a schedule $S$
$F_i$	flow time of $T_i$
$S_i$	stretch of $T_i$
$z_l$	size of $V_l$
$\varphi : T \rightarrow K$	gives the key carried by a request
$\Psi : M \rightarrow 2^K$	gives the key subset owned by a machine
$\Pi : T \rightarrow M \times \mathbb{N}$	gives the machine and start time of a request
$\alpha$	bandwidth inverse
$\beta$	latency
$\lambda$	submission rate
$\eta$	Weibull scale parameter
$\theta$	Weibull shape parameter
$\mathcal{L}$	load
$d$	duration of the simulation



**Table 4.** Competitive analysis results related to maximum (weighted) flow minimization.

Problem Opt	Offline		Online		
	Approx	C	S	Competitive Ratio	
$1 r_i F_{\max}$ FIFO [14]		no	no	– FIFO is 1-competitive	
$P r_i F_{\max}$		no	no	– LB of $2 - \frac{1}{m}$ – FIFO is $(3 - \frac{2}{m})$ -competitive [14]	
$P2 r_i F_{\max}$		no	no	– LB of 2 [49] – FIFO is 2-competitive [1, 49]	
$P r_i, pmtn F_{\max}$		no	no	– LB of $2 - \frac{1}{m}$ – FIFO is $(3 - \frac{2}{m})$ -competitive [49] – $(2 - \frac{1}{m})$ -competitive algorithm [1]	
$Q r_i, pmtn^* F_{\max}$		yes	no	– SLOW-FIT is $\Omega(m)$ -competitive – GREEDY is $\Omega(\log m)$ -competitive – $O(1)$ -competitive algorithm [7]	
$1 r_i, p_i = 1  \max w_i F_i$				– no 1-competitive algorithm [Th. 5] – SINGLE-UNIT has no competitive ratio [Th. 6]	
$P   \max w_i F_i$	$- 2 - \frac{1}{m}$ [Th. 3]				
$P r_i  \max w_i F_i$		yes	no	– LB: $\Omega(W)$ [7]	
$R r_i, pmtn  \max w_i F_i$ LP [43]					
$1 r_i S_{\max}$	$-$ LB: $\Omega(n^{1-\varepsilon})$ [14]	yes	no	– FIFO is $P$ -comp [43] – LB: $1 + \frac{\sqrt{5}-1}{2}P$ – $(1 + \frac{\sqrt{5}-1}{2}P)$ -comp algo [29]	
$1 r_i, pmtn S_{\max}$	$- 1 + \varepsilon$ [14]	yes	no	– $\max(\alpha, 1 + \frac{P}{\alpha})$ -comp algo [14]	

**Table 5.** Competitive analysis results related to sum (weighted) flow minimization.

Problem Opt	Offline		Online		
	Approx	C	S	Competitive Ratio	
$1 r_i  \sum F_i$	$- O(\sqrt{n})$ $-$ LB: $\Omega(n^{\frac{1}{2}-\varepsilon})$ [38]	no	no	– FIFO is $P$ -comp [43]	
$1 r_i, pmtn  \sum F_i$ SRPT [5]		yes	no	– SRPT is 1-comp	
$1 r_i, pmtn  \sum F_i$ SRPT		no	$1 + \varepsilon$	– SETF is $(1 + \frac{1}{\varepsilon})$ -comp [37]	
$1 r_i, pmtn  \sum F_i$ SRPT		no	no	– RMLF is $O(\log n)$ -comp [12]	
$P r_i  \sum F_i$	$- O(\sqrt{\frac{n}{m} \log \frac{n}{m}})$ $-$ LB: $\Omega(n^{\frac{1}{3}-\varepsilon})$ [45]	no	no	– Random is $O(\varepsilon^{-3} \log \frac{1}{\varepsilon})$ -comp [21]	
$P r_i, pmtn^*  \sum F_i$	$- O(\log P)$	no	no	– $O(\min(\log P, \log n))$ -comp algo [4] – LB: $\Omega(\log P)$	
$P r_i, pmtn  \sum F_i$		yes	no	– SRPT is $O(\min(\log P, \log \frac{n}{m}))$ -comp – LB: $\Omega(\log(\frac{n}{m} + P))$ (randomized) [45]	
$P r_i, pmtn  \sum F_i$		no	no	– RMLF is $O(\log n \cdot \min(\log P, \log \frac{n}{m}))$ -comp [12]	
$P \mathcal{M}_i, r_i, pmtn^*  \sum F_i$	$- O(\log P)$ [31]	no	no	– no LB [31]	
$1 r_i  \sum w_i F_i$	$- O(1)$ [6]			$O(1)$	
$1 r_i, pmtn  \sum w_i F_i$	$- 2 + \varepsilon$ [21] $- O(\log n + \log P)$ [8]	yes	no	– $O(\log^2 P)$ -comp algo – LB: 1.618 – LB: $\frac{4}{3}$ (randomized) [21] – $O(\log W)$ -comp algo [8]	
$1 r_i, pmtn  \sum w_i F_i$		no	$1 + \varepsilon$	– $(1 + \frac{1}{\varepsilon})$ -comp algo [8]	
$P r_i, pmtn  \sum w_i F_i$		no	no	– LB: $\Omega(\min(\sqrt{P}, \sqrt{W}, (\frac{n}{m})^{\frac{1}{4}}))$ (randomized) [21]	
$R r_i, pmtn^*  \sum w_i F_i$		no	$1 + \varepsilon$	– $O((1 + \frac{1}{\varepsilon})^2)$ -comp algo [20]	
$1 r_i  \sum S_i$		no	no	– FIFO is $P^2$ -comp [43]	
$1 r_i, pmtn  \sum S_i$		yes	no	– SRPT is 2-comp [50]	
$1 r_i, pmtn  \sum S_i$		no	$1 + \varepsilon$	– MLF is $O((\frac{1}{\varepsilon})^5 \log^2 P)$ -comp [9]	
$P r_i, pmtn  \sum S_i$		yes	no	– SRPT is 14-comp [50] – 9.82-comp algo [21]	
$P r_i, pmtn^*  \sum S_i$		yes	no	– 17.32-comp algo [21]	

**Table 6.** Competitive analysis results related to  $\ell_p$ -norm minimization.

Problem	Offline		Online	
	Opt	Approx	C	S
$1 r_i, pmtn \ F_i\ _p$	yes	no	-	no $n^{o(1)}$ -comp algo [10]
$1 r_i, pmtn \ F_i\ _p$	yes	$1 + \varepsilon$	-	SJF is $O(\frac{1}{\varepsilon})$ -comp - SRPT is $O(\frac{1}{\varepsilon})$ -comp [10]
$1 r_i, pmtn \ F_i\ _p$	no	$1 + \varepsilon$	-	SETF is $O(\frac{1}{\varepsilon^{2+2/p}})$ -comp [10]
$1 r_i, pmtn \ S_i\ _p$	yes	no	-	no $n^{o(1)}$ -comp algo [10]
$1 r_i, pmtn \ S_i\ _p$	yes	$1 + \varepsilon$	-	SJF is $O(\frac{1}{\varepsilon})$ -comp - SRPT is $O(\frac{1}{\varepsilon})$ -comp [10]
$1 r_i, pmtn \ S_i\ _p$	no	$1 + \varepsilon$	-	LB: $\Omega(\min(n, \log P))$ - SETF is $O(\frac{1}{\varepsilon^{3+1/p}} \log^{1+1/p} P)$ -comp [10]

**Table 7.** Classification of scheduling problems. Arrows are reduction relationships, e.g.,  $A \rightarrow B$  means  $B$  is more difficult than  $A$ . Entries marked with a symbol ? mean that the corresponding problem complexity is still unknown. A + means the problem is NP-hard (via the reduction relationship), while a - indicates a polynomially solvable problem. Incompatible problem designations are noted  $\emptyset$ .

$\sum w_i C_i$	1	$\longrightarrow$	$P$	$\longrightarrow$	$Q$	$\longrightarrow$	$R$
$\mathcal{M}_i$	?		s. NP-hard [17]		+		+
$r_i, \mathcal{M}_i, p_i = 1$	?		s. NP-hard [17]		+		+
$r_i, p_i = p$	-		p. solvable [15]		?		?
$r_i, pmtn$	s. NP-hard [40]		+		+		+
$\sum C_i$	1	$\longrightarrow$	$P$	$\longrightarrow$	$Q$	$\longrightarrow$	$R$
$r_i$	s. NP-hard [44]		+		+		+
$\mathcal{M}_i$	-		-		-		p. solvable [17]
$r_i, \mathcal{M}_i, p_i = 1$	-		-		-		p. solvable [17]
$r_i, p_i = p$	-		p. solvable [54]		?		$\emptyset$
$r_i, pmtn$	p. solvable [5]		s. NP-hard [11]		+		+
$\mathcal{M}_i, pmtn$	-		p. solvable [15]		?		s. NP-hard [55]
$r_i, pmtn, p_i = p$	-		-		p. solvable [39]		?
$\sum S_i$	1	$\longrightarrow$	$P$	$\longrightarrow$	$Q$	$\longrightarrow$	$R$
$r_i$	NP-hard [43]		+		+		+
$\max w_i F_i$	1	$\longrightarrow$	$P$	$\longrightarrow$	$Q$	$\longrightarrow$	$R$
$r_i$	NP-hard [14]		+		+		+
$r_i, pmtn$	-		-		-		p. solvable [43]
$r_i, pmtn^*$	-		NP-hard [Th. 4]		+		+
$p_i = p$	p. solvable [Th. 1]		NP-hard [Sec. 4.1]		+		+
$p_i = p$	-		p. solvable [Th. 2]		?		$\emptyset$
$F_{\max}$	1	$\longrightarrow$	$P$	$\longrightarrow$	$Q$	$\longrightarrow$	$R$
$r_i$	p. solvable [14]		NP-hard [Sec. 4.1]		+		+
$S_{\max}$	1	$\longrightarrow$	$P$	$\longrightarrow$	$Q$	$\longrightarrow$	$R$
$r_i$	NP-hard [14]		+		+		+