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# Shared-object system equilibria: Delay and throughput analysis <sup>☆</sup>



Iosif Salem <sup>\*</sup>, Elad M. Schiller, Marina Papatriantafidou, Philippas Tsigas

Department of Computer Science and Engineering, Chalmers University of Technology, S-412 96, Göteborg, Sweden

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## ABSTRACT

We consider shared-object systems that require their threads to fulfill the system jobs by first acquiring sequentially the objects needed for the jobs and then holding on to them until the job completion. Such systems are in the core of a variety of shared-resource allocation and synchronization systems. This work opens a new perspective to study the expected job delay and throughput analytically, given the possible set of jobs that may join the system dynamically. We identify the system dependencies that cause contention among the threads as they try to acquire the job objects. We use these observations to define the shared-object system equilibria. We note that the system is in equilibrium whenever the rate in which jobs arrive at the system matches the job completion rate. These equilibria consider not only the job delay but also the job throughput, as well as the time in which each thread blocks other threads in order to complete its job. We then further study in detail the thread work cycles and, by using a graph representation of the problem, we are able to propose procedures for finding and estimating equilibria, i.e., discovering the job delay and throughput, as well as the blocking time. To the best of our knowledge, this is a new perspective, that can provide better analytical tools for the problem. That is, our methods can be used to estimate performance measures similar to ones that can be acquired through experimentation on working systems and simulations, e.g., as job delay and throughput in (distributed) shared-object systems.

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## 1. Introduction

Our problem's domain considers computing entities, which we call threads. Each thread runs a sequential program (a job) that has to acquire reusable resources (objects), often several at the same time, for a bounded time of use. To guarantee deadlock absence, it is important that all threads acquire the objects in an ordered manner. For example, one can deterministically define a total order among the objects, such that the threads acquire them in totally ordered manner. A common way to model such systems is to consider a generalization of the dining philosophers problem, as in [19,22], in which every job includes a fixed set of objects that it may need. This approach provides a worst-case complexity analysis, which is exponential on the system's parameters.

We provide a new perspective that enables an analysis of the evaluation metrics by considering measures both at the system level and at the level of each resource. In particular, we consider performance measures that are associated with

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<sup>\*</sup> Corresponding author.

E-mail addresses: iosif@chalmers.se (I. Salem), elad@chalmers.se (E.M. Schiller), ptrianta@chalmers.se (M. Papatriantafidou), tsigas@chalmers.se (P. Tsigas).

each resource, such as the job delay and completion rate, as well as the blocking time of each thread on each object. On the system level, we consider the job arrival and completion rates, as well as the total number of threads and objects.

We study shared-object systems that require their threads to fulfill the system jobs by first acquiring sequentially all of the job objects. The job then holds on to these objects until the job operation is done. We identify the system dependencies that cause contention among the threads as they try to acquire the job objects. We study the (stochastic) processes of job arrival and completion with an emphasis on the cases in which the job arrival rate matches the job completion rate, i.e., the job throughput. In these cases, the system is in a *shared-Object System Equilibrium* (OSE). For a given  $\varepsilon > 0$  and an OSE, we say that the system is in an  $\varepsilon$ -OSE when the completion rate of any job differs from the one of an OSE by at most  $\varepsilon$ . We study the conditions for a given shared-object system to be in an OSE as well as contention-related properties of OSEs, i.e., the *expected* job delay and completion rate, as well as the time in which each thread blocks other threads and by that prevents them from making progress. We propose an analytical procedure for finding (approximate) OSEs, which we call  $\varepsilon$ -OSEs (for a given error  $\varepsilon$ ). Moreover, we estimate the performance measures of systems that are in  $\varepsilon$ -OSE.

The existing practice considers job delay and completion rate as the performance measures of working systems. Empirical experiments often study shared-resource systems at their saturation point in which the system is at its peak utilization. Let us describe peak utilization scenarios using two vectors; one for job arrival rates and another for their completion rates. A saturation point is the case in which: (1) the system is in equilibrium, i.e., the arrival rate of any particular job matches the completion rate of this job, as well as (2) the system is at the stage at which a higher arrival rate of any job to the system cannot increase its completion rate. Our study considers the entire range of these equilibria rather than just peak utilization scenarios (Section 2).

### 1.1. Related work

We consider a generalization of the dining philosophers problem, as in [19,22], in which every job includes a fixed set of objects that it may need. This problem has well-known results studying the worst-case job delays, which may even be exponential on metrics, such as the chromatic number of the resource graph [18,19]. In this graph, the vertices (objects) are connected if there is at least one thread that may request them both at any point in time. In the context of actual systems, the expected time is rather different than the worst case and therefore computer experiments are the common way for evaluating the system performance.

Systems that support atomic synchronization primitives, such as compare-and-swap (CAS) [14], are motivating examples for our model. In particular, while CAS provides mutually exclusive read and write access to one memory location (word), extensions for accessing many memory locations exist in the literature, such as [13,17]. Harris et al. [13] propose a multi-word compare and swap extension of CAS (double-word CAS and multi-word CAS), while Luchangco et al. [17] propose an atomic primitive that allows reading many words but writing only to one. Our work can provide an analytical early stage evaluation of such systems, by adjusting the job size and the job operation times accordingly.

### 1.2. Our contribution

We study analytical tools that provide the means to estimate performance measures of working distributed systems. In the context of synchronization challenges that are modeled via a generalization of the dynamic dining philosophers problem, our analytical tools are the first, to the best of our knowledge, to consider performance measures similar to the ones that can be acquired via experimentation on working systems and simulations.

For a given number of threads and objects, as well as the jobs and their arrival rates, we provide a way to analyze the delay of jobs and their completion rates as well as the time for which the threads are blocked. Throughout our analysis we use the thread work cycle events (sections 5.2 and 5.4) to verify our modeling approach. In addition to the job completion period (Approximation 3), we analyze a number of key properties, such as the probability of a thread to request a particular resource after the acquisition of another specific resource, the time during which threads that have acquired a particular resource block other threads that ask to access the same resource (Approximation 4), as well as the time between two requests to access such resources (Approximation 5). Our analysis is based on estimating pairwise states (Section 5.5) that capture these blocking periods, the delay and the throughput with respect to every pair of system items (threads or objects). Since these properties have interdependencies due to thread blocking, we show how the concept of thread work cycles can be represented in subsystems that also include such interdependencies but have no thread blocking. This way, we can resolve these interdependencies (Theorem 6) and estimate the performance of the given (distributed) shared resource system. We present a procedure for satisfying approximately the equilibrium conditions and by that find an  $\varepsilon$ -OSE as well as the performance measures of the studied system (Section 10). In particular, in Algorithm 3 (Section 10) we compute the first three moments of these pairwise states, and hence the first three moments of job delays and throughput, in an  $\varepsilon$ -OSE (if such exists).

Our contribution can facilitate early-stage evaluations of systems that are similar to the studied one. Moreover, using our proposed methods, one can analytically, rather than via empirical experiments, study trade-offs among OSEs. Such trade-offs can facilitate the design of mechanisms for adjusting the number of threads and job arrival rates according to the performance measures of a dynamic system.

Notation	Meaning	Page
$objects = (o_1, \dots, o_M)$	object set, where $M =  objects $	3
$threads = (t_1, \dots, t_N)$	thread set, where $N =  threads $	3
$job_i = (obj_{s_i}, operation_i)$	the $i$ th job, with object sequence $obj_{s_i}$ and operation $operation_i$	3
$O_i$	operation time of $job_i$	3
$Q_{thread}(t_n)$	queue of $t_n$ 's pending jobs	3
$Q_{object}(o_i)$	queue of $o_i$ 's pending requests	3
$\lambda_{i,n}$	$job_i$ 's arrival rate to $t_n$ (Exponential distribution)	3
$I[i, n]$	inter-arrival time of $job_i$ to $t_n$	3

Fig. 1. A summary of the basic notation of Section 2.

**Paper organization** This paper is organized as follows. In Section 2 we present the system settings for this work. We present the necessary background knowledge in Section 3. In Section 4 we present a high-level description of our approaches. In Section 5 we present a model for the studied problem, which captures the system's dependencies and forms a basis for our analysis and proofs. We then present in detail our solution in the remaining sections. Note that once we find an  $\varepsilon$ -OSE, we can estimate its performance measures, i.e., job delay, completion rate, and blocking time. To this end, we develop a number of analytical tools for OSEs. In Section 6 we give estimations for the probabilities of threads requesting access to objects. Given the job arrival rates, we show how to estimate the probabilities for threads to follow a certain object acquisition sequence (Section 6). We are then able to formulate recursive equations (with interdependencies) for calculating the blocking periods and the completion rates (sections 7, and respectively, 8). We overcome these dependencies and solve these recursive equations by analyzing the thread work cycles (Section 9). In Section 10 we present Algorithm 3, which gives a procedure for finding OSEs and computing delay and throughput if such exist. In Section 11 we conclude this work.

## 2. System settings and problem definition

We consider a system that includes (*system*) items, which are (totally ordered) *objects*,  $(o_1, \dots, o_M)$ , and (totally ordered) *threads*,  $(t_1, \dots, t_N)$ . The objects are shared in a mutually exclusive way, i.e., only one thread at a time may gain access to an object. Each thread is to carry out one *job* at a time, where  $job_i = (obj_{s_i}, operation_i)$ ,  $J$  is the number of the system's jobs,  $i \in [1, J]$  and  $obj_{s_i} = (o_{i_1}, \dots, o_{i_k})$  is an arbitrary, non-empty subsequence of  $(o_1, \dots, o_M)$ , and thus  $obj_{s_i}$  follows the same order.

A thread carries out  $job_i$  by gaining mutually exclusive access to the objects in  $obj_{s_i}$  and in the order implied by  $obj_{s_i}$ , executing the operation  $O_i$ , and then releasing access to the objects in  $obj_{s_i}$ . We assume that  $obj_{s_i}$  is a fixed vector and that different jobs may have different object vectors of different lengths. Moreover, we assume that every object is included in the object set of at least one job. Furthermore, the (*job*) operation time,  $O_i$ , is a random variable with a known distribution. Namely, we assume that the time it takes to execute the job operation is known by its first three moments.

Throughout this paper we consider that random variables are known when we know their first three moments. Therefore, we will focus on computing the first three moments of the studied problem's unknown random variables. We denote by  $E[X^m]$  the  $m$ -th moment of a random variable  $X$ . We give a summary of the section's basic notation in Fig. 1.

### 2.1. Job arrival rates and job-to-thread assignment

We assume that the time between two consecutive arrivals of  $job_i$  to  $t_n$  is a random variable  $I[i, n]$  (inter-arrival period), where  $i \in [1, J]$ ,  $n \in [1, N]$ . We define the *job arrival rate*,  $\lambda_{i,n}$ , in which  $job_i$  arrives at the system that then places  $job_i$  in a (first in, first out) queue,  $Q_{thread}(t_n)$ , where  $\lambda_{i,n}$  is a positive real number. The inter-arrival period,  $I[i, n]$ , follows an exponential distribution,  $Exp(\lambda_{i,n})$ . Note that this is a common way to model arrivals, e.g. [7]. As soon as  $t_n$  becomes available, the system assigns to  $t_n$  the job that is on  $Q_{thread}(t_n)$ 's top. Moreover, we assume that at least one job is arriving to every thread's queue. We focus on systems that can be in an equilibrium for which the number of pending jobs in  $Q_{thread}(t_n)$  is bounded.

Our assumption that the job arrival rates follow exponential distributions allows us to consider the inter-arrival time of jobs to the entire system as an exponential distribution of rate  $\sum_{i,n} \lambda_{i,n}$  (cf. Poisson process merging and splitting properties [1,5]). Thus, defining the system to have separate queues for each thread does not compromise generality, since a system scheduler assigns every arriving job to a thread.

### 2.2. Acquisition requests and periods

A thread can acquire a particular object,  $o_\ell$ , by pending its (*acquisition*) request in a (first in, first out) queue  $Q_{object}(o_\ell)$  until all (previously) waiting threads in  $Q_{object}(o_\ell)$  have acquired and released  $o_\ell$ . The *acquisition period*,  $A$ , is a known random variable (i.e., we know its first three moments) that refers to a period that starts when a thread has acquired an object (or just been assigned to a new job) and ends as soon as that thread places a request for the next object.

Once the thread sequentially acquires the entire object set,  $o_{i_1}, \dots, o_{i_k}$  of  $job_i$ , it executes the job operation,  $operation_i$ . When  $operation_i$  is completed, the thread releases access to the object set and  $job_i$  is completed. We say that a thread is *blocking*, when other threads are queuing for its acquired objects. That happens whenever different jobs have overlapping object vectors. Note however that threads carry out jobs within finite time even in the presence of blocking, because threads acquire their job's objects following the order of the job's object set and these sets follow the ascending object order. The maximum number of pending requests in an object's queue is  $N - 1$ , since every thread can carry out one job at a time.

### 2.3. Job delay and throughput

We define the *job delay* on  $t_n$ ,  $\tilde{D}_{t_n}$ , to be the random variable that gives the time between the arrival of a job to  $t_n$ 's queue and the completion of that job. Moreover, we denote by  $\tilde{T}_{t_n}$  the random variable that gives the time between consecutive job completions of  $t_n$ . Then, we define each thread's *completion rate* (throughput) by  $1/E[\tilde{T}_{t_n}]$ , where  $E[\tilde{T}_{t_n}]$  is the expected value of  $\tilde{T}_{t_n}$ .

### 2.4. Problem definition: computing shared-object system equilibria

*Shared-object system equilibria* For a given system,  $\psi = \{\tilde{D}_{t_n}, \tilde{T}_{t_n}\}_{n \in [1, N]}$  is the *system state*. Suppose that a system is in a state in which, for every thread the job arrival rate is equal to the job completion rate, i.e.,  $\forall n \in [1, N], \sum_{i=1}^J \lambda_{i,n} = 1/E[\tilde{T}_{t_n}]$ . Note that we refer to  $\sum_{i=1}^J \lambda_{i,n}$  as  $t_n$ 's (aggregate) arrival rate (cf. Section 2.1). We say that  $\psi^* = \{\tilde{D}_{t_n}^*, \tilde{T}_{t_n}^*\}_{n \in [1, N]}$  is the *shared-Object System Equilibrium* (OSE). For a given  $\varepsilon > 0$  and an OSE  $\psi^*$ , we say that the system state  $\psi$  is an  $\varepsilon$ -OSE when  $\forall n \in [1, N], |\tilde{D}_{t_n}^* - \tilde{D}_{t_n}| < \varepsilon \wedge |\tilde{T}_{t_n}^* - \tilde{T}_{t_n}| < \varepsilon$  holds. Namely, the corresponding values of each item in  $\psi$  and  $\psi^*$  differ by less than  $\varepsilon$ .

We remark that a system cannot always reach a state that satisfies the OSE conditions, and thus neither the ones of an  $\varepsilon$ -OSE. We refer to the random variable *blocking*( $n$ ), which gives the time between the assignment of a job to  $t_n$  until the completion of that job, as  $t_n$ 's *blocking period*. Equilibria are *unreachable* when there is a thread with blocking period that is longer than the inter-arrival time of jobs to that thread. Note that in that case, the thread's queue is increasing continuously.

*The studied problem* In this work we study the problem of computing an  $\varepsilon$ -OSE  $\psi^* = \{\tilde{D}_{t_n}^*, \tilde{T}_{t_n}^*\}_{n \in [1, N]}$ , basing on the known system parameters and a given error  $\varepsilon$ . Specifically, we consider the problem of computing the first three moments of the job delay,  $\tilde{D}_{t_n}^*$ , and of the time between consecutive job completions,  $\tilde{T}_{t_n}^*$ , of the system's threads, when the system is in  $\varepsilon$ -OSE (for a given  $\varepsilon$ ). We consider as known parameters, the number of threads  $N$  and objects  $M$ , the set of jobs  $\{job_i\}_{i \in [1, J]}$  (which includes the object sets and job operation times), as well as the set  $\{\lambda_{i,n}\}_{i \in [1, J], n \in [1, N]}$  of job-to-thread arrival rates.

Computing the job delay and throughput is non-trivial due to the fact that they both depend on blocking, i.e., the cases of threads waiting for other threads to release objects that they want to acquire. That is, job delay and throughput depend on the waiting time of a job in a thread's queue and the waiting times of the thread's object acquisition requests in the object queues of the job's object set. For example, there can be an instantiation of the system, in which  $t_x$  has access to  $o_k$  and waits for access to  $o_{k+1}$ , while  $t_y$ 's request is pending in  $o_k$ 's queue. Thus, the delay of the job that  $t_y$  is carrying out, directly depends on the time for which  $t_x$  is holding access to  $o_k$ , which includes the time for which  $t_x$  is waiting for accessing  $o_{k+1}$  (and possibly other objects). Therefore, the key challenge that we address is to effectively model and analyze these dependencies. Section 4 gives a complete overview of our approach.

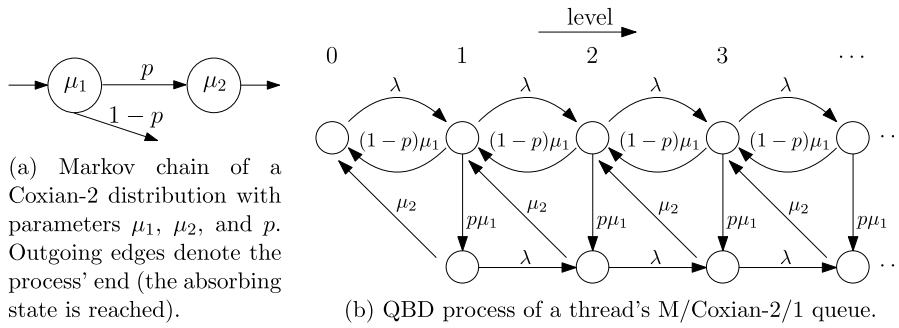
## 3. Background

In this section we explain how existing tools from queuing theory [1] can be deployed to compute the delay  $\tilde{D}_{t_n}$  and job completion period  $\tilde{T}_{t_n}$  of the thread queues, given the distribution of the job blocking periods (Section 3.1). Then, we present more complex tools from queuing networks [5], which we will use for analyzing shared-object systems (Section 3.2).

### 3.1. Computing job delay and throughput when the job blocking period is known

We can compute  $\tilde{D}_{t_n}$  and  $\tilde{T}_{t_n}$  using the distribution of job arrivals to  $t_n$ ,  $I(n)$ , as well as the distribution of the blocking period, *blocking*( $n$ ) (Section 2.4), i.e., the time between job assignment and job completion. Since the job-to-thread arrivals follow exponential distributions,  $Exp(\lambda_{i,n})$ ,  $I(n)$  follows a known exponential distribution with parameter  $\sum_{i=1}^J \lambda_{i,n}$  (Section 2.1). However, the distribution of *blocking*( $n$ ) is unknown, since it depends on thread blocking.

In our analysis, we provide an algorithm for computing *blocking*( $n$ )'s first three moments (cf. Algorithm 3 and Section 8), and below we explain how we can use these moments to compute  $\tilde{D}_{t_n}$  and  $\tilde{T}_{t_n}$ . Queuing theory provides a queue's performance parameters in its steady-state, i.e., the case where the arrival and completion rates match, which implies that  $\tilde{T}_{t_n}$  follows the same distribution with  $I(n)$ . Specifically, it gives the steady-state probabilities for the queue length from which we can compute the distributions of the queue waiting time and the job delay.



**Fig. 2.** Fig. 2b depicts the Markov chain (QBD process) that represents the M/Coxian-2/1 queue of a thread,  $t_n$ . The arrival rate is  $\lambda = \sum_i \lambda_{i,n}$ , and  $\mu_1, \mu_2$ , as well as  $p$  are the parameters of the Coxian-2 distribution (Fig. 2a) that matches  $blocking(n)$ 's moments (blocking period). The QBD process' states are organized in levels, which denote the number of jobs in  $t_n$ 's queue (including the one that  $t_n$  is possibly carrying out). The single state in level 0 denotes that the thread is idle. In level  $i, i > 0$ , there are two states due to  $blocking(n)$ 's Coxian-2 distribution. The upper state ends with rate  $(1 - p)\mu_1$ , the transition rate from the upper to the lower state is  $p\mu_1$ , and the lower state ends with rate  $\mu_2$ .

We compute the steady-state probabilities of  $t_n$ 's queue,  $Q_{thread}(t_n)$ , by analyzing it as an M/Coxian-2/1 queue. An M/Coxian-2/1 queue is a queue in which the arrivals follow an exponential distribution (denoted by M) and the blocking period follows a Coxian-2 distribution [1] (Fig. 2a), while 1 denotes that only  $t_n$  carries out the pending jobs of its queue (cf. Kendall notation of queues [1]). By our assumptions  $I(n)$  follows indeed an exponential distribution. A Coxian-2 distribution is a special case of a phase-type distribution [1], which represents the time until a Markov process with two states reaches an absorption (ending) state, and is commonly used for fitting unknown distributions [1,2]. Hence, after computing the first three moments of  $blocking(n)$  using the algorithm that we propose in this paper (Algorithm 3 and Section 8), we can use the moments of  $blocking(n)$  to match it with a Coxian-2 distribution (moment matching method, [2,23] and [1, Section 2.5]).

To analyze the M/Coxian-2/1 queue that models  $Q_{thread}(t_n)$ 's arrival and blocking distributions, we use the standard approach of the Matrix Geometric Method (MGM) [20]. We define a Markov chain (Fig. 2b) that has the structure of a quasi-birth-death (QBD) process [8] using  $I(n)$  and  $blocking(n)$  (as in [21, Section 3.2] and [12]). The QBD process considers the growth and decrease in the number of jobs in  $Q_{thread}(t_n)$  (including the one that  $t_n$  is carrying out). Each level corresponds to the queue's length (i.e., 0, 1, 2, ...) and the states of each level correspond to the two states of the Coxian-2 distribution of  $blocking(n)$ , except for level zero that has only one state ( $t_n$  is idle). Transitions from level  $i$  to  $i + 1$  are determined by  $\sum_{i=1}^J \lambda_{i,n}$  ( $Q_{thread}(t_n)$ 's arrival rate), and transitions from  $i$  to  $i - 1$  are determined by the parameters of the Coxian-2 distribution that matches the moments of  $blocking(n)$ .

The MGM [20] provides the steady-state probabilities for each state of  $t_n$ , due to the Markov chain's QBD structure. Thus, the (steady-state) probability of the QBD process' zero-level state,  $u_{n,0}$ , gives the probability of  $t_n$  to be idle. The MGM is an iterative method and its running time is in  $O(I_{MGM} \cdot m^3)$ , where  $m$  is the maximum number of states in each QBD level and  $I_{MGM}$  is the number of iterations until the method converges. As we described above,  $m = 2$ , since the Coxian-2 distribution is a Markov chain with two states (Fig. 2). Latouche and Ramaswami in [16, Remark 4.3], explain that in order to have a number of iterations,  $I_{MGM}$ , that exceeds 40, it must be (practically) possible for the queue length to grow up to  $10^{12}$ . Since this is considered impractical in the setting of shared-object systems (and in generally practical settings), we can assume that  $I_{MGM}$  is a small number, and thus MGM's running time is (practically) constant.

### 3.2. Relevant tools from queuing networks

Our solution uses tools from queuing networks [5]. Although queuing theory celebrated results provide closed forms for single queues, e.g., M/M/c, M/G/1 [1], and queuing networks, e.g., Jackson [15,5], BCMP [3], and Gordon–Newell networks [9], closed form results are far from been the common case. Specifically, there are no relevant closed-form results that can be used for systems like ours in which a thread can block other threads for a non-exponentially distributed period.

We use tools from queuing networks, where non-exact solutions are often provided [5]. In particular, we consider the work of Ramesh and Perros [23] who study a message passing system of multi-tier server networks in which processes communicate iteratively via what is known in the computer systems community as synchronous I/O (also called blocking I/O). Namely, at any point in time, each process handles at most one (outgoing) connection, which gets blocked when sending a message. Ramesh–Perros [23] use a framework proposed by Baynat and Dallery [4] for estimating the system state. The authors of [23,4] demonstrate the convergence of their iterative methods via numerical experiments, while their algorithms run in polynomial time on the system's size.

## 4. Overview of the proposed solution

In this section we provide an overview of our approach for computing job delay and throughput, when a shared-object system is in equilibrium (Section 2.4). In Section 3.1 we showed how to compute the delay and throughput of a thread's

queue, say  $Q_{thread}(t_n)$  of  $t_n$ , when the job blocking period  $blocking(n)$ , i.e., the time between a job assignment and the job completion, is known. By the definition of shared-object systems,  $blocking(n)$ , for every  $n \in [1, N]$ , depends on thread blocking, i.e., the time during which a thread waits for other threads to release the objects that it needs to acquire. Thus, we focus on computing  $blocking(n)$ , when the system is in equilibrium ( $\varepsilon$ -OSE), i.e., when the job arrival and completion rates match (Section 2.4).

To the end of computing  $blocking(n)$ , we provide a comprehensive model of the system's events, which captures the dependencies among threads. Basing on these events, we define the system's performance parameters, i.e., the delay, blocking period, and throughput of thread requests for accessing objects, the throughput of every system item, as well as the probability for each acquisition request to occur (Section 5).

Through our model, we are able to connect shared-object systems with relevant analytical tools from Queuing Networks (Section 3.2). Specifically, we identified two methods that are relevant for computing job delay and throughput in  $\varepsilon$ -OSEs. The method of network approximations considers systems with continuous arrivals that follow Exponential distributions and deterministic acquisition of system items, however it does not consider thread blocking [8, Section 8.2]. Instead, the approximation methods of Ramesh and Perros [23] consider systems that can analyze thread blocking (Section 3.2).

In Section 6, we use methods from network approximations [8, Section 8.2] to approximate the probabilities of demand requests to occur. Then, in sections 7–8, we follow the approach of [23] to approximate the system's performance parameters. In Section 9 we define closed subsystems (where jobs are circulating instead of arriving externally and leaving the system) that we use to complete the computation of the system's performance parameters. As in [23], these subsystems preserve the system's performance parameters, but are not subject to thread blocking, and hence can be analyzed through the framework of Baynat and Dallery [4] for closed systems (Section 9.2).

We continue Section 9 by proving Theorem 6, which states that the decomposition of shared-object systems to closed subsystems can be mapped to the decomposition that Ramesh and Perros use for their queuing networks [23]. This proof provides the justification of our approximations. We base our proofs on the model that we provided in Section 5. Then, we present Algorithm 3 (Section 10), which consolidates our approaches for computing the system's performance parameters (including job delay and throughput) in  $\varepsilon$ -OSE (if such exists).

In the remainder of this section we give an overview for each component of our analysis. We outline our modeling approach and the approximation of the system's performance parameters in Section 4.1. In Section 4.2 we summarize the decomposition to closed subsystems that are not subject to thread blocking and the proof of the mapping to the queuing networks of [23]. In Section 4.3 we present an overview of the algorithm for computing job delay and throughput in  $\varepsilon$ -OSEs.

#### 4.1. Modeling dependencies and approximating the system's performance parameters

We base our modeling approach (Section 5) on defining all the events that occur in a shared-object system. We define events for job assignment, object acquisition requests, supply of access to objects, and object release. By that, we define the *thread work cycles*, which depict the sequence of events that occur when a thread is carrying out a job and the fact that threads alternate between idle periods (of possibly zero length) and periods in which they carry out jobs.

We depict dependencies through an *acquisition graph*, which we construct by combining the job object sets and arrival rates to threads. The graph's vertices are the system's items (threads and objects) and each edge depicts a direct dependency. An edge from a thread and to an object shows that this thread carries out at least one job that starts with that object and an edge from one object to another one shows that there is at least one job object set that includes these two objects consecutively.

To the end of capturing dependencies, we define the system's performance parameters based on the edges of the acquisition graph. That is, each edge depicts a sequence of (two) acquisition requests that occur in the system. We first define blocking period  $B$  and delays  $D$  for each edge. Then, we define the inter-demand period  $T$  for each edge, as well as, the item inter-demand period  $\mathcal{T}_s$  for each system item  $s$ , which relates to the time between consecutive acquisition requests. We show that the inter-demand periods follow the same distribution with the time between release events (e.g. job completions), which we use to compute throughput.

In Section 7 we approximate the request blocking period through the delay for acquiring the job's remaining objects, as in [23]. By that, we identify forward dependencies, i.e., the blocking period of a request to an object  $o_d$  depends on the delay of requests to objects  $o_{d'}$ ,  $d' \in (d, M]$ . In Section 8 we approximate the inter-demand period of an object  $o_d$  (by which we compute throughput), by the inter-demand periods of the threads that (possibly) start their jobs by demanding access to  $o_d$  as well as the inter-demand periods of each object  $o_j$ ,  $j \in [1, d]$ . Moreover, in Section 8 we also approximate the thread inter-demand periods, which depend on the job arrival rates and on  $blocking(n)$ . Since not all of these requests occur with the same rate, we use the request probabilities (Section 5) as weights in the approximations of blocking and inter-demand periods. In Section 6 we provide an approximation of these probabilities that bases only on the job arrival rates and the job object sets, which follows the approach of network approximations in [8, Section 8.2].

#### 4.2. Resolving dependencies

We resolve dependencies by decomposing the shared object system to closed subsystems, for each object demand request (Section 9). We refer to these closed subsystems with the term *contention subsystems* and define them such that they are

**Algorithm 1:** Finding an  $\varepsilon$ -OSE (procedure sketch).

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1 Input:  $M, N, \{job_i\}_{i \in [1, J]}, \{\lambda_{i,n}\}_{n \in [1, N], i \in [1, J]}$ , demand request probabilities,  $\varepsilon$ ;
2 Output: job delay and throughput; request blocking, delay, inter-demand periods;
3 Start by assuming that all queues are empty;
4 repeat
5   let  $prevSet \leftarrow$  inter-demand periods of all items;
6   for  $d = M$  to 1 (* backward iteration *) do
7     foreach demand request to  $o_d$  (equiv. edge in the acquisition graph) do
8       Approximate the demand request's delays and inter-demand periods through the respective contention subsystem (Section 9);
9       Approximate the demand request's blocking period (Section 7);
10  foreach  $n \in [1, N]$  do
11    Approximate  $t_n$ 's inter-demand period (Section 8) and upon OSE condition violation call return('no OSE')
12  for  $d = 1$  to  $M - 1$  (* forward iteration *) do
13    Approximate the inter-demand periods of requests to  $o_d$  through the respective contention subsystem (Section 9);
14    Approximate the inter-demand period of  $o_d$  (Section 8);
15 until the system has reached equilibrium (test for  $\varepsilon$ -OSE using the inter-demand period of every item and the values in  $prevSet$ );
16 return job delay and throughput; request blocking, delay, inter-demand periods;

```

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not subject to blocking, and yet they preserve the system's performance parameters. We define contention subsystems as closed systems that include subsets of the system's items. The key steps in this definition are that (i) blocking periods in contention subsystems include the entire time that a thread accesses an object, but the thread does not maintain access to that object when it tries to acquire the next object of its job, and (ii) the order in which threads access objects in the shared-object system is preserved in the contention subsystems. This decomposition follows the approach of [23]. Then, we compute the delay and throughput of demand requests through the framework of Baynat and Dallery for closed systems, which we adapt to the context of shared-object systems (Section 9.2).

We then prove that the decomposition of shared-object systems to contention subsystems can be mapped to the decomposition that Ramesh and Perros present in [23] to analyze queuing networks (Section 9). We present the proof for the case of a system with only three objects,  $M = 3$ , and then present the proof for the general case of systems with  $M$  objects.

### 4.3. Finding approximate equilibria

We compute an approximate equilibrium,  $\varepsilon$ -OSE, when such is reachable. We propose a procedure that always halts (Algorithm 1 presents the solution sketch and we detail the entire procedure in Section 10). It returns the system in an  $\varepsilon$ -OSE state whenever the job arrival and completion rates differ by at most  $\varepsilon$ , or indicates that the system cannot be in a state of an OSE.

The procedure starts with a system state that represents the case in which all queues are empty (line 3). It then estimates the state of a system in which threads can block one another, and the delay grows as more requests are pending in the queues. The procedure works in iterations and decides when to stop updating the item inter-demand periods, i.e., it stops whenever there is no item for which the change in its inter-demand period is greater than  $\varepsilon$  since the previous iteration (lines 5 to 15).

The procedure repeatedly improves an  $\varepsilon$ -OSE estimation until the system state satisfies the conditions of an approximate equilibrium. It deals with interdependencies using alternating backward and forward iterations (lines 6, and respectively, 12). Namely, we resolve the forward dependencies in which a demand's blocking period depends on delays for objects with higher index by *iterating backwards*. This backward iteration starts from  $d = M$  and counts downwards. Similarly, we use *forward iterations* for resolving backward dependencies with respect to  $o_d$ 's item inter-demand period, because all of  $o_d$ 's backward dependencies are resolved. This loop also updates the thread inter-demand periods (line 11). Together with the estimation of the thread inter-demand periods, the procedure checks whether the OSE condition is violated (Section 2.4). In case the OSE condition is violated, the loop breaks and the procedure returns. We show that each iteration takes  $O(M^2 \cdot N^4 + M^3)$  time (Section 10.5).

## 5. Modeling dependencies in shared-object systems

*Overview* In this section we give a comprehensive model for shared-object systems, on which we will base our analysis. We start by defining all the events that occur in the system, through the concepts of job acquisition paths (Section 5.1) and (thread) work cycles (Section 5.2). Then, we model the dependencies between events by defining the acquisition graph (Section 5.3), conditional events that occur within a work cycle, as well as consecutive events that occur in consecutive work cycles (Section 5.4). We also define the probability of conditional events to occur (Section 5.5), i.e., the probability of a thread,  $t_n$ , to demand access to an object,  $o_d$ , immediately after (i)  $t_n$  has been assigned a job, or (ii)  $t_n$  has acquired access to an object,  $o_k$ . We refer to items (i) and (ii) as supply events.

We build up on these definitions to model the system's performance parameters, in a manner that captures the dependencies between the system's items. Given the occurrence of a supply event of a thread (see items (i) and (ii) above), we

Notation	Meaning	Page
$path_{i,n}$	acquisition path $(t_n, o_{i_1}, \dots, o_{i_k})$	8
$cycle(t_n, job_i)$	work cycle of $t_n$ when carrying out $job_i$	8
$\sigma_i(t_n)$	event of $job_i$ 's assignment to $t_n$	8
$\sigma_i(t_n, o_d)$	event of $t_n$ gaining access to $o_d$ , while carrying out $job_i$	8
$\delta_i(t_n, o_d)$	event of $t_n$ demanding access to $o_d$ , while carrying out $job_i$	8
$\phi_i(t_n, o_d)$	event of $t_n$ releasing $o_d$ , while carrying out $job_i$	8
$\Phi_i(t_n)$	event of $t_n$ releasing all objects of $job_i$	8
$\bullet$	an arbitrary sequence (according to context)	9
$\mathcal{G} = (V, E)$	acquisition graph	9
$\delta_{i,n}(d   s) \equiv \langle \delta_i(t_n, s)   \sigma_i(t_n, s) \rangle$	conditional demand event, for $job_i$ and $t_n$	9
$\phi_{i,n}(d   s) \equiv \langle \phi_i(t_n, d)   \sigma_i(t_n, s) \rangle$	conditional release event, for $job_i$ and $t_n$	8
$c[s, o_d]$	pairwise state for items $s$ and $d$	10
$s.T[d]$	inter-demand period for items $s$ and $d$	10
$s.D[d]$	delay for items $s$ and $d$	10
$s.B[d]$	blocking period for items $s$ and $d$	10
$R(s, o_d)$	pairwise request probability for items $s$ and $d$	11
$R$	request probability matrix	11
$\mathcal{T}_s$	item $s$ 's inter-demand period	11
$\psi(\mathcal{G}) = \{c[s, o_d]\}_{(s, o_d) \in E}$	state of system $\mathcal{G} = (V, E)$	12
$\tau(\mathcal{G}) = \{\mathcal{T}_{item}\}_{item \in V \setminus \{o_M\}}$	system inter-demand periods for system state $\psi(\mathcal{G})$	12
$\psi^*(\mathcal{G})$	system state in OSE	12
$f_{s, o_d}$	job completion period	14

Fig. 3. A summary of the basic notation of Section 5.

define random variables for: (a) the time between consecutive (access) demand events for an object (inter-demand period), (b) the time between the consecutive event in which the thread sends a demand request for an object until it releases that object (blocking period), and (c) the time between the consecutive event in which the thread gains access to an object until the thread releases that object (delay). We refer to these three random variables as the pairwise state, as they give the system's performance parameters with respect to pairs of system items (Section 5.5). To the end of defining the job throughput, as well as the rate in which objects are released, we define the item inter-demand period in Section 5.6. We end the section by using the pairwise states to refine the definition of a shared-object system equilibrium (Section 5.7), which we gave in the system settings section. We give a summary of the section's basic notation in Fig. 3, for quick reference.

### 5.1. Acquisition paths

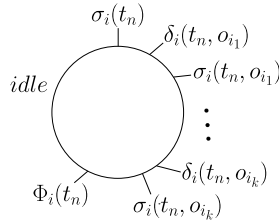
Suppose that the system assigns  $job_i$  to  $t_n : 1 \leq n \leq N$ . In this case,  $job_i$ 's (acquisition) path is the vector,  $path_{i,n} = (t_n, o_{i_1}, \dots, o_{i_k})$ , which denotes that  $t_n$  sequentially acquires  $o_{i_1}, \dots, o_{i_k}$  and then carries out  $job_i$ 's operation, i.e., operation $_i$ .

### 5.2. Work cycles: demand, supply, and release

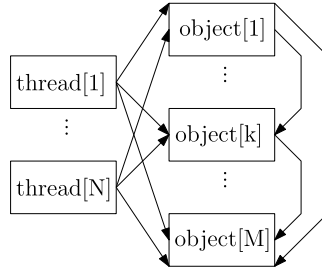
The thread work cycle,  $cycle(t_n, job_i)$ , refers to the events that occur during the period that starts when the system assigns  $job_i$  to  $t_n$  and ends immediately before the next assignment of any job to  $t_n$ . It starts with the event  $\sigma_i(t_n)$  in which the system assigns  $job_i$  to  $t_n$ . For each object  $o_\ell$  of  $job_i$ 's object vector,  $(o_{i_1}, \dots, o_{i_k})$ , the work cycle includes the events in which  $t_n$  demands (requests) access to  $o_\ell$ , denoted by  $\delta_i(t_n, o_\ell)$  and the event in which the system supplies (provides) access to  $o_\ell$ , denoted by  $\sigma_i(t_n, o_\ell)$ . Upon the event of  $job_i$ 's completion  $t_n$  releases each  $o_\ell$ ,  $\ell \in \{i_1, \dots, i_k\}$ , which we denote by the release event  $\phi_i(t_n, o_\ell)$  of the work cycle. For simplicity, we refer to the sequence of these release events  $\Phi_i(t_n) = (\phi_i(t_n, o_{i_1}), \dots, \phi_i(t_n, o_{i_k}))$  as a single event and assume that  $t_n$  releases all its acquired objects instantaneously and immediately after the operation time,  $O_i$ , which is a known random variable. Immediately after the event  $\Phi_i(t_n)$ , the thread work cycle starts a (possibly zero length) idle period, before the system assigns the next (and possibly different than the previous) job to  $t_n$  so that the next work cycle begins.

We illustrate the thread work cycle in Fig. 4. We assume that events are instantaneous and mark them as points on a thread's work cycle. Note however, that between a supply event and the next demand event (as well as between the last supply event and the release event), there is a random length period which refers to scheduling uncertainties, i.e. the (random) acquisition period  $A$ , which follows a known distribution (and the operation time  $O_i$ , respectively). Hence, we denote  $t_n$ 's work cycle for  $job_i$  as in Equation (1):

$$cycle(t_n, job_i) \equiv (\sigma_i(t_n), \delta_i(t_n, o_{i_1}), \sigma_i(t_n, o_{i_1}), \dots, \delta_i(t_n, o_{i_k}), \sigma_i(t_n, o_{i_k}), \Phi_i(t_n)) \quad (1)$$



**Fig. 4.** The work cycle of  $t_n$  for  $job_i$ , with object set  $obj_{s_i} = (o_{i_1}, \dots, o_{i_k})$ . After an idle period  $job_i$  is assigned to  $t_n$  ( $\sigma_i(t_n)$ ), which acquires  $job_i$ 's objects ( $\delta_i(t_n, o_{i_1})$  to  $\sigma_i(t_n, o_{i_k})$ ), executes  $job_i$ 's operation ( $\sigma_i(t_n, o_{i_k})$  to  $\Phi_i(t_n)$ ), and then releases  $job_i$ 's objects ( $\Phi_i(t_n)$ ).



**Fig. 5.** An acquisition graph,  $\mathcal{G}$ .

### 5.3. Subpaths and acquisition graph

Let  $s$  (source) and  $d$  (destination) be (possibly consecutive) items on a path. We define the set  $\epsilon(s, o_d) = \{(s, \bullet, o_d) \mid \exists job_i : path_i = (\bullet, s, \bullet, o_d, \bullet)\}$  of all subpaths between  $s$  and  $o_d$ , where  $\bullet$  denotes a finite, possibly empty, item sequence. The acquisition graph,  $\mathcal{G} = (V, E)$ , is a simple directed graph, where  $V = \{t_1, \dots, t_N, o_1, \dots, o_M\}$  are the system items (Fig. 5). The edges  $E = \{(s, o_d) \mid \exists job_i : path_i = (\bullet, s, o_d, \bullet)\}$  are two consecutive items on a path. That is,  $\mathcal{G}$  includes an edge for two system items if and only if there exists a job, such that these two items are consecutive in its path, e.g., a thread and the first job object or two consecutive objects of a job.

### 5.4. Conditional and consecutive events

In this section, we consider an event that occurs at item  $d$  (destination) in condition to an event occurrence at item  $s$  (source), where  $(\bullet, s, o_d, \bullet)$  is a subpath of  $job_i$  and both events belong to the same work cycle of  $job_i$  that  $t_n$  carries out. We define conditional events, which capture the dependencies within a work cycle, as well as consecutive events, which capture the dependencies between consecutive work cycles. These definitions are the basis for modeling the system's state in Section 5.5.

#### 5.4.1. Conditional demand and supply events

Consider a subsequence  $(\sigma_i(t_n, s), \delta_i(t_n, o_d))$  of  $cycle(t_n, job_i)$ 's events. We denote by  $\delta_{i,n}(o_d | s) \equiv \langle \delta_i(t_n, o_d) \mid \sigma_i(t_n, s) \rangle$  the conditional (demand) event,  $\delta_i(t_n, o_d)$ , in which  $t_n$  requests access to  $o_d$  immediately after the supply event,  $\sigma_i(t_n, s)$ , in a timing order (i.e. in the actual sequence in which these events occur). Note that the event  $\sigma_i(t_n, s)$  may refer to: (1) access to object  $s$ , or (2)  $job_i$ 's assignment to  $s = t_n$  (Fig. 4), i.e.,  $\sigma_i(t_n) \equiv \sigma_i(t_n, t_n)$ . E.g.,  $\delta_{i,n}(o_j | o_k)$  denotes the conditional demand event  $\langle \delta_i(t_n, o_j) \mid \sigma_i(t_n, o_k) \rangle$  in which  $t_n$  requests access to  $o_j$  immediately after gaining access to  $o_k$ , where  $k \in [1, M - 1]$ ,  $j \in (k, M]$ , and  $n \in [1, N]$  (i.e.,  $o_k$  has lower index than  $o_j$ ). Another example is the case  $\delta_{i,n}(o_j | t_n)$ , where the conditional demand event  $\langle \delta_i(t_n, o_j) \mid \sigma_i(t_n, t_n) \rangle$  refers to  $t_n$ 's request to access  $job_i$ 's first object,  $o_j$ , immediately after the assignment of  $job_i$  to  $t_n$ . In a similar manner, denote by  $\phi_{i,n}(o_d | s) \equiv \langle \phi_i(t_n, o_d) \mid \sigma_i(t_n, s) \rangle$  the conditional (release) event, in which  $t_n$  releases  $o_d$  at event  $\phi_i(t_n, o_d)$  that occurs after the supply event,  $\sigma_i(t_n, s)$  and at the same work cycle (we will mainly use  $\phi_{i,n}(s | s)$ ).

#### 5.4.2. Events of arbitrary jobs and threads

In some parts of our modeling, we consider an arbitrary  $job_i$  that an arbitrary  $t_n$  carries out. We then write  $\delta(o_d | s)$ ,  $\sigma(s)$  and  $\phi(o_d | s)$  instead of  $\delta_{\bullet, \bullet}(o_d | s)$ ,  $\sigma_{\bullet, \bullet}(s)$ , and respectively,  $\phi_{\bullet, \bullet}(o_d | s)$  when referring to events from the sets  $\{\delta_{i,n}(o_d | s) : i \in [1, J], n \in [1, N]\}$ ,  $\{\sigma_{i,n}(s) : i \in [1, J], n \in [1, N]\}$ , and respectively,  $\{\phi_{i,n}(o_d | s) : i \in [1, J], n \in [1, N]\}$ , where  $i \in [1, J]$  and  $n \in [1, N]$ . Given subpath  $(\bullet, \ell_1, \dots, \ell_k, \bullet)$ , denote by  $\delta(\ell_k | \ell_1, \dots, \ell_{k-1})$  the occurrence of  $\delta(\ell_k | \ell_{k-1})$ , which happens immediately after  $\delta(\ell_{k-1} | \ell_{k-2}), \dots, \delta(\ell_2 | \ell_1)$ .

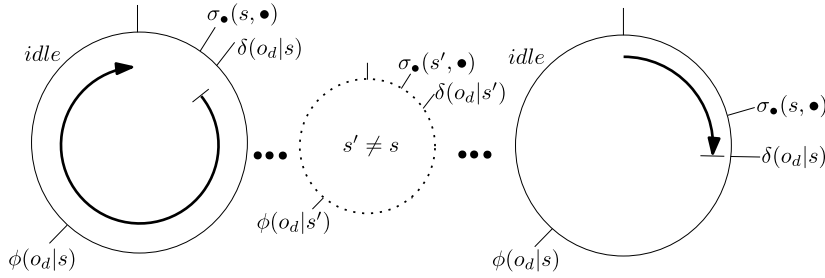


Fig. 6.  $(s, o_d)$ 's inter-demand period,  $s.T[d]$ , i.e., the period between two consecutive  $\delta(o_d|s)$  events.

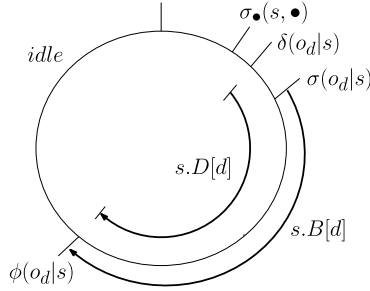


Fig. 7. The delay  $s.D[d]$  and blocking  $s.B[d]$  start from  $\delta(o_d|s)$ , and respectively,  $\sigma(o_d|s)$ , and both end at  $\phi(o_d|s)$ .

5.4.3. Consecutive events

To the end of defining throughput (inter-demand period) of a system item  $s$  in Section 5.5, we define consecutive demand events that follow supply events of  $s$ . We say that  $\delta_{i,n}(o_k|s)$  occurs consecutively after  $\delta_{j,n'}(o_\ell|s)$ , when all the following conditions hold:

- (1)  $\delta_{j,n'}(o_\ell | s) = \langle \delta_j(t_{n'}, o_\ell) | \sigma_j(t_{n'}, s) \rangle$  is part of  $t_{n'}$ 's work cycle that includes the event  $\sigma_j(t_{n'}, s)$  and the event  $\delta_j(t_{n'}, o_\ell)$  in which after  $s$ 's supply,  $t_{n'}$  requests access to  $o_\ell$ ,
- (2)  $\phi_j(t_{n'}, s)$  in which  $t_{n'}$  releases item  $s$ , and
- (3)  $\delta_{i,n}(o_k | s) = \langle \delta_i(t_n, o_k) | \sigma_i(t_n, s) \rangle$  is part of  $t_n$ 's work cycle (which is the successive of  $cycle(t_n, job_j)$ ), which includes the events  $\sigma_i(t_n, s)$  and  $\delta_i(t_n, o_k)$ , in which after the supply of  $s$ ,  $t_n$  requests access to  $o_k$ .

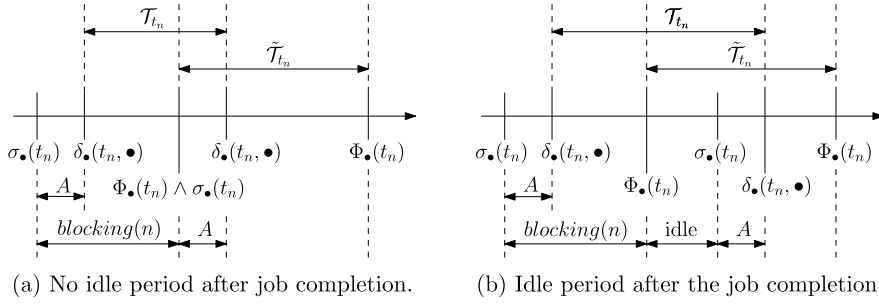
5.5. Pairwise states and request probabilities

The definition of the studied equilibria (at the system level) is based on item-level definitions that consider  $\mathcal{G}$ 's edges,  $(s, o_d) \in E$ . We present a definition of the (pairwise) state,  $c[s, o_d]$ , which considers the delay, blocking and inter-demand periods that are related to the edge  $(s, o_d)$  of  $\mathcal{G}$  and its conditional events. These periods refer to the time it takes threads to request access to  $o_d$ , and release it subsequently (after the acquisition of item  $s$ ) as well as the time between such (consecutive) requests that are made by (possibly) different threads. Moreover, when estimating the value of the pairwise-state,  $c[s, o_d]$ , we need to consider the probabilities that are related to the edge  $(s, o_d)$  and its conditional events.

5.5.1. Pairwise states

To the end of approximating  $\tilde{T}_{t_n}$ ,  $\tilde{D}_{t_n}$ , and  $blocking(n)$ , for  $n \in [1, N]$ , we define the pairwise states, which capture the throughput, delay, and blocking between  $t_n$  and every system object. To compute the latter, we extend the definition of pairwise states to pairs of objects, since jobs might include more than one object. In sections 7–8 we will show how we can approximate  $\tilde{T}_{t_n}$ ,  $\tilde{D}_{t_n}$ , and  $blocking(n)$  through the pairwise states.

We refer to  $(s, d)$ 's pairwise state  $c[s, o_d] = s.\langle T[d], D[d], B[d] \rangle$  as the tuple that includes the request completion rate, request delay, and respectively, blocking period with relation to the events  $\delta(o_d|s)$ , where  $d \in [1, M]$  refers to  $o_d$  and  $s$  can be either a thread or  $o_\ell$ ,  $\ell \in [1, d]$ . The  $(s, o_d)$ 's request inter-demand period,  $s.T[d]$ , refers to the period between the consecutive events,  $\langle \delta_i(t_n, o_d) | \sigma_i(t_n, s) \rangle$  and  $\langle \delta_j(t_{n'}, o_d) | \sigma_j(t_{n'}, s) \rangle$  (Fig. 6), where  $i, j \in [1, J]$  and  $n, n' \in [1, N]$ . Furthermore,  $(s, o_d)$ 's delay,  $s.D[d]$ , refers to a period that starts on the event  $\delta(o_d|s)$  in which a thread requests access to  $o_d$  (immediately after gaining access to item  $s$ ) and ends upon the event  $\phi(o_d|s)$  in which that thread releases  $o_d$  (during the same work cycle). In addition,  $(s, o_d)$ 's blocking,  $s.B[d]$ , is the fraction of  $(s, o_d)$ 's delay  $s.D[d]$  in which the thread blocks other threads from gaining access to  $o_d$ , i.e., the period between the event  $\langle \sigma_i(t_n, o_d) | \sigma_i(t_n, s) \rangle$  in which  $t_n$  gains access to  $o_d$ , and the event  $\phi_i(t_n, o_d)$  in which  $t_n$  releases  $o_d$  (Fig. 7). Note that each of  $c[s, o_d]$ 's three elements is a random variable (for which maintaining the first three moments provides sufficient accuracy).



**Fig. 8.** Illustration of the fact that  $\mathcal{T}_{t_n}$  (inter-demand period) and  $\tilde{\mathcal{T}}_{t_n}$  (time between consecutive job completions) follow the same distribution. In both figures, the horizontal line denotes the time horizon, while the vertical lines mark events that occurred, which are denoted below them.  $\mathcal{T}_{t_n}$  starts with the first demand event ( $\delta_\bullet(t_n, \bullet)$ ) that follows the job assignment ( $\sigma_\bullet(t_n)$ ) and it continues until the job completion ( $\Phi_\bullet(t_n)$ ). Then there is a possibly zero length idle period (Fig. 8b) until the next job assignment ( $\sigma_\bullet(t_{n+1})$ ), and  $\mathcal{T}_{t_n}$  ends at the event  $\delta_\bullet(t_n, \bullet)$ . Similarly,  $\tilde{\mathcal{T}}_{t_n}$  starts at the event of job completion ( $\Phi_\bullet(t_n)$ ), which is followed by a possibly zero length idle period, and ends upon the job completion of the next job ( $\sigma_\bullet(t_{n+1})$  to  $\Phi_\bullet(t_{n+1})$ ).

### 5.5.2. Pairwise request probabilities

An essential component of our analysis is the probability of an event  $\delta(o_d|s)$  to occur, i.e., the probability of a demand event to object  $o_d$  to occur immediately after the supply event of item  $s$ , within the same work cycle. Given that a thread has gained access to item  $s$ , i.e.,  $\sigma_\bullet(t_\bullet, s)$  occurred, then either  $\delta_\bullet(t_\bullet, o_d)$  will occur immediately after, or the thread will release  $s$  in case the job is completed. We refer to the probability of  $\delta(o_d|s)$  to occur as the (pairwise) request probability,  $R(s, o_d)$ .

The exact values of these probabilities can be computed when we are aware of all the events that occurred during a time horizon  $t$ . In this case, we denote these probabilities with  $R_t(s, o_d)$ . When the information about the number of system events during the horizon  $t$  is not available or we consider the values of these probabilities independently of  $t$ , we use the notation  $R(s, o_d)$ . In the following we define  $R(s, o_d)$  and  $R_t(s, o_d)$ . In this work, we do not focus on a specific horizon  $t$  neither we assume that we have knowledge of the number of events that have occurred during some  $t$ . Hence, in Section 6 we propose an approximation of  $R(s, o_d)$ , based on the system's input parameters.

**Definition of  $R(s, o_d)$**  For a randomly chosen work cycle that includes the event,  $\sigma_\bullet(t_\bullet, s)$ , of a thread gaining access to item  $s$ , we define  $\Omega(s) = \{\delta(o_d|s) : (s, o_d) \in E \text{ is an edge in } \mathcal{G} \cup \{\phi(s|s)\}\}$  as the probability space of the possible events to occur immediately after  $\sigma_\bullet(t_\bullet, s)$ . Moreover,  $R(s, o_d)$  and  $R(s, s)$  are the probabilities of  $\Omega(s)$ 's events  $\delta(o_d|s)$ , and respectively,  $\phi(s|s)$ . Namely,  $R(s, o_d)$  denotes the probability of a demand event,  $\delta_\bullet(t_\bullet, o_d)$  to occur immediately after the supply event,  $\sigma_\bullet(t_\bullet, s)$  and in the same (randomly chosen) work cycle. Moreover,  $R(s, s)$  denotes the probability of a release event,  $\phi_\bullet(t_\bullet, s)$ , to occur immediately after its related supply event,  $\sigma_\bullet(t_\bullet, s)$  and during the same (randomly chosen) work cycle. Note that  $R(s, s)$ 's definition requires that  $s$  is the last object to which a thread gains access during its work cycle.

We define the request probability matrix  $R$  to be a  $(N + M) \times (N + M)$  row stochastic matrix, such that the  $(s, o_d)$  element of  $R$  is the probability  $R(s, o_d)$ . Note that by the definition of the state space,  $\Omega(s)$ , the following hold: (i) for every two items  $s$  and  $x$ , such that  $(s, x)$  is not an edge of  $\mathcal{G}$ ,  $R(s, x) = 0$  holds, and (ii)  $R(s, s) + \sum_d R(s, o_d) = 1$  holds. The matrix  $R$  has a block form (Equation (2)), where  $R_{N,N}$  is an  $N \times N$  zero matrix,  $R_{N,M} = (R(t_n, o_j))_{n \in [1,N], j \in [1,M]}$  is an  $(N \times M)$  matrix,  $R_{M,N}$  is an  $M \times N$  zero matrix, and  $R_{M,M} = (R(o_j, o_k))_{j,k \in [1,M]}$  is an  $M \times M$  matrix. Note that  $R_{M,M}$  is an upper triangular matrix, since the acquisition order of objects (implied by the ascending index order of  $obj_{s_i}$  in  $job_i = \langle obj_{s_i}, operation_i \rangle$ ) restricts each thread to request an object of higher index than the one of the last object that it gained access to.

$$R = \left( \begin{array}{c|c} R_{N,N} & R_{N,M} \\ \hline R_{M,N} & R_{M,M} \end{array} \right) \quad (2)$$

**Definition of  $R_t(s, o_d)$**  In this case, we restrict the (random) choice of the work cycle to the time interval  $t = [t_{start}, t_{end}]$  and assume the knowledge of all events that occurred in the system during that period. For the time interval  $t = [t_{start}, t_{end}]$ , we define  $R_t(s, o_d) = \alpha_t(s, o_d) / \eta_t(s)$ , to be the number of  $\delta(o_d|s)$  occurrences, over the number of  $\sigma(s)$  occurrences and  $R_t(s, s) = \beta_t(s) / \eta_t(s)$  to be the number of  $\phi(s|s)$  occurrences, over the number of  $\sigma(s)$  occurrences, where  $\#_t X$  denotes the number of event  $X$  occurrences in  $t = [t_{start}, t_{end}]$ . Moreover, we define (i)  $\alpha_t(s, o_d) = \sum_{i,n} \#_t \delta_{i,n}(o_d|s)$ , when  $s = o_\ell$ ,  $\ell \in [1, d]$ , and (ii)  $\alpha_t(s, o_d) = \sum_{i,n} \#_t \delta_{i,n}(o_d|s)$ , when  $s = t_n$  :  $n \in [1, N]$ , the number of  $\delta(o_d|s)$  events that occurred during  $t = [t_{start}, t_{end}]$ . Furthermore,  $\beta_t(s) = \sum_{i,n} \#_t \phi_{i,n}(s|s)$  and  $\eta_t(s) = \sum_{i,n} \#_t \sigma_i(t_n, s)$  denote the number of  $\phi(s|s)$ , and respectively,  $\sigma(s)$  events that occurred during  $t = [t_{start}, t_{end}]$ . Note that profiling tools can be the basis for estimating  $R_t(s, o_d)$  and  $R_t(s, s)$ .

### 5.6. Item inter-demand period

To the end of defining the job completion rate (throughput), as well as the rate in which an object is released, we define the item inter-demand period. Consider  $job_i$  and  $job_{i'}$ , where  $i, i' \in [1, J]$ , such that  $o_{i_1}$  and  $o_{i'_1}$  are the first objects in the

object vectors of  $job_i$ , and respectively,  $job_{i'}$ , and assume that  $t_n$  carries out  $job_i$  and  $job_{i'}$  consecutively. We refer to  $t_n$ 's inter-demand period,  $\mathcal{T}_{t_n}$ , as the period between  $\delta_i(t_n, o_{i_1})$  and the demand event  $\delta_{i'}(t_n, o_{i'_1})$ .

We remark that the time between (consecutive) job completions of  $t_n$ ,  $\tilde{\mathcal{T}}_{t_n}$  (Section 2.3), follows the same distribution with the thread inter-demand period,  $\mathcal{T}_{t_n}$  (essentially, the time between consecutive job assignments). We illustrate this point in Fig. 8, as well as in the following. Recall that *blocking*( $n$ ) denotes the job blocking period for  $t_n$  (Section 2.4), i.e., the time between the assignment and completion of a job at  $t_n$ . Also, recall that  $\tilde{D}_{t_n}$  denotes the job delay for  $t_n$  (Section 2.4), i.e., the time between a job arrival to  $Q_{t_n}(t_n)$  and the completion of that job. When there is an idle period after a job completion ( $t_n$ 's queue is empty), upon the next job arrival to  $t_n$ 's queue, the job is immediately assigned to  $t_n$ . In the latter case, the job delay and blocking period are equal. Let  $idl_{t_n}$  be the random variable that denotes the length of  $t_n$ 's idle periods ( $idl_{t_n} = 0$  when there is no idle period between consecutive jobs).

By the definition of the work cycle events (Section 5.2),  $\tilde{\mathcal{T}}_{t_n}$  (time between job completions) follows the distribution of  $idl_{t_n} + \text{blocking}(n)$ . That is, after a job completion event, there is an idle period (of possibly zero length), hence  $idl_{t_n}$ . In case  $t_n$ 's queue is empty, then the next job that arrives is immediately assigned to  $t_n$ , hence the next job completion after the idle period occurs after a period equal to  $\text{blocking}(n)$ . In case  $t_n$ 's queue is not empty, then the next job is immediately assigned to  $t_n$ , hence the time until the next job completion is again  $\text{blocking}(n)$ . Similarly,  $\mathcal{T}_{t_n}$  follows the distribution of  $(\text{blocking}(n) - A) + idl_{t_n} + A = \text{blocking}(n) + idl_{t_n}$ . That is,  $\mathcal{T}_{t_n}$  starts with a demand event for the first object of a job, hence there is a period of  $\text{blocking}(n) - A$  until  $t_n$  completes that job. Then, there is an idle period of length  $idl_{t_n}$ , until the next job assignment. After the next job assignment, there is a period of length  $A$  (acquisition period) until the demand event for the first object of that job.

We refer to  $o_k$ 's inter-demand period,  $\mathcal{T}_{o_k}$ , as the period between two consecutive conditional (demand) events for accessing an object in  $\{o_\ell : \ell \in (k, M)\}$  immediately after gaining access to  $o_k$  by two, possibly different, threads, where  $k \in [1, M - 1]$ . Namely,  $\mathcal{T}_{o_k}$  is the period between  $\delta(o_j|o_k)$  and the successive event  $\delta(o_{j'}|o_k)$ , where  $j, j' \in (k, M]$ . Similarly to  $\mathcal{T}_{t_n}$ ,  $1/E(\mathcal{T}_{o_d})$  estimates (due to using the expected value of  $\mathcal{T}_{o_d}$ ) the number of job completions that include  $o_d$  per time unit.

Note that in systems where jobs with paths  $(\bullet, o_d, o_{d'}, \bullet)$  do not exist, we assume that  $\mathcal{T}_{o_d}$  is the time between two consecutive  $\sigma_\bullet(\bullet, o_d)$  events (which definitely occur due to our assumptions in Section 2). Our definition of  $\mathcal{T}_s$  for a system item  $s$ , will play a crucial role in resolving dependencies in Section 9 (cf. Section 4). Specifically, it will allow us to define subsystems that include less system items (hence the focus on the time between requests), that preserve the shared-object system's performance parameters.

### 5.7. Shared-object system equilibria

In this section, we refine the definitions of system state and OSEs given in Section 2.4, basing on the pairwise states. For a given system,  $\psi(\mathcal{G}) = \{c[s, o_d]\}_{(s, o_d) \in E}$  is the system state (set), where  $\mathcal{G} = (V, E)$  is the acquisition graph. For a given  $\psi(\mathcal{G})$ , the inter-demand period of the system is the set  $\tau(\mathcal{G}) = \{\mathcal{T}_{item}\}_{item \in V \setminus \{o_M\}}$ .

Suppose that the system is in a state in which  $\sum_{i \in [1, J]} \lambda_{i, n} = 1/E[\mathcal{T}_{t_n}]$ , for every  $n \in [1, N]$ . That is, the job arrival and completion rates match for every thread's queue. We say that  $\psi^*(\mathcal{G}) = \{c^*[s, d]\}_{(s, o_d) \in E}$ , is the shared-Object System Equilibrium (OSE). Given  $\psi^*(\mathcal{G})$ , the respective inter-demand period of the system is  $\tau^*(\mathcal{G}) = \{\mathcal{T}_{item}^*\}_{item \in V \setminus \{o_M\}}$ . For a given  $\varepsilon > 0$  and an OSE  $\psi^*(\mathcal{G})$ , we say that the system state  $\psi(\mathcal{G})$  is an  $\varepsilon$ -OSE when  $\forall item \in V \setminus \{o_M\}, \mathcal{T}_{item} \in \tau^*(\mathcal{G}), |\mathcal{T}_{item} \in \tau(\mathcal{G}) : |\mathcal{T}_{item}^* - \mathcal{T}_{item}| < \varepsilon$  holds. Namely, the corresponding values of each item in  $\tau(\mathcal{G})$  and  $\tau^*(\mathcal{G})$  differ by less than  $\varepsilon$ .

## 6. Request probabilities

In this section we provide approximations of the pairwise request probabilities  $R(s, o_d)$  (Section 5.5.2). Recall that  $R(s, o_d)$  denotes the probability of a thread to demand access to  $o_d$ , immediately after the supply event  $\sigma_\bullet(\bullet, s)$  (the latter denotes either a job assignment event or the event of a thread gaining access to object  $s$ ). Moreover,  $R(s, s)$  denotes the probability of a job to be completed at object  $s$ .

The fact that the pairwise request probabilities depend on the arrival rates of the corresponding jobs is the basis of our estimation of  $R(s, o_d)$  (Approximation 1), where  $(s, o_d)$  is an edge in the acquisition graph  $\mathcal{G}$ . That is, a higher arrival rate of jobs that include  $s$  and  $o_d$  in their acquisition paths, increases the probability of  $\delta_{\bullet, \bullet}(s, o_d)$  events to occur (Section 5.4.2). We follow the approach of network approximations [8, Section 8.2] for estimating the probabilities  $R(s, o_d)$ . In network approximations, queuing systems (Section 3) with arrivals that follow exponential distributions and jobs that have deterministic routing, but exponentially distributed service times, are approximated by Jackson queuing networks (for which an exact analysis is feasible) [15,5]. This method cannot be applied entirely for the analysis of shared-object systems, since it considers exponentially distributed blocking periods and it does not consider thread blocking. However, as mentioned in [8, Section 8.2], combinations of multiple (non-exponentially distributed) arrivals to a system item's queue, tend to be exponentially distributed.

In Lemma 2 we prove that our estimations of  $R(s, o_d)$  and  $R(s, s)$  define indeed a probability, i.e., for any item  $s$ ,  $R(s, s) + \sum_{d \neq s} R(s, o_d) = 1$ . This implies that the probability matrix  $R$ , which contains the estimates of  $R(s, o_d)$  and  $R(s, s)$ , is a

stochastic matrix. Let  $\langle s_1, \dots, s_\ell \rangle$  be a vector of objects,  $objs_i$  be the object vector of  $job_i$  and  $i \in [1, J]$ . We define the following characteristic functions with values in  $\{0, 1\}$ :

$$starts_i(\langle s_1, \dots, s_\ell \rangle) \Leftrightarrow objs_i = (s_1, \dots, s_\ell, \bullet) \tag{3}$$

$$includes_i(\langle s_1, \dots, s_\ell \rangle) \Leftrightarrow objs_i = (\bullet, s_1, \dots, s_\ell, \bullet) \tag{4}$$

$$ends_i(\langle s_1, \dots, s_\ell \rangle) \Leftrightarrow objs_i = (\bullet, s_1, \dots, s_\ell) \tag{5}$$

**Approximation 1.** Equation (6) and Equation (7) approximate  $R(s, o_d)$ , when  $s = t_n : n \in [1, N]$ , and respectively,  $s = o_j : j \in [1, M - 1]$ . Moreover, for any object  $s$ , Equation (8) approximates  $R(s, s)$ .

$$R(t_n, o_d) \approx \frac{(\sum_i \lambda_{i,n} \cdot starts_i(\langle o_d \rangle))}{(\sum_i \lambda_{i,n})} \tag{6}$$

$$R(o_j, o_d) \approx \frac{\sum_{i,n} \lambda_{i,n} \cdot includes_i(\langle o_j, o_d \rangle)}{\sum_{i,n} \lambda_{i,n} \cdot includes_i(\langle o_j \rangle)} \tag{7}$$

$$R(s, s) \approx \frac{(\sum_{i,n} \lambda_{i,n} \cdot ends_i(\langle s \rangle))}{(\sum_{i,n} \lambda_{i,n} \cdot includes_i(\langle s \rangle))} \tag{8}$$

Equation (6) estimates  $R(t_n, o_d)$  by the sum of arrival rates of jobs that start with  $o_d$  at  $t_n$ , divided by the sum of the arrival rates of all the jobs that are assigned to  $t_n$ . Equation (7) estimates  $R(o_j, o_d)$  by the sum of arrival rates of jobs that include the subvector  $\langle o_j, o_d \rangle$  in their object vector (assigned to any thread), divided by the sum of arrival rates of jobs that include the subvector  $\langle o_j \rangle$  in their object vector (to any thread), where  $j \in [1, M - 1]$  and  $d \in [j, M]$ . Equation (8) estimates  $R(s, s)$  by the sum of arrival rates of jobs with object vectors that end with the subvector  $\langle s \rangle$  (assigned to any thread), divided by the sum of arrival rates of jobs that include the subvector  $\langle s \rangle$  in their object vector (assigned to any thread), where  $s$  is a system object. Note that in any other case, we define  $R(s, o_d) = 0$ , since no conditional demand events  $\delta(o_d|s)$  or conditional release events  $\phi(s)$  occur in these cases.

We prove that the estimation of the request probabilities in Approximation 1 also defines a probability (Lemma 2).

**Lemma 2.** For  $R(s, o_d)$ 's estimation (Approximation 1), it holds that: (1)  $\sum_d R(t_n, o_d) = 1$ , where  $n \in [1, N]$  and  $o_d$  is an object, (2)  $R(s, s) + \sum_{d \neq s} R(s, o_d) = 1$ , and (3)  $R$  is a row stochastic matrix.

**Proof.** Equation (9) demonstrates claim (1).

$$\begin{aligned} \sum_d R(t_n, o_d) &= \frac{\sum_d \sum_i \lambda_{n,i} \cdot starts_i(\langle o_d \rangle)}{\sum_i \lambda_{n,i}} \\ &= \frac{\sum_i \lambda_{n,i} \sum_d starts_i(\langle o_d \rangle)}{\sum_i \lambda_{n,i}} \\ &= \frac{\sum_i \lambda_{n,i} \cdot 1}{\sum_i \lambda_{n,i}} \\ &= 1 \end{aligned} \tag{9}$$

For any object  $s \neq o_M$ , Equation (11) demonstrates claim (2) due to Equation (10), which holds since a job object vector that includes object  $s$ , either ends with  $s$  or includes more items  $o_d \neq s$ .

$$\begin{aligned} ends_i(\langle s \rangle) + \sum_{d \neq s} includes_i(\langle s, o_d \rangle) &= includes_i(\langle s \rangle) \tag{10} \\ R(s, s) + \sum_{d \neq s} R(s, o_d) &= \frac{\sum_{n,i} \lambda_{n,i} \cdot ends_i(\langle s \rangle)}{\sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s \rangle)} + \frac{\sum_{d \neq s} \sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s, o_d \rangle)}{\sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s \rangle)} \\ &= \frac{\sum_{n,i} \lambda_{n,i} \cdot ends_i(\langle s \rangle) + \sum_{d \neq s} \sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s, o_d \rangle)}{\sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s \rangle)} \\ &= \frac{\sum_{n,i} \lambda_{n,i} (ends_i(\langle s \rangle) + \sum_{d \neq s} includes_i(\langle s, o_d \rangle))}{\sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s \rangle)} \\ &= \frac{\sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s \rangle)}{\sum_{n,i} \lambda_{n,i} \cdot includes_i(\langle s \rangle)} \\ &= 1 \end{aligned} \tag{11}$$

As for claim (3), we note that claims (1) and (2) imply that our estimation of the block matrices  $R_{N,M}$  and  $R_{M,M}$  of the matrix  $R$  are row stochastic (Equation (2)). Since the block matrices  $R_{N,N}$  and  $R_{M,N}$  are zero matrices, our estimation of  $R$  forms a row stochastic matrix.  $\square$

## 7. Blocking periods

In this section we estimate the blocking periods of the pairwise states (Section 5.5.1), i.e., the time between the events of supply and release of access to an object. Recall that the supply event of item  $s$ , may refer to either the assignment of a job to  $s = t_n$  or the event in which a thread acquires access to  $s = o_j$ . We estimate the blocking period  $s.B[d]$ , i.e., the time from the event in which a thread acquires access to  $o_d$  immediately after the occurrence of a supply event of item  $s$ , until that thread releases  $o_d$ .

The  $s.B[d]$  blocking period is an effect of multiple threads' job paths, i.e., the  $(\bullet, s, o_d)$  and the remaining  $(\bullet, s, o_d, \bullet)$  paths. The former case corresponds to the job completion period (Approximation 3), whereas the latter also includes the dependency on the delay of acquiring the path's remaining objects (Approximation 4). Our approximations follow the approach of [23]. In Section 9 we show that the computation of the pairwise states can be indeed based on tools from [23].

### 7.1. Job completion periods

Let  $f_{s,o_d}$  denote the fraction of the blocking period that refers to jobs with paths  $(\bullet, s, o_d)$ . That is,  $f_{s,o_d}$  is the time between the supply event  $\sigma_{\bullet, \bullet}(\bullet, o_d)$  and the release event  $\phi_{\bullet, \bullet}(\bullet, o_d)$  of the same work cycle, for jobs with paths  $(\bullet, s, o_d)$  (cf. Section 5.4.2). We estimate  $f_{s,o_d}$  by the operation time average of jobs with  $(\bullet, s, o_d)$  paths, weighted by the probability for the related events to occur (Approximation 3). Approximation 3 defines  $f_{s,o_d} = \sum_{i=1}^J \text{weight}_i(s, o_d) \cdot O_i$  as a weighted average of all the operation times. We define these weights as follows. If  $s$  is an object, then Equation (13) defines  $\text{weight}_i(s, o_d)$  and Equation (12) defines the normalizing constant for all weights.

$$W_{s,o_d} = \sum_{i=1}^J \sum_{n=1}^N \lambda_{i,n} \cdot \text{ends}_i((s, o_d)) \quad (12)$$

$$\text{weight}_i(s, o_d) = (\sum_{n=1}^N \lambda_{i,n} \cdot \text{ends}_i((s, o_d))) / W_{s,o_d} \quad (13)$$

Similarly, if  $s$  is a thread,  $t_n$ , then Equation (15) defines  $\text{weight}_i(s, o_d)$  and Equation (14) defines the normalizing constant for all weights.

$$W_{s,o_d} = \sum_{i=1}^J \lambda_{i,n} \cdot \text{ends}_i((o_d)) \quad (14)$$

$$\text{weight}_i(s, o_d) = (\lambda_{i,n} \cdot \text{ends}_i((o_d))) / W_{s,o_d} \quad (15)$$

**Approximation 3** (as in [23]). The blocking period of jobs with paths  $(\bullet, s, o_d)$  is a weighted average,  $f_{s,o_d} = \sum_{i=1}^J \text{weight}_i(s, o_d) \cdot O_i$ , of the respective job operation times.

### 7.2. Acquiring the remaining objects

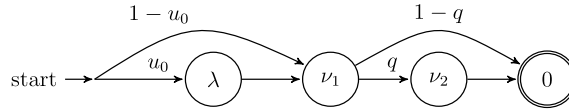
In the case of  $(\bullet, s, o_d, \bullet)$  paths, the blocking period  $s.B[d]$  depends on the completion period of jobs with  $(\bullet, s, o_d)$  paths,  $f_{s,o_d}$ , as well as on the jobs with  $(\bullet, s, o_d, o_{d'}, \bullet)$  paths. In the case of jobs with  $(\bullet, s, o_d, o_{d'}, \bullet)$  paths, the blocking period of  $o_d$  equals the delay for  $o_{d'}$ . That is, the time between the events of acquiring and releasing access to  $o_d$ , equals the time between the events of queuing an acquisition request in the queue of  $o_{d'}$  and the release of  $o_{d'}$  (as well as the other objects of that job). Since  $d' \in (d + 1, M]$ , Approximation 4 is an average over all possible choices of  $d'$ , weighted by the pairwise probabilities, as in [23].

**Approximation 4** (as in [23]). The blocking period of jobs with  $(\bullet, s, o_d, \bullet)$  paths can be estimated by  $s.B[d] = R(s, o_d) \cdot R(o_d, o_d) \cdot f_{s,o_d} + \sum_{d'=d+1}^M R(s, o_d) \cdot R(o_d, o_{d'}) \cdot (A + o_d \cdot D[d'])$ .

Note that Approximation 4's recursive equation details a forward dependency on the delays  $o_d \cdot [d']$ ,  $d \in (d + 1, M]$ . Thus, it is possible to compute this estimation for  $d = M$  directly from the input parameters (sections 6 and 7.1), i.e.,  $s.B[M] = R(s, o_M) \cdot R(o_M, o_M) \cdot f_{s,o_M}$ . Then, given the delays  $s.D[M]$ , it is possible to compute the blocking periods  $s.B[M - 1]$ , and so on until  $s.B[1]$ . This computation is the basis of the backward iterations (Section 4) to resolve these dependencies (Section 9).

## 8. Item inter-demand periods

The inter-demand period of an item  $s$ ,  $\mathcal{T}_s$ , is the time between two consecutive demand requests that follow the supply of item  $s$  (Section 5.6). In this section, we approximate the item inter-demand period, which together with the blocking period,  $s.B[d]$  (Section 7), are essential for calculating the delay,  $s.D[d]$  (Section 9), where  $d \in [1, M]$  and  $(s, o_d)$  is an edge in the acquisition graph  $\mathcal{G}$ . In Section 8.1 we estimate  $\mathcal{T}_{t_n}$ , for every thread  $t_n$  and in Section 8.2 we estimate  $\mathcal{T}_{o_d}$ , for every object  $o_d$ . The estimation of  $\mathcal{T}_{t_n}$  depends on the job arrival process and the job blocking period, and the estimation of  $\mathcal{T}_{o_d}$  bases on the pairwise inter-demand periods,  $s.T[d]$ , where  $s$  is a system item.



**Fig. 9.** The Markov process that models  $\tilde{\mathcal{T}}_{t_n}$ . The process starts after a job completion on  $t_n$ . If  $Q_{thread}(t_n)$  is empty (with steady-state probability  $u_0$ ) the next job arrives with rate  $\lambda$ . After a job has arrived or in case  $Q_{thread}(t_n)$  is not empty (which occurs with probability  $1 - u_0$ ), the blocking period begins. The blocking period follows a Coxian-2 distribution, and thus it consists of two states with rates  $\nu_1$  and  $\nu_2$ . The blocking period ends with rate  $\nu_1$  with probability  $1 - q$ , by moving to the absorbing (ending) state, marked with 0. Otherwise, the blocking period continues to the second state (of rate  $\nu_2$ ) with probability  $q$ , after which it also moves to the absorbing state.

8.1. Thread inter-demand period

We estimate the inter-demand period of a thread  $t_n$ ,  $\mathcal{T}_{t_n}$ , through a Markov process, following the approach of [23]. Recall that  $\mathcal{T}_{t_n}$  follows the same distribution with the time between job completions,  $\tilde{\mathcal{T}}_{t_n}$  (Fig. 8, Section 5.6). Thus, we focus on computing the first three moments of  $\tilde{\mathcal{T}}_{t_n}$ . We achieve the latter, by defining a Markov process which describes  $\tilde{\mathcal{T}}_{t_n}$ , such that  $\tilde{\mathcal{T}}_{t_n}$  follows the distribution of the time until the Markov process reaches an absorption (ending) state [23]. By the definition of  $\tilde{\mathcal{T}}_{t_n}$ , the absorbing state is the event of job completion. In Fig. 9 we define a Markov process that models  $\tilde{\mathcal{T}}_{t_n}$ , which we explain below.

The Markov process of Fig. 9 is defined as follows. By the definition of  $\tilde{\mathcal{T}}_{t_n}$ , the process starts upon a job completion event (and ends in the next job completion event). Hence, in the beginning of the process the queue of  $t_n$  is empty with steady-state probability  $u_0$  (Section 3.1), or non-empty (with probability  $1 - u_0$ ), and in the latter case the blocking period of the next job begins. Thus, if  $t_n$ 's queue is empty, the next job arrives with rate  $\lambda = \sum_{i=1}^J \lambda_{i,n}$  (first state in Fig. 9), and the blocking period begins immediately after the job arrival.

Since the distribution of the blocking period,  $blocking(n)$ , is unknown, we use its moments to match it with a Coxian-2 distribution (Section 3.1 and [2]). We denote the parameters of the Coxian-2 distribution that matches the moments of  $blocking(n)$  with  $\nu_1$ ,  $q$ , and  $\nu_2$  (Section 3.1). By the definition of Coxian-2 distributions, the blocking period either ends after the state with rate  $\nu_1$  with probability  $q$ , or it continues (with probability  $1 - q$ ) to the state with rate  $\nu_2$ , after which it certainly ends. The end of the blocking period (job completion) sets the end of  $\tilde{\mathcal{T}}_{t_n}$ 's period, which is modeled by the absorbing (ending) state of the Markov process (state 0 in Fig. 9).

Recall that  $\tilde{\mathcal{T}}_{t_n}$  follows the distribution of the time until the Markov process of Fig. 9 reaches an absorption state. The latter time follows a phase-type distribution, by the distribution's definition [1,21]. In the following we define the parameters of  $\tilde{\mathcal{T}}_{t_n}$ 's phase-type distribution, based on the Markov process of Fig. 9, which will then allow us to compute  $\tilde{\mathcal{T}}_{t_n}$ 's moments.

A phase-type distribution is defined by an initial probability vector  $c$  (probability of starting in each state) and a transition rate matrix  $Q$  (rates of transitions between states), both determined by the Markov process. By Fig. 9,  $c = (u_0, 1 - u_0, 0, 0)$ , where each of the elements corresponds to the probability of starting in each of the states of the Markov process in the following order:  $\lambda$ ,  $\nu_1$ ,  $\nu_2$ , and 0. Similarly, the matrix  $Q$  is a  $4 \times 4$  matrix with block form  $Q = \begin{bmatrix} S & S^0 \\ \mathbf{0} & 0 \end{bmatrix}$ , where  $Q(x, y)$  is the transition rate of moving from state  $x$  to state  $y$ , multiplied by the transition's probability,  $\mathbf{0}$  is a  $1 \times 3$  vector of zeros,  $\mathbf{1}$  is a  $3 \times 1$  vector of ones, and  $S^0 = -S\mathbf{1}$ . Note that the last column and row of  $Q$  correspond to the absorbing state and each diagonal element is defined by the row's sum times  $-1$ . By Fig. 9, we have the following:

$$Q = \begin{bmatrix} -\lambda & \lambda & 0 & 0 \\ 0 & -\nu_1 & q\nu_1 & (1-q)\nu_1 \\ 0 & 0 & -\nu_2 & \nu_2 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{ and } S = \begin{bmatrix} -\lambda & \lambda & 0 \\ 0 & -\nu_1 & q\nu_1 \\ 0 & 0 & -\nu_2 \end{bmatrix}.$$

The  $m$ -th moment of  $\mathcal{T}_{t_n}$ , which equals the one of  $\tilde{\mathcal{T}}_{t_n}$ , is  $E[\mathcal{T}_{t_n}^m] = E[\tilde{\mathcal{T}}_{t_n}^m] = (-1)^m m! cS^{-m}\mathbf{1}$  [1].

We define the function  $augmntThreadBlock(I(n), blocking(n))$ , which estimates  $\mathcal{T}_{t_n}$ 's moments as we explained above. The function input includes the inter-arrival times  $I(n)$  (which follows an  $Exp(\sum_{i=1}^J \lambda_{i,n})$  distribution) and the function  $blocking(n)$ , which we approximate by  $blocking(n) = A + \sum_{d=1}^M R(t_n, o_d) \cdot t_n \cdot D[d]$ , i.e., the average time it takes  $t_n$  to complete a job ( $t_n \cdot D[d]$  ends on job completion). Moreover,  $augmntThreadBlock(I(n), blocking(n))$  outputs the estimation of  $\mathcal{T}_{t_n}$  and checks if the OSE condition is violated (line 11 in Algorithm 1 of Section 4.3), i.e., the rate  $\sum_{i=1}^J \lambda_{i,n}$  that defines  $I(n)$  is greater or equal than  $1/E[blocking(n)]$  for every  $n \in [1, N]$ . We detail the calculation of the pairwise delays,  $s.D[d]$ , in Section 9.

8.2. Object inter-demand period

The inter-demand period  $\mathcal{T}_{o_d}$  of an object  $o_d$  is the time between two consecutive demand events that immediately follow the events of a thread gaining access to  $o_d$  (Section 5.6). As we showed in Section 5.6,  $\mathcal{T}_{o_d}$  follows the same distribution

with the time between two consecutive release events of  $o_d$ , which defines the completion rate of jobs that include  $o_d$  ( $o_d$ 's throughput). By its definition,  $\mathcal{T}_{o_d}$  depends on the rate in which threads place acquisition requests in  $o_d$ 's queue, as well as on the job completion period on  $o_d$ ,  $f_{s,o_d}$  (Section 7). In the following, we detail an approximation of  $\mathcal{T}_{o_d}$  (Approximation 5), which follows the approach of [23].

Consider an edge  $(s, o_d)$  of the acquisition graph  $\mathcal{G}$ . Threads that execute jobs that have an acquisition path equal to  $(\bullet, s, o_d, \bullet)$  request access to  $o_d$ , immediately after the supply of item  $s$ . Therefore, Approximation 5 computes  $\mathcal{T}_{o_d}$  by a weighted average of  $\mathcal{T}_s$  (inter-demand period of item  $s$ ) and  $f_{s,o_d}$  (job completion period), for every item  $s$ , such that  $(s, o_d)$  is an edge in  $\mathcal{G}$ . The weight  $\omega(s, o_d)$  depends on the probability  $R(s, o_d)$  as well as on the pairwise inter-demand period  $s.T[d]$ . That is,  $\omega(s, o_d)$  depends on the probability of a thread to demand access to  $o_d$ , immediately after a supply event of item  $s$ , as well as on the time between such demands. We denote with  $arrivals(o_d)$  the set of all items  $s$ , such that  $(s, o_d)$  is an edge in  $\mathcal{G}$ . For example,  $arrivals(o_2) = thread \cup \{o_1\}$  and  $thread = \{t_1, \dots, t_N\}$ .

**Approximation 5** (as in [23]). Let  $\omega(s, o_d) = R(s, o_d) \cdot s.T[d]$  and  $arrivals(o_d) = thread \cup \{o_j \mid j \in [1, d-1]\}$ . The inter-demand period  $\mathcal{T}_{o_d}$  of  $o_d$  is:

$$\mathcal{T}_{o_d} = \frac{\sum_{s \in arrivals(o_d)} \omega(s, o_d) \cdot (\mathcal{T}_s + f_{s,o_d})}{\sum_{s \in arrivals(o_d)} \omega(s, o_d)}$$

Approximation 5 details  $\mathcal{T}_{o_d}$ 's backward dependency via its recursive equation that calculates  $\mathcal{T}_{o_j}$ ,  $j \in [1, d-1]$ , before calculating  $\mathcal{T}_{o_d}$ . Moreover, the calculation of  $\mathcal{T}_{o_d}$  depends on the inter-demand periods, which is  $t_n.T[d]$ , of  $(t_n, o_d)$  and respectively,  $s.T[d]$ , where  $d \in [1, M]$  and  $s \in thread \cup \{o_j \mid j \in [1, d-1]\}$ . We use forward iterations (Section 4) for resolving such dependencies (Section 10). Furthermore, in Section 9 we calculate the pairwise inter-demand periods  $s.T[d]$  for  $(s, o_d)$  in  $\mathcal{G}$ .

## 9. Resolving dependencies: pairwise delay and throughput computation

We showed how to estimate the blocking period of an object,  $s.B[d]$ , while depending on the delay for acquiring other objects,  $o_d.D[d']$  (Section 7), as well as how to estimate the inter-demand periods  $\mathcal{T}_{t_n}$  and  $\mathcal{T}_{o_d}$ , while depending on the  $s.T[d]$  pairwise inter-demand periods, due to  $(\bullet, s, o_d, \bullet)$  paths (Section 8). Recall that these variables are inter-dependent due to blocking. Theorem 6 demonstrates that we can resolve these interdependencies by representing the thread work cycles as a contention subsystem, in a way that is not subject to blocking and yet preserves these interdependencies.

To the end of proving Theorem 6, we first define contention subsystems in Section 9.1. Contention subsystems are closed systems that we construct basing on the items  $s$  and  $o_d$ , as well as on distinct copies (relay nodes) of every object  $o_j$ , such that  $(\bullet, s, o_j, \bullet)$  is a job path, where  $j \neq d$ . These subsystems effectively represent the system parameters and thread blocking, because by their definition the time during which a thread is accessing an item in the contention subsystem includes the item's entire blocking period in the shared-object system.

Then, we present the Baynat–Dallery framework (Section 9.2), which is an adaptation of Baynat and Dallery's algorithm [4] to the setting of shared-object systems. The Baynat–Dallery framework's input is a contention subsystem for item  $s$  and  $o_d$  and its output is (the distributions of)  $s.T[d]$  and  $s.D[d]$ . We provide the key steps of Theorem 6's proof by looking into the case of  $M = 3$  in Section 9.3, before giving the complete proof in Section 9.4, using background knowledge [4,23] (which we refer to in Section 3).

**Theorem 6.** Let  $s \in S_{o_d}$ , where  $S_{o_d} \in \{thread\} \cup \{o_j \mid j \in [1, d]\}$ . The Baynat–Dallery framework can approximate the pairwise delay  $s.D[d]$  and pairwise inter-demand period  $s.T[d]$  through the contention subsystem  $\mathcal{CS}(S_{o_d}, o_d) = (\mathcal{H}(S_{o_d}, o_d), (\mathcal{R}_s)_{s \in S_{o_d}}, (\mathcal{B}_s)_{s \in S_{o_d}})$ , where  $S_{o_d} \in \{thread\} \cup s_{o_d}$  and  $s_{o_d} = \{o_i \mid i \in [1, d-1]\}$ . The running time of each framework iteration is  $O(M \cdot N^4)$ .

### 9.1. Contention subsystems

Given any pair of system items,  $s$  and  $o_d$ , we calculate the (pairwise) state  $c[s, o_d]$  for  $\mathcal{G}$ 's edge  $(s, o_d)$  using a construction that we name contention subsystem  $\mathcal{CS}(S_{o_d}, o_d)$ , where  $d \in [1, M]$ ,  $s \in S_{o_d}$  and  $S_{o_d}$  is either the set of all threads,  $S_{o_d} = thread$ , representing  $(t_n, d, \bullet)$  job paths, or a set including a single object,  $S_{o_d} = \{o_j\}$ ,  $j \in [1, d-1]$ , representing  $(\bullet, o_j, o_d, \bullet)$  paths. For every item  $s \in S_{o_d}$ , we use the thread work cycle,  $cycle(t_n, job_j)$  of  $t_n$ ,  $n \in [1, N]$ , carrying out  $job_j$ , (Section 5), to show that the contention subsystem  $\mathcal{CS}(S_{o_d}, o_d)$  represents the state of the shared-object system, with respect to the interdependencies among the delay  $s.D[d]$  and the pairwise inter-demand period  $s.T[d]$  when the blocking time and the item inter-demand periods are known.

Let  $o_d \in \{o_1, \dots, o_M\}$ ,  $s_{o_d} = \{o_1, \dots, o_{d-1}\}$  (i.e.,  $s_{o_d} = \emptyset$  when  $d = 1$ ), and  $S_{o_d} \in \{thread\} \cup s_{o_d}$ , where  $thread = \{t_1, \dots, t_N\}$ . Moreover, let  $Rel(thread, o_d) = [1, M] \setminus \{d\}$  and  $Rel(\{o_i\}, o_d) = [i+1, M] \setminus \{d\}$ , where  $\{o_i\} \in s_{o_d}$ . We partition the  $(\bullet, s, \bullet)$  paths to three sets,  $\mathcal{P}(s, o_d) = \cup_{\ell \in [1,3]} \mathcal{P}_\ell$ , where  $\mathcal{P}_1 = \{path \mid path = (\bullet, s, o_d, \bullet)\}$ ,  $\mathcal{P}_2 = \{path \mid path = (\bullet, s, o_i, \bullet, o_d, \bullet) \wedge i \in Rel(S_{o_d}, o_d) \setminus [d+1, M]\}$ ,  $\mathcal{P}_3 = \{path \mid path = (\bullet, s, \bullet) \wedge o_d \notin path\}$ .

A contention subsystem, is denoted by  $\mathcal{CS}(S_{o_d}, o_d) = (\mathcal{H}(S_{o_d}, o_d), (\mathcal{R}_s)_{s \in S_{o_d}}, (\mathcal{B}_s)_{s \in S_{o_d}})$  and defined by (1)–(3).

(1) The contention graph  $\mathcal{H}(S_{o_d}, o_d) = (\mathcal{V}, \mathcal{E})$  has the set of vertices  $\mathcal{V} = \cup_{s \in S_{o_d}} \mathcal{V}_s$ , and the set of edges  $\mathcal{E} = \cup_{s \in S_{o_d}} \mathcal{E}_s$ , such that for every  $s \in S_{o_d}$ ,  $\mathcal{V}_s = \{s\} \cup \{d\} \cup \{\text{relay}(s, o_j) \mid j \in \text{Rel}(S_{o_d}, o_d)\}$  and  $\mathcal{E}_s = \mathcal{E}_s^1 \cup \mathcal{E}_s^2 \cup \mathcal{E}_s^3$ , where  $\mathcal{E}_s^1 = \{(s, o_d), (o_d, s)\}$ ,  $\mathcal{E}_s^2 = \cup_{j \in \text{Rel}(S_{o_d}, o_d) \setminus [d+1, M]} \{(s, \text{relay}(s, o_j)), (\text{relay}(s, o_j), o_d), (o_d, s)\}$ , and  $\mathcal{E}_s^3 = \cup_{j \in \text{Rel}(S_{o_d}, o_d)} \{(s, \text{relay}(s, o_j)), (\text{relay}(s, o_j), s)\}$ , i.e.,  $\mathcal{E}_s^k$  corresponds to the partition  $\mathcal{P}_k$ , where  $k \in [1, 3]$ . Note that  $\mathcal{H}(S_{o_d}, o_d)$  is a simple graph, i.e., there are no multiple edges between two vertices. Moreover,  $\text{relay}(s, o_j)$  is a distinct copy of a relay  $o_j$ ,  $j \in \text{Rel}(S_{o_d}, l)$ , for  $s \in S_{o_d}$ . A relay node  $\text{relay}(s, o_j)$  will allow us to separately analyze the effect of jobs with paths  $(\bullet, s, o_j, \bullet)$  on  $s.T[d]$  and  $s.D[d]$ . For example, jobs with paths  $(t_n, o_j, \bullet)$  and  $(t_{n'}, o_j, \bullet)$  effect differently  $s.T[d]$  and  $s.D[d]$ , for  $s \in \{t_n, t_{n'}\}$ . This decomposition technique follows the approach of [23].

(2) The request probability matrices  $\mathcal{R}_s$  for  $\mathcal{H}(S_{o_d}, o_d) = (\mathcal{V}, \mathcal{E})$  and  $s \in S_{o_d}$ .  $\mathcal{R}_s(s, o_d)$  depicts the probability of a path  $(\bullet, s, o_d, \bullet)$ . Moreover,  $\mathcal{R}_s(s, \text{relay}(s, o_j))$  depicts the probability of a path  $r = (\bullet, s, o_j, \bullet)$ , while  $\mathcal{R}_s(\text{relay}(s, o_j), o_d)$  depicts the probability that  $r = (\bullet, s, o_j, \bullet, o_d, \bullet)$ . Furthermore,  $\mathcal{R}_s(v, s)$ ,  $v \in \mathcal{V}_s \setminus \{s\}$ , depicts the probability of a thread becoming idle or starting a new job after the completion of a job, which is a certain event and therefore  $\mathcal{R}_s(v, s) = 1$ ,  $v \in \mathcal{V}_s \setminus \{s\}$ .

(3) The blocking periods,  $(\mathcal{B}_s)_{s \in S_{o_d}}$ , where  $\mathcal{B}_s$  is a function over the set of items in  $\mathcal{V}_s$ , and  $s \in S_{o_d}$  refers to the thread blocking periods on each of  $\mathcal{V}_s$ 's items. Note that  $\mathcal{E}_s^i$  forms a directed circle in  $\mathcal{H}(S_{o_d}, o_d)$ , where  $s \in S_{o_d}$  and  $i \in [1, 3]$ . A demand request to  $o_d$  that follows the supply of  $s \in S_{o_d}$  and possibly the supply of a relay object,  $o_j$ ,  $j \in \text{Rel}(S_{o_d}, o_d) \setminus [d+1, M]$ , is blocking  $o_d$  for  $\mathcal{B}_s(o_d) = s.B[d]$  time. A demand request to node  $\text{relay}(s, o_j)$  that follows the supply of  $s \in S_{o_d}$ , blocks that node for a period of  $\mathcal{B}_s(\text{relay}(s, o_j)) = s.D[j]$ , if  $j \in [d+1, M]$  and  $\mathcal{B}_s(\text{relay}(s, o_j)) = W(s, \text{relay}(s, o_j), o_d)$ , if  $j \in \text{Rel}(S_{o_d}, o_d) \setminus [d+1, M]$ , where  $W(s, \text{relay}(s, o_j), o_d)$  equals the delay  $s.D[j]$  minus the blocking period of a possibly subsequent demand event to  $o_d$ . Once a job is completed, another demand event follows the supply of  $s \in \mathcal{V}_s$  after a period of  $\mathcal{B}_s(s) = \mathcal{T}_s$  (by the definition of  $\mathcal{T}_s$ ). Lemma 7 of Section 9.4 shows that a contention subsystem represents the dependencies among the threads in a shared-object system with respect to its state.

## 9.2. Baynat–Dallery framework

In this section, as a background knowledge, we discuss a variation on Baynat and Dallery's framework [4] that we adapt to the context of shared-object systems (Algorithm 2). The  $BDF()$  function denotes our adapted version of Baynat and Dallery's framework. For every  $s \in S_{o_d}$ , this function takes a contention subsystem,  $\mathcal{CS}(S_{o_d}, o_d)$ , which is the tuple  $(\mathcal{H}(S_{o_d}, o_d), (\mathcal{R}_s)_{s \in S_{o_d}}, (\mathcal{B}_s)_{s \in S_{o_d}})$ , as an input and returns an estimation of the delay  $s.D[d]$  and inter-demand period  $s.T[d]$ . Namely,  $(s.T[d], s.D[d])_{s \in S_{o_d}} = BDF(\mathcal{CS}(S_{o_d}, o_d))$ . The solution of Baynat and Dallery is based on iterative approximations of the demand arrival rates and request completion rate to  $o_d$  with the ones in the subgraph  $\mathcal{H}_s(S_{o_d}, o_d) = (\mathcal{V}_s, \mathcal{E}_s)$ , and vice versa, until, for every  $s \in S_{o_d}$ , their absolute difference is below a given threshold. The authors of [4] demonstrate the convergence of their iterative methods via numerical experiments. Baynat and Dallery [4] show that each iteration has polynomial running time, which is  $O(M \cdot N^4)$  for the OSE case (Lemma 9).

We complete this section with a detailed explanation of Algorithm 2. The procedure starts by an initialization phase (lines 7–9), which is followed by a repeat-until loop (lines 10–24) and the output calculation (lines 25–26) before returning the output (line 27).

### 9.2.1. Variables

Let  $s \in S_{o_d}$  denote a thread, if  $S_{o_d} = \text{thread}$ , or an object, if  $S_{o_d} = \{o_j\}$ , where  $j \in [1, d-1]$ . For item  $v \in \mathcal{V}_s$ , we define  $\mathcal{I}_s(v)$ ,  $\mathcal{B}_s(v)$  and  $\mathcal{C}_s(v)$  to be item  $v$ 's the inter-arrival time  $\mathcal{I}_s(v)$ , blocking period  $\mathcal{B}_s(v)$ , and respectively, inter-demand period  $\mathcal{C}_s(v)$ . With respect to the  $BDF()$  function,  $\mathcal{I}_s(v)$  is the time between two demand events to item  $v$ ,  $\mathcal{B}_s(v)$  is the blocking period of an arbitrary demand event to  $v$ , and respectively,  $\mathcal{C}_s(v)$  is the time between two release events on  $v$ . Note that when  $s$  is a thread ( $S_{o_d} = \text{thread}$ ),  $\mathcal{I}_s(s)$  is the time between two object release events by  $s$ ,  $\mathcal{B}_s(s)$  is the time from an object release event until the next job completion by  $s$ , and respectively,  $\mathcal{C}_s(s)$  is the time between two job completions by  $s$ . Baynat and Dallery approximate  $\mathcal{I}_s(v)$ ,  $\mathcal{B}_s(v)$  and  $\mathcal{C}_s(v)$  using exponential distributions with parameters (rates)  $\gamma_s(v)$ ,  $\mu_s(v)$ , and respectively,  $\nu_s(v)$ . Note that these random variables depend only on  $s$  and  $v$ , due to the definition of the contention subsystem (Section 9.1) and Lemma 7 of Section 9.4. The  $BDF()$  function estimates  $\gamma_s(v)$ ,  $\mu_s(v)$  and  $\nu_s(v)$  and uses them to compute  $s.D[j]$  and  $s.T[j]$  for every  $s \in S_{o_d}$ .

We define the subgraph  $\mathcal{H}_s(S_{o_d}, o_d) = (\mathcal{V}_s, \mathcal{E}_s)$  of  $\mathcal{H}(S_{o_d}, o_d)$  (Section 9.1). Note that when  $S_{o_d} = \text{thread}$ , thread  $s = t_n$  requests to access only to items in  $\mathcal{H}_s(S_{o_d}, o_d)$ 's subgraph. Similarly, when  $S_{o_d} = \{o_\ell\}$ , a thread that has access to  $s = o_\ell$  requests to access only to  $\mathcal{H}_s(S_{o_d}, o_d)$ 's items, where  $\ell \in [1, d-1]$ . Baynat and Dallery treat these subgraphs as Gordon–Newell networks [9,6]. The  $BDF()$ 's repeat-until loop (lines 10–24) alternates between computing  $\gamma_s(v)$ ,  $\mu_s(v)$  and  $\nu_s(v)$  for the Gordon–Newell network defined by the subgraph  $\mathcal{H}_s(S_{o_d}, o_d)$ , for every  $s \in S_{o_d}$  and the same values for every individual item  $v \in \mathcal{V}$ . The iterations stop when for two consecutive loops there is no  $s \in S_{o_d}$  and  $v \in \mathcal{V}_s$ , such that the values of  $\mu_s(v)$  differ more than a given  $\varepsilon$  (line 24).

### 9.2.2. Initialization phase

The  $BDF()$  function initializes  $\mu_s(v)$  with  $1/E(\mathcal{B}_s(v))$  (lines 7–8) and computes the steady-state probabilities of a thread to demand or have access to item  $v$ , after the supply of item  $s$ . It does that through the function  $\text{stationary}()$ , which takes

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**Algorithm 2:** The  $BDF()$  function for estimating delay and pairwise inter-demand period through a contention subsystem.

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1 Input:  $\mathcal{CS}(S_{o_d}, o_d) = (\mathcal{H}(S_{o_d}, d), (\mathcal{R}_s)_{s \in S_{o_d}}, (\mathcal{B}_s)_{s \in S_{o_d}})$ ;
2 Output:  $(s.T[d], s.D[d])_{s \in S_{o_d}}$ ;
3 Macros:
4  $converged(prev, curr) = (\nexists \mu_s(v) \in prev, \mu'_s(v) \in curr : |\mu_s(v) - \mu'_s(v)| \geq \epsilon)$ ;
5  $Z(v) = \{s \in S_{o_d} | v \in \mathcal{V}_s\}$ ;
6 begin
7   foreach  $s \in S_{o_d}$  do
8     foreach  $v \in \mathcal{V}_s$  do  $\mu_s(v) \leftarrow 1/E(\mathcal{B}_s(v))$ 
9   foreach  $s \in S_{o_d}$  do  $(steadyStateProbabilities_s(v))_{v \in \mathcal{V}_s} \leftarrow stationary(\mathcal{R}_s)$ 
10  repeat
11    let  $oldValues = (\mu_s(v))_{s \in S_{o_d}, v \in \mathcal{V}}$ ;
12    foreach  $s \in S_{o_d}$  do
13       $GordonNewellConstant_s \leftarrow \sum_{v \in \Theta(s)} steadyStateProbabilities_s(v) / \mu_s(v)$ ;
14      foreach  $v \in \mathcal{V}_s$  do
15         $subgraphMarginalProbs_{s,v}(1) \leftarrow \frac{steadyStateProbabilities_s(v)}{\mu_s(v) \cdot GordonNewellConstant_s}$ ;
16         $subgraphMarginalProbs_{s,v}(0) \leftarrow 1 - subgraphMarginalProbs_{s,v}(1)$ ;
17         $\gamma_s(v) \leftarrow \mu_s(v) \cdot \frac{subgraphMarginalProbs_{s,v}(1)}{subgraphMarginalProbs_{s,v}(0)}$ ;
18      foreach  $v \in V$  do
19        foreach  $s \in Z(v)$  do
20           $itemMarginalProbs_{s,v}(0) \leftarrow idleProb(v, s, \{\gamma_s(v)\}_{s \in S_{o_d}}, \{\mu_s(v)\}_{s \in S_{o_d}}, (\mathcal{R}_s)_{s \in S_{o_d}})$ ;
21           $itemMarginalProbs_{s,v}(1) \leftarrow 1 - itemMarginalProbs_{s,v}(0)$ ;
22          foreach  $s \in Z(v)$  do  $v_s(v) \leftarrow \gamma_s(v) \cdot \frac{itemMarginalProbs_{s,v}(0)}{itemMarginalProbs_{s,v}(1)}$ 
23        foreach  $s \in S_{o_d}$  do (foreach  $v \in \mathcal{V}_s$  do  $\mu_s(v) \leftarrow v_s(v)$ );
24  until  $converged(oldValues, \{\mu_s(v)\}_{s \in S_{o_d}, v \in \mathcal{V}})$ ;
25  foreach  $s \in S_{o_d}$  do
26    let  $(s.D[d], s.T[d]) = (1/(\mu_s(o_d) \cdot subgraphMarginalProbs_{s,o_d}(0)), 1/\gamma_s(o_d))$ ;
27  return  $(s.T[d], s.D[d])_{s \in S_{o_d}}$ ;

```

---

the stochastic matrix  $\mathcal{R}_s$  as an input. The function  $stationary()$  outputs the steady state vector,  $steadyStateProbabilities_s$ , which has the size of  $|\mathcal{V}_s|$ . Moreover,  $steadyStateProbabilities_s$  satisfies the equations  $\pi \cdot \mathcal{R}_s = \pi$  and  $\sum_{i=1}^{|\mathcal{V}_s|} \pi_i = 1$  (line 9).

### 9.2.3. The repeat-until loop

The  $BDF()$  function's repeat-until loop calculates  $\gamma_s(v)$  (lines 12–17),  $v_s(v)$  (lines 18–22) and  $\mu_s(v)$  (line 23). We calculate the Gordon–Newell normalizing constant (line 13) and the marginal probabilities of Gordon–Newell (lines 14–16). Using these marginal probabilities, we calculate  $\gamma_s(v)$  for every  $s \in S_{o_d}$  and  $v \in \mathcal{V}_s$  (line 17).

We find the marginal probability of an item to be idle through the  $idleProb()$  function (lines 18–21) and then calculate  $v_s(v)$  (line 22) for every  $s \in Z(v)$ , where  $Z(v) = \{s \in S_{o_d} | v \in \mathcal{V}_s\}$  (line 5). The  $idleProb()$  function calculates item  $v$ 's marginal probability to be idle through the underlying Markov chain of a multi-class queue with exponential arrivals ( $\gamma_s(v)$  for every  $s \in Z(v)$ ). It also calculates the blocking periods ( $\mu_s(v)$  for every  $s \in Z(v)$ ). Note that the queue length is limited by the maximum number of pending demands ( $N$  when  $S_{o_d} = thread$  and 1 when  $S_{o_d} = \{o_j\}$ ,  $j \in [1, d - 1]$ ) [4,5].

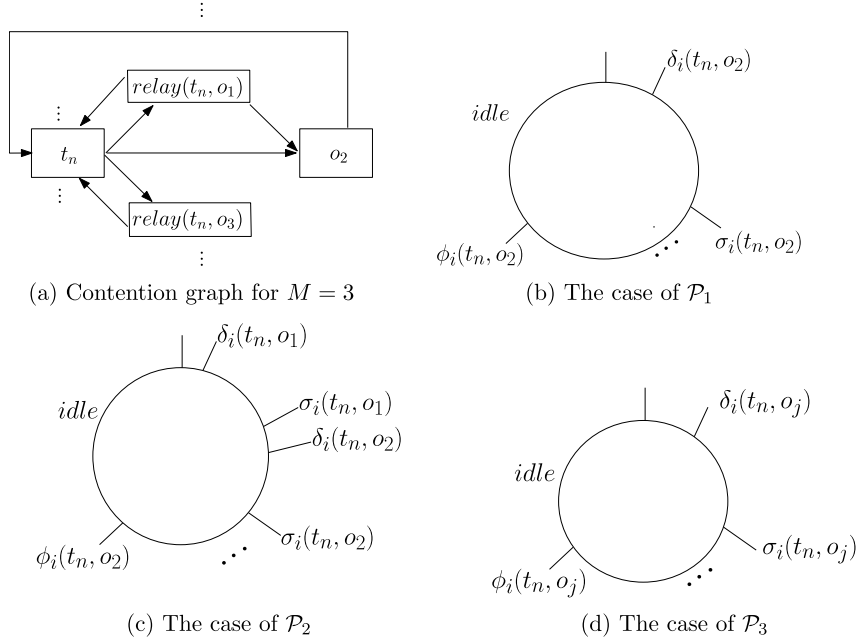
The calculation  $\mu_s(v)$ 's new estimates (line 23) happens before the next iteration. In order to check the convergence condition, each iteration begins with storing in the  $oldValues$  variable the last estimations of  $\mu_s(v)$  for every  $s \in S_{o_d}$  and  $v \in \mathcal{V}_s$  (line 24).

### 9.2.4. $BDF()$ 's output

We estimate  $s.D[d]$  through the delay in  $o_d$ 's queue in the contention subsystem (line 26), i.e. by  $Exp(\mu_s(o_d) \cdot subgraphMarginalProbs_{s,o_d}(0))$ . Moreover, we obtain an estimation of the inter-demand period  $s.T[d]$  through  $Exp(\gamma_s(o_d))$  (line 26). The  $BDF()$  function returns the output in line 27.

## 9.3. The case of systems with $M = 3$ objects

We use an illustrative example that shows how the contention subsystem of  $S_{o_2} = thread$  and  $o_2$  represents the dependencies among the threads of a system with  $M = 3$  objects and  $N$  threads, with respect to the delays and pairwise inter-demand periods, when the blocking times and the item inter-demand periods are known. We construct the contention subsystem  $\mathcal{CS}(thread, o_2) = (\mathcal{H}(thread, o_2), (\mathcal{R}_s)_{s \in thread}, (\mathcal{B}_s)_{s \in thread})$  based on the work cycles related to the delay  $t_n.D[2]$  and inter-demand period  $t_n.T[2]$ , for every  $s = t_n \in thread$ . We explain the representation of work cycles by a contention graph, which is illustrated in Fig. 10a, and the adaptation of the request probabilities and blocking times to the ones of the



**Fig. 10.** The contention graph for  $CS(thread, 2)$  and the work cycles partitions,  $\mathcal{P}(s, o_2) = \cup_{\ell \in [1,3]} \mathcal{P}_\ell$ , of  $(s, \bullet)$  paths, where  $\mathcal{P}_1 = \{\chi | \chi = (s, o_2, \bullet)\}$ ,  $\mathcal{P}_2 = \{\chi | \chi = (s, o_1, o_2, \bullet)\}$ ,  $\mathcal{P}_3 = \{\chi | \chi = (s, \bullet) \wedge o_2 \notin \chi, s = t_n\}$ .

contention subsystem. The challenge here is to demonstrate that a dynamic system that is based on correlated events with dependencies that are due to blocking and follow non-deterministic schedules can be represented by these subsystems. After demonstrating this part of the proof, the rest of the proof follows by matching between the subsystems presented here to the one by Ramesh-Perros [23], which use a framework proposed by Baynat and Dallery [4] for estimating our system's state.

### 9.3.1. Contention graph of $CS(thread, o_2)$

Let  $\mathcal{H}(thread, o_2) = (\mathcal{V}, \mathcal{E})$  for  $S_{o_d} = thread$  (Fig. 10a). Given an arbitrary thread,  $s = t_n$ ,  $n \in [1, N]$ , let  $\mathcal{P}(s, o_2) = \cup_{\ell \in [1,3]} \mathcal{P}_\ell$  be a partition of  $(s, \bullet)$  paths, where  $\mathcal{P}_1 = \{path | path = (s, o_2, \bullet)\}$ ,  $\mathcal{P}_2 = \{path | path = (s, o_1, o_2, \bullet)\}$  and  $\mathcal{P}_3 = \{path | path = (s, \bullet) \wedge o_2 \notin path\}$ . Moreover, let  $\mathcal{V} = \cup_{n \in [1, N]} \mathcal{V}_s$  be the union of  $\mathcal{V}_s = \{s, relay(s, o_1), o_d, relay(s, o_3)\}$ , where  $relay(s, o_j)$ ,  $j \in \{1, 3\}$ , are  $s$ 's distinct copies of a relay object,  $o_j$ , which allow us to distinguish paths with respect to threads. The contention graph's nodes  $s, relay(s, o_j)$  and  $o_d$  represent  $s, o_j$  and, respectively  $o_d$ , in the shared-object system, where  $j \in \{1, 3\}$ .

The edges  $\mathcal{E} = \cup_{n \in [1, N]} \mathcal{E}_s$  follow the path partition cases,  $\{\mathcal{E}_\ell\}_{\ell \in [1,3]}$ . Let  $job_i$  be a job that  $s = t_n$  carries out. The edge sets  $\mathcal{E}_\ell$ , where  $\ell \in [1, 3]$ , are defined as follows:

- $\mathcal{P}_1$ 's case refers to work cycles, for which  $s$  demands access to  $o_2$ , once it is assigned with  $job_i$ . When  $s$  gains access to  $o_d$ ,  $job_i$  might require  $s$  to demand access to  $o_3$ . Upon  $job_i$ 's completion  $s$  releases any acquired object. Thus, the edges in  $\mathcal{E}_1 = \{(s, o_2), (o_2, s)\}$  (Fig. 10a) represent the work cycle subvectors  $(\delta_i(s, o_2))$ , and respectively,  $(\sigma_i(s, o_2), \dots, \phi_i(s, o_2), \dots)$  (Fig. 10b).
- $\mathcal{P}_2$ 's case refers to work cycles, for which  $s$ 's demand for access to  $o_1$  is followed by  $s$ 's demand for access to  $o_2$  after  $o_1$ 's supply, which is then followed by  $job_i$ 's completion. Thus, the edges in the set  $\mathcal{E}_2 = \{(s, relay(s, o_1)), (relay(s, o_1), o_2), (o_2, s)\}$  (Fig. 10a) represent the work cycle subvectors  $(\delta_i(s, o_1))$ ,  $(\sigma_i(s, o_1), \delta_i(s, o_2))$ , and respectively,  $(\sigma_i(s, o_2), \dots, \phi_i(s, o_2), \dots)$  (Fig. 10c).
- $\mathcal{P}_3$ 's case refers to work cycles, for which  $s$  demands access to  $o_j$  and then completes  $job_i$ , where  $j \in \{1, 3\}$ . Therefore, the edges in  $\mathcal{E}_3 = \{(s, relay(s, o_j)), (relay(s, o_j), s)\}$  (Fig. 10a), represent the subvector  $(\delta_i(s, o_j))$ , and respectively,  $(\sigma_i(s, o_j), \dots, \phi_i(s, o_j), \dots)$  of the work cycle (Fig. 10d).

### 9.3.2. $CS(thread, o_2)$ 's blocking times and request probabilities

We complete the example in which we show how the contention subsystem represents the dependencies among the threads in the shared-object system. We refer to an arbitrary job, say  $job_i$ , that  $s = t_n$  carries out and explain how the contention subsystem's request probabilities  $(\mathcal{R}_s)_{n \in [1, N]}$  and blocking periods  $(\mathcal{B}_s)_{n \in [1, N]}$  represent the request probabilities, and respectively, the blocking periods in the shared-object system. We justify this representation using the work cycle of  $job_i$ , when its path is in the path partition  $\mathcal{P}_j$ , for every  $j \in [1, 3]$ . Note that for each such path partition, the period

between two consecutive work cycles completed by  $s$  is represented by  $\mathcal{B}_s(s) = \mathcal{T}_s$  (Fig. 10). Namely, if  $s$  carries out  $job_i$  and consecutively  $job_{i'}$ , and their first demand requests are  $\delta_i(s, o_2)$ , and respectively,  $\delta_{i'}(s, d')$ , the blocking period  $\mathcal{B}_s(s)$  represents the period between these two events (in the contention subsystem).

*The case of  $(s, o_1, \bullet)$  paths* Consider the case where  $s$  carries out  $job_i$  with path  $r = (s, o_1, \bullet)$ , where  $r \in \mathcal{P}_2$ , if  $o_2$  is included in  $r$  and  $r \in \mathcal{P}_3$ , if  $o_2$  is not included in  $r$ . We present the request probabilities among  $s$ ,  $relay(s, o_1)$  and  $o_2$ , as well as the blocking times on each of these items in the contention subsystem.

*The probability  $\mathcal{R}_s(s, relay(s, o_1))$*  The probability  $\mathcal{R}_s(s, relay(s, o_1)) = R(s, o_1)$  (by the definition of  $R$ ) denotes the contention subsystem event of  $s$  demanding access to  $relay(s, o_1)$ , which represents  $s$  demanding access to  $o_1$  immediately after  $job_i$ 's assignment in the shared-object system (Figs. 10c and 10d, when  $j = 1$ ).

*The blocking period  $\mathcal{B}_s(relay(s, o_1))$*  Let  $W(s, o_1, o_2)$  denote the period during which  $s$  blocks  $o_1$ , minus the possible blocking period on  $o_2$  (after the supply of access to  $o_1$ ) in the shared-object system. Moreover, let  $X(s, o_1, o_2) = \Pr[(s, o_1, o_2)] \cdot o_1.B[2]$  denote the (possible) blocking period of  $s = t_n$  to  $o_2$ , after gaining access to  $o_1$  in the shared-object system, where the probability  $\Pr[(s, o_1, o_2)] = R(s, o_1) \cdot R(o_1, o_2)$  denotes the event of  $s$  demanding access to  $o_1$  and successively to  $o_2$ . Namely,  $X(s, o_1, o_2)$  is the time between the work cycle events  $\delta_i(s, o_2)$  and  $\phi_i(o_2, s)$  times the probability of  $s$  to demand access to  $o_2$  after gaining access to  $o_1$  (Fig. 10c). Thus, in the shared-object system  $W(s, o_1, o_2) = s.D[1] - X(s, o_1, o_2)$ . Therefore,  $\mathcal{B}_s(relay(s, o_1)) = W(s, o_1, o_2)$  represents the period during which  $s$  blocks  $relay(s, 1)$  before possibly demanding access to  $o_2$  in the contention subsystem.

*The probabilities  $\mathcal{R}_s(relay(s, o_1), o_2)$  and  $\mathcal{R}_s(relay(s, o_1), s)$*  Let  $\mathcal{F}_{(s, o_1, o_2)}$  and  $\mathcal{F}'_{(s, o_1, o_2)}$  denote the events in which  $s$  demands access to  $o_2$  after gaining access to  $o_1$  in the shared-object system, and respectively, to  $relay(s, o_1)$  in the contention subsystem. The event  $\mathcal{F}'_{(s, o_1, o_2)}$  in the contention subsystem represents the event  $\mathcal{F}_{(s, o_1, o_2)}$  in the shared-object system, and therefore, the probability of  $\mathcal{F}'_{(s, o_1, o_2)}$  is given by  $\mathcal{R}_s(relay(s, o_1), o_2) = \Pr[(s, o_1, o_2)]$  (Fig. 10c). Moreover, when the event  $\mathcal{F}'_{(s, o_1, o_2)}$  (and thus the event  $\mathcal{F}_{(s, o_1, o_2)}$ ) does not occur (Fig. 10d), the respective job is completed and  $s = t_n$  becomes idle or starts a new job with probability  $\mathcal{R}_s(relay(s, o_1), s) = 1 - \mathcal{R}_s(relay(s, o_1), o_2)$ .

*The case of  $(s, o_2, \bullet)$  paths* Consider the case where  $job_i$ 's path is  $(s, o_2, \bullet) \in \mathcal{P}_1$ . In Fig. 10b,  $s$  demands access to  $o_2$  immediately after it is assigned with  $job_i$ . This is represented in  $\mathcal{CS}(thread, o_2)$  by  $s$  demanding access to  $o_2$ , with probability  $\mathcal{R}_s(s, o_2) = R(s, o_2)$ . Moreover,  $s$  blocks  $o_2$  for a period of  $\mathcal{B}_s(o_2) = s.B[2]$  in  $\mathcal{CS}(thread, o_2)$ , which represents the period between the events  $\sigma_i(s, o_2)$  and  $\phi_i(s, o_2)$  in Figs. 10b and 10c. After the job completion and the release event of  $o_2$  in  $\mathcal{CS}(thread, o_2)$ ,  $s$  enters, with probability  $\mathcal{R}_s(o_2, s) = 1$ , an idle period (of possibly zero length) until it starts carrying out a new job.

*The case of  $(s, o_3)$  paths* Consider the case where  $s$  carries out  $job_i$  with path  $r = (s, o_3) \in \mathcal{P}_3$ . In  $\mathcal{CS}(thread, o_2)$ ,  $s$  demands access to  $relay(s, o_3)$ , with probability  $\mathcal{R}_s(s, relay(s, o_3)) = R(s, o_3)$ , which represents  $s$  demanding access to  $o_3$  immediately after  $job_i$ 's assignment in the shared-object system (Fig. 10d). The blocking period of  $s$  on  $relay(s, o_3)$  is  $\mathcal{B}_s(relay(s, o_3)) = s.D[3]$ , which in the shared-object system represents the time that  $s$  is waiting to gain access to  $o_3$  and then blocking it, i.e., the period between the work cycle events  $\delta_i(s, o_3)$  and  $\phi_i(s, o_3)$  (Fig. 10d). After the job completion and the release event of  $relay(s, o_3)$  in  $\mathcal{CS}(thread, o_2)$ ,  $s$  enters, with probability  $\mathcal{R}_s(relay(s, o_3), s) = 1$ , an idle period (of possibly zero length) until it starts carrying out a new job.

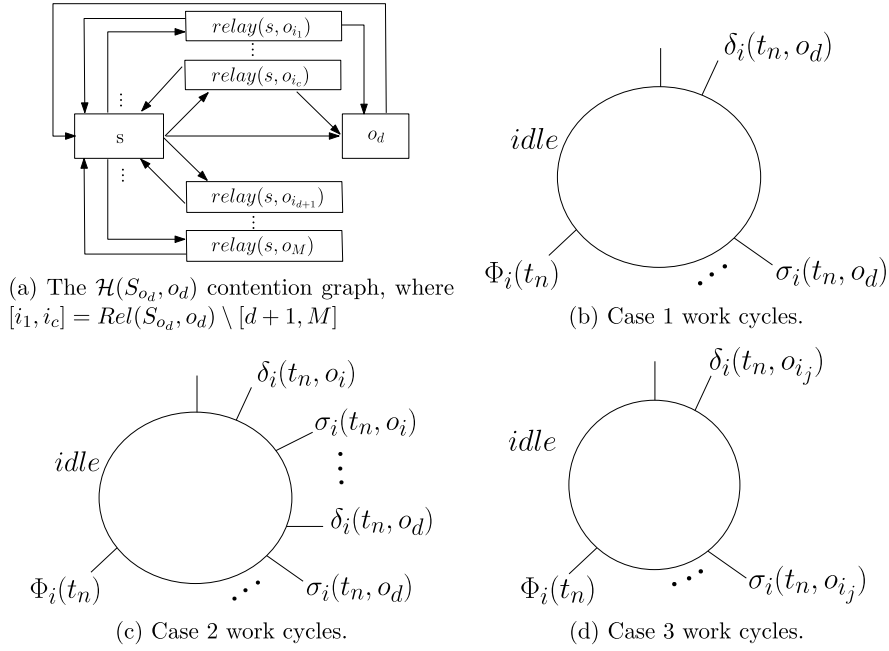
The subsystem  $\mathcal{CS}(thread, o_2) = (\mathcal{H}(thread, o_2), (\mathcal{R}_s)_{s \in thread}, (\mathcal{B}_s)_{s \in thread})$ , which we described above, is a contention subsystem that represents the dependencies among the thread set,  $thread$ , and  $o_2$  in the shared-object system.

#### 9.4. The case of systems with $M$ objects

In this section we prove that Theorem 6 follows from Lemmas 7, 8 and 9 (Corollary 10).

**Lemma 7.** Consider a contention subsystem  $\mathcal{CS}(S_{o_d}, o_d) = (\mathcal{H}(S_{o_d}, o_d), (\mathcal{R}_s)_{s \in S_{o_d}}, (\mathcal{B}_s)_{s \in S_{o_d}})$ , where  $S_{o_d} \in \{thread\} \cup s_{o_d}$  and  $s_{o_d} = \{\{o_i\} \mid i \in [1, d - 1]\}$ . Suppose that we are given the shared-object system's blocking and item inter-demand periods, as well as the request probabilities  $R$ . It holds that  $\mathcal{CS}(S_{o_d}, o_d)$  represents the dependencies among the threads in the shared-object system and the system's state.

**Proof.** We show a mapping of the shared-object system's state to the contention subsystem  $\mathcal{CS}(S_{o_d}, o_d)$ . Given the shared-object system's blocking and item inter-demand periods, as well as the request probabilities, we construct the contention subsystem  $\mathcal{CS}(S_{o_d}, o_d) = (\mathcal{H}(S_{o_d}, o_d), (\mathcal{R}_s)_{s \in S_{o_d}}, (\mathcal{B}_s)_{s \in S_{o_d}})$  based on the work cycles related to jobs with  $(\bullet, s, \bullet)$  paths, where  $s \in S_{o_d}$  and  $s_{o_d} = \{\{o_i\} \mid i \in [1, d - 1]\}$ . We explain the representation of work cycles by the contention graph  $\mathcal{H}(S_{o_d}, o_d)$ , as well as the representation of the shared-object system's request probabilities and state, i.e., blocking, pairwise



**Fig. 11.** The contention graph for  $\mathcal{CS}(S_{o_d}, o_d)$  and the work cycles partitions,  $\mathcal{P}(s, o_d) = \cup_{\ell \in [1,3]} \mathcal{P}_\ell$ , of  $(\bullet, s, \bullet)$  paths, where  $\mathcal{P}_1 = \{\text{path} \mid \text{path} = (\bullet, s, o_d, \bullet)\}$ ,  $\mathcal{P}_2 = \{\text{path} \mid \text{path} = (\bullet, s, o_i, \bullet, o_d, \bullet) \wedge i \in \text{Rel}(S_{o_d}, o_d) \setminus [d+1, M]\}$ ,  $\mathcal{P}_3 = \{\text{path} \mid \text{path} = (\bullet, s, \bullet) \wedge o_d \notin \text{path}\}$ .

inter-demand period and delay, by  $(\mathcal{R}_s)_{s \in S_{o_d}}$ , and respectively,  $(\mathcal{B}_s)_{s \in S_{o_d}}$  in the contention subsystem. This construction is the mapping that proves the lemma’s statement.

The proof is organized as follows. In the first part, we construct the contention graph  $\mathcal{H}(S_{o_d}, o_d) = (\mathcal{V}, \mathcal{E})$  using the work cycles related to  $(\bullet, s, \bullet)$  paths. Moreover, in the second part we show that  $(\mathcal{R}_s)_{s \in S_{o_d}}$  and  $(\mathcal{B}_s)_{s \in S_{o_d}}$  represent the dependencies and the shared-object system’s state with respect to  $(\bullet, s, \bullet)$  paths. In our construction, we assume the knowledge of the item inter-demand periods  $\mathcal{T}_v$ , the system’s state delay and blocking periods, as well as the request probabilities  $R$ .

**Part I: The graph  $\mathcal{H}(S_{o_d}, o_d)$  represents the work cycles related to the  $(\bullet, s, \bullet)$  paths.** Let  $\mathcal{H}(S_{o_d}, o_d) = (\mathcal{V}, \mathcal{E})$  be the contention graph of  $\mathcal{CS}(S_{o_d}, o_d)$  (Fig. 11a) and consider  $s$  to be an arbitrary element of  $S_{o_d}$ . Recall that  $\text{Rel}(\text{thread}, o_d) = [1, M] \setminus \{d\}$  and  $\text{Rel}(\{o_\ell\}, o_d) = [\ell + 1, M] \setminus \{d\}$ , where  $\ell \in [1, d]$ . Moreover, let  $\mathcal{P}(s, o_d) = \cup_{\ell \in [1,3]} \mathcal{P}_\ell$  be a path partition of  $(\bullet, s, \bullet)$  paths, where  $\mathcal{P}_1 = \{\text{path} \mid \text{path} = (\bullet, s, o_d, \bullet)\}$ ,  $\mathcal{P}_2 = \{\text{path} \mid \text{path} = (\bullet, s, o_\ell, \bullet, o_d, \bullet) \wedge \ell \in \text{Rel}(S_{o_d}, o_d) \setminus [d+1, M]\}$  and  $\mathcal{P}_3 = \{\text{path} \mid \text{path} = (\bullet, s, \bullet) \wedge o_d \notin \text{path}\}$ . We explain the representation of the thread work cycles for jobs with  $(\bullet, s, \bullet)$  paths by the graph  $\mathcal{H}(S_{o_d}, o_d)$ .

We define the elements of  $\mathcal{V}$  and  $\mathcal{E}$ . Let  $\mathcal{V} = \cup_{s \in S_{o_d}} \mathcal{V}_s$ , where  $\mathcal{V}_s = \{s, o_d\} \cup \{\text{relay}(s, o_j) \mid j \in \text{Rel}(S_{o_d}, o_d)\}$ . The nodes  $\text{relay}(s, o_j)$ ,  $j \in \text{Rel}(S_{o_d}, o_d)$ , are  $s$ ’s distinct copies of a relay object,  $o_j$ , which allow us to distinguish paths with respect to threads. The edges  $\mathcal{E} = \cup_{s \in S_{o_d}} \mathcal{E}_s$  follow the three path partition cases, i.e.,  $\mathcal{E}_s = \cup_{\ell \in [1,3]} \mathcal{E}_\ell$ , where  $\mathcal{E}_1 = \{(s, o_d), (o_d, s)\}$ ,  $\mathcal{E}_2 = \{(s, \text{relay}(s, o_j)), (\text{relay}(s, o_j), o_d), (o_d, s)\}$  and  $\mathcal{E}_3 = \{(s, \text{relay}(s, o_j)), (\text{relay}(s, o_j), s)\}$ . Let  $\text{job}_i$  be a job that  $t_n$  carries out, such that item  $s$  is either included in  $\text{job}_i$ ’s object vector or  $s = t_n$ , and let  $\text{cycle}(t_n, \text{job}_i)$  be the respective work cycle. The edges in the sets  $\mathcal{E}_\ell$ , where  $\ell \in [1, 3]$ , represent the events in every possible  $\text{cycle}(t_n, \text{job}_i)$  after the supply of item  $s$ , if  $s$  is an object, or after the assignment of  $\text{job}_i$  to  $s$ , if  $s = t_n$ . For brevity, we refer to both events as the supply of item  $s$ . The edge sets are defined according to the three sets of the path partition  $\mathcal{P}(s, o_d) = \cup_{\ell \in [1,3]} \mathcal{P}_\ell$  as follows.

- $\mathcal{P}_1$ ’s case refers to work cycles, for which  $t_n$  demands access to  $o_d$ , immediately after the supply of item  $s$ . When  $t_n$  gains access to  $o_d$ ,  $\text{job}_i$  might require  $t_n$  to demand access to another object,  $o_{d'}$ , where  $d' \in [d+1, M]$ . Upon  $\text{job}_i$ ’s completion  $t_n$  releases any acquired object (event  $\Phi_i(t_n)$  of the work cycle). Thus, the edges  $(s, o_d)$  and  $(o_d, s)$  of  $\mathcal{E}_1$  (Fig. 11a) represent the subvectors  $(\delta_i(t_n, o_d))$ , and respectively,  $(\sigma_i(t_n, o_d), \dots, \Phi_i(t_n))$  of the work cycle (Fig. 11b).
- $\mathcal{P}_2$ ’s case refers to work cycles for which  $t_n$ , after the supply of item  $s$ , demands access to  $o_j$ , where  $j \in \text{Rel}(S_{o_d}, o_d) \setminus [d+1, M]$ , and subsequently to  $o_d$ . Note that, by the definition of  $\mathcal{P}_2$ ,  $t_n$  might also demand access to other objects in  $\{o_{j+1}, \dots, o_M\} \setminus \{o_d\}$ . Thus, the edges  $(s, \text{relay}(s, o_j)), (\text{relay}(s, o_j), o_d), (o_d, s)$  of  $\mathcal{E}_2$  (Fig. 11a) represent the subvectors  $(\delta_i(t_n, o_j)), (\sigma_i(t_n, o_j), \dots, \delta_i(t_n, o_d))$ , and respectively,  $(\sigma_i(t_n, o_d), \dots, \Phi_i(t_n))$  of the work cycle (Fig. 11c).
- $\mathcal{P}_3$ ’s case refers to work cycles, for which  $t_n$ , after the supply of item  $s$ , demands access to  $o_j$ , where  $j \in \text{Rel}(S_{o_d}, o_d)$ . Note that, by the definition of  $\mathcal{P}_3$ ,  $t_n$  might also demand access to other objects in  $\{o_{j+1}, \dots, o_M\}$ , but not to  $o_d$ . Thus, the edges  $(s, \text{relay}(s, o_j))$  and  $(\text{relay}(s, o_j), s)$  of  $\mathcal{E}_3$  (Fig. 11a), represent the subvectors  $(\delta_i(t_n, o_j))$ , and respectively,  $(\sigma_i(t_n, o_j), \dots, \Phi_i(t_n))$ , where  $j \in \text{Rel}(S_{o_d}, o_d)$  of the work cycle (Fig. 11d).

**Part II:**  $(\mathcal{R}_s)_{s \in S_{o_d}}$  and  $(\mathcal{B}_s)_{s \in S_{o_d}}$  represent the dependencies and the shared-object system's state with respect to  $(\bullet, s, \bullet)$  paths. We refer to an arbitrary job, say  $job_i$ , that  $t_n$  carries out and explain how the contention subsystem's request probabilities  $(\mathcal{R}_s)_{s \in S_{o_d}}$  and blocking periods  $(\mathcal{B}_s)_{s \in S_{o_d}}$  represent the request probabilities, and respectively, the blocking periods in the shared-object system. We verify this representation using the work cycle of  $job_i$ , when its path is in the path partition  $\mathcal{P}_j$ , for every  $j \in [1, 3]$ . We remind that throughout this proof we refer to the supply of item  $s$  as the supply of access to  $o_\ell$  for  $t_n$ , if  $s = o_\ell$ ,  $\ell \in [1, d-1]$ , or the assignment of  $job_i$  to  $t_n$ , if  $s = t_n$ .

Note that for each such path partition, the period between two consecutive work cycles for jobs that include item  $s$  is represented by  $\mathcal{B}_s(s) = \mathcal{T}_s$  (Fig. 10). Namely, the blocking period  $\mathcal{B}_s(s)$  in the contention subsystem represents the period between the event of  $t_n$  releasing item  $s$  due to  $job_i$ , and consecutively, another thread, say  $t_{n'}$ , releasing item  $s$  due to a job, say  $job_{i'}$ , in the shared-object system. We show this representation by looking into three cases of path partitions, i.e., (1) paths  $(\bullet, s, o_d, \bullet)$  in  $\mathcal{P}_1$ , (2) paths  $r = (\bullet, s, o_j, \bullet)$ , where  $j \in Rel(S_{o_d}, o_d) \setminus [d+1, M]$  ( $r \in \mathcal{P}_2$ , if  $o_d$  is included in  $r$  and  $r \in \mathcal{P}_3$ , if  $o_d$  is not included in  $r$ ) and (3) paths  $r = (t_n, \bullet, s, o_j, \bullet)$ , where  $j \in Rel(S_{o_d}, o_d)$ , and  $o_d \notin r$ , i.e.,  $r \in \mathcal{P}_3$ .

- (1) Consider the case where  $job_i$ 's path is in partition  $\mathcal{P}_1$ , i.e.,  $t_n$  carries out  $job_i$  with path  $(\bullet, s, o_d, \bullet)$ . In Fig. 11b,  $t_n$  demands access to  $o_d$  immediately after the supply of item  $s$ . This event is represented in the contention subsystem by  $t_n$  demanding access to  $o_d$ , with probability  $\mathcal{R}_s(s, o_d) = R(s, o_d)/K(S_{o_d}, o_d)$  (by the definition of  $R$ ), where  $K(S_{o_d}, o_d) = \sum_{v \in Rel(S_{o_d}, o_d) \cup \{d\}} R(s, o_v)$  is a normalizing constant. Furthermore,  $t_n$  blocks  $o_d$  for a period of  $\mathcal{B}_s(o_d) = s.B[d]$  in the contention subsystem, which represents the period between the events  $\sigma_i(t_n, o_d)$  and  $\Phi_i(t_n)$  in the work cycles presented in Figs. 11b and 11c. This is due to the fact that  $s.B[d]$  also considers requests for accessing  $o_d$  while following either job path  $(t_n, \bullet, s, o_d, \bullet)$  or  $(t_n, s, \bullet, o_d, \bullet)$  (Approximation 4). After the job completion and the release event of  $o_d$ , another supply event of item  $s$  occurs or it becomes idle. Namely, if  $s = t_n$ ,  $s$  will either start carrying out the next pending job or it will become idle, and if  $s = o_\ell$ , the thread on  $s$ 's queue top will gain access to  $s$  in case the queue is not empty, otherwise  $s$  will become idle. These are certain events in the shared-object system and therefore occur with probability  $\mathcal{R}_s(o_d, s) = 1$  in the contention subsystem.
- (2) Consider the case where  $t_n$  carries out  $job_i$  with path  $r = (\bullet, s, o_j, \bullet)$ , where  $j \in Rel(S_{o_d}, o_d) \setminus [d+1, M]$ . Note that  $r \in \mathcal{P}_2$ , if  $o_d$  is included in  $r$  and  $r \in \mathcal{P}_3$ , if  $o_d$  is not included in  $r$ . We present the request probabilities among  $s, relay(s, o_j)$  and  $o_d$ ,  $j \in Rel(S_{o_d}, o_d) \setminus [d+1, M]$ , as well as the blocking times on each of these items in the contention subsystem. We present (i) the probability  $\mathcal{R}_s(s, relay(s, o_j))$ , (ii) the blocking period  $\mathcal{B}_s(relay(s, o_j))$  and (iii) the probabilities  $\mathcal{R}_s(relay(s, o_j), o_d)$  and  $\mathcal{R}_s(relay(s, o_j), s)$ .
  - (i) The probability  $\mathcal{R}_s(s, relay(s, o_j)) = R(s, o_j)/K(S_{o_d}, o_d)$  (by the definition of  $R$ ) denotes the contention subsystem event of  $t_n$  demanding access to  $relay(s, o_j)$  after the supply of item  $s$ , which represents  $t_n$  demanding access to  $o_j$  immediately after the supply of item  $s$  in the shared-object system (Figs. 11c and 11d, when  $j \in Rel(S_{o_d}, o_d) \setminus [d+1, M]$ ).
  - (ii) Consider the case where  $t_n$  might demand access to objects in  $\{o_{j+1}, \dots, o_M\}$ , after the supply of  $o_j$  in the shared-object system. Let  $W(s, o_j, o_d)$  as the period during which  $t_n$  blocks  $o_j$  minus  $t_n$ 's possible blocking period on  $o_d$  in the shared-object system, due to a path in  $\mathcal{P}_2$ . We refer to  $X(s, o_j, o_d) = \sum_{\ell=j}^{d-1} \Pr[(s, o_j, \bullet, o_\ell, o_d)] \cdot o_\ell.B[d]$  as the possible blocking period of  $t_n$  to  $o_d$ , after gaining access to  $o_j$  in the shared-object system. Note that the probability  $\Pr[(s, o_j, \bullet, o_\ell, o_d)] = R(s, o_j) \cdot [\sum_{k=1}^{j-\ell} R^k(o_\ell, o_j)] \cdot R(o_\ell, o_d)$  denotes the event in which  $t_n$ , after the supply of item  $s$ , demands access to  $o_j$ , possibly to other objects in  $\{o_{j+1}, \dots, o_{\ell-1}\}$ , to  $o_\ell$  and successively to  $o_d$  (since  $R$  is a stochastic matrix). Namely, let  $X(s, o_j, o_d)$  denote the time between the work cycle events  $\delta_i(t_n, o_d)$  and  $\Phi_i(t_n)$  times the probability of  $t_n$  to demand access to  $o_j$ , after gaining access to  $s$ , and subsequently to  $o_d$  (Fig. 11c). Thus, in the shared-object system  $W(s, o_j, o_d) = s.D[j] - X(s, o_j, o_d)$ . Therefore, the period during which  $t_n$  blocks  $relay(s, o_j)$ , after the supply of item  $s$ , and before possibly demanding access to  $o_d$  in the contention subsystem is represented by  $\mathcal{B}_s(relay(s, o_j)) = W(s, o_j, o_d)$ .
  - (iii) Let  $\mathcal{F}_{(s, o_j, o_d)}$  and  $\mathcal{F}'_{(s, o_j, o_d)}$  denote the event in which  $t_n$ , demands access to  $o_j$ , after the supply of item  $s$ , and subsequently to  $o_d$  in the shared-object system, and respectively, the event in which  $t_n$ , after the supply of item  $s$ , demands access to  $relay(s, o_j)$  and consecutively to  $o_d$  in the contention subsystem. Note that  $t_n$  might demand access to other objects in  $\{o_{j+1}, \dots, o_{d-1}\}$  in the shared-object system. The event contention subsystem  $\mathcal{F}'_{(s, o_j, o_d)}$  represents the event  $\mathcal{F}'_{(s, o_j, o_d)}$  in the shared-object system, and therefore, the probability of  $\mathcal{F}'_{(s, o_j, o_d)}$  is given by  $\mathcal{R}_s(relay(s, o_j), o_d)$  which equals to  $\Pr[(s, o_j, o_d)]$  (Fig. 11c). Moreover, when the event  $\mathcal{F}'_{(s, o_j, o_d)}$  (and thus the event  $\mathcal{F}_{(s, o_j, o_d)}$ ) does not occur (Fig. 11d), the respective job is completed and  $t_n$  becomes idle or starts a new job with probability  $\mathcal{R}_s(relay(s, o_j), s) = 1 - \mathcal{R}_s(relay(s, o_j), o_d)$ .
- (3) Consider the case where  $t_n$  carries out  $job_i$  with path  $r = (t_n, \bullet, s, o_j, \bullet)$ , where  $j \in Rel(S_{o_d}, o_d)$ , and  $o_d \notin r$ , i.e.,  $r \in \mathcal{P}_3$ . In the contention subsystem,  $t_n$ , after the supply of item  $s$ , demands access to  $relay(s, o_j)$ , with probability  $\mathcal{R}_s(s, relay(s, o_j)) = R(s, o_j)$  (by the definition of  $R$ ), which represents  $t_n$  demanding access to  $o_j$  immediately after the supply of item  $s$  in the shared-object system (Fig. 11d). The blocking period of  $t_n$  on  $relay(s, o_j)$  is  $\mathcal{B}_s(relay(s, o_j)) = s.D[j]$ , which in the shared-object system represents the time that  $t_n$  is waiting to gain access to  $o_j$ , blocks  $o_j$ , possibly demands access to other objects (except for  $o_d$ ), and then releases all of its acquired objects. Namely,  $\mathcal{B}_s(relay(s, o_j))$  represents the period between the work cycle events  $\delta_i(t_n, o_j)$  and  $\Phi_i(t_n)$ , after the supply of item  $s$

(Fig. 11d). After the job completion and the release event of  $relay(s, o_j)$  in the contention subsystem, either another thread gains access to item  $s$  or item  $s$  becomes idle (no thread is accessing it), i.e., this event is certain to happen in the shared-object system.

The  $\mathcal{CS}(S_{o_d}, o_d) = (\mathcal{H}(S_{o_d}, o_d), (\mathcal{R}_s)_{s \in S_{o_d}}, (\mathcal{B}_s)_{s \in S_{o_d}})$  contention subsystem, which we described above, represents the dependencies among the item set,  $S_{o_d}$ , and  $o_d$  in the shared-object system. Therefore, the proof is complete.  $\square$

**Lemma 8.** *The framework of Baynat and Dallery can approximate the delay  $s.D[d]$  and inter-demand period  $s.T[d]$  through the contention subsystem  $\mathcal{CS}(S_{o_d}, o_d)$ .*

**Proof.** We first give the definition of a *Ramesh–Perros subsystem* (RPS) that is introduced in [23] and show that a contention subsystem can be directly mapped to an RPS. Ramesh and Perros show that we can find the pairwise inter-demand period, and delay of (blocking) communications in an RPS using a framework proposed by Baynat and Dallery in [4]. Thus, we can use the Baynat–Dallery framework to estimate the values of  $s.T[d]$  and  $s.D[d]$ , for every  $s \in S_{o_d}$ , given a contention subsystem  $\mathcal{CS}(S_{o_d}, o_d)$  as an input. In Section 9.2, we presented an adapted version of the Baynat–Dallery framework (Algorithm 2) and explained the calculation of the delay  $s.D[d]$  and inter-demand period  $s.T[d]$ , given the contention subsystem  $\mathcal{CS}(S_{o_d}, o_d)$ .

A Ramesh–Perros subsystem is defined as follows. Let  $\{o[1], \dots, o[M]\}$  be a set of servers, such that tier- $d$  includes only server  $o[d]$ , where  $d \in [1, M]$ , and  $\{t[1], \dots, t[N]\}$  be a set of clients. Moreover, let  $s_{o_d} = \{\{o[1]\}, \dots, \{o[d-1]\}\}$  (i.e.,  $s_{o_d} = \emptyset$  when  $d = 1$ ) and  $S_{o_d} \in \{\{t[1], \dots, t[N]\}\} \cup s_{o_d}$ . A Ramesh–Perros subsystem, is denoted by  $\mathcal{RP}(S_{o_d}, o_d) = (\mathcal{H}(S_{o_d}, o_d), (\mathcal{R}_x)_{x \in S_{o_d}}, (\mathcal{B}_x)_{x \in S_{o_d}})$  and defined as follows:

- (1) The RPS graph  $\mathcal{H}(S_{o_d}, o_d) = (\mathcal{V}, \mathcal{E})$  has the set of vertices  $\mathcal{V} = \cup_{x \in S_{o_d}} \mathcal{V}_x$ , and the set of edges  $\mathcal{E} = \cup_{x \in S_{o_d}} \mathcal{E}_x$ , such that  $\mathcal{V}_x = \{x\} \cup \{o[d]\} \cup \{relay(x, o_j) \mid j \in \text{Re1}(S_{o_d}, o_d)\}$  and  $\mathcal{E}_x = \mathcal{E}_x^1 \cup \mathcal{E}_x^2 \cup \mathcal{E}_x^3$ , where  $\text{Re1}(\{t[1], \dots, t[N]\}, o_d) = [1, M] \setminus \{d\}$ ,  $\text{Re1}(\{o[i]\}, o_d) = [i+1, M] \setminus \{d\}$ , where  $o[i] \in S_{o_d}$ ,  $\mathcal{E}_x^1 = \{(x, o[d]), (o[d], x)\}$ ,  $\mathcal{E}_x^2 = \cup_{j \in \text{Re1}(S_{o_d}, o_d) \setminus [d+1, M]} \{(x, relay(x, o_j)), (relay(x, o_j), o[d]), (o[d], x)\}$ , and  $\mathcal{E}_x^3 = \cup_{j \in \text{Re1}(S_{o_d}, o_d)} \{(x, relay(x, o_j)), (relay(x, o_j), x)\}$ . Note that  $\mathcal{H}(S_{o_d}, o_d)$  is a simple directed graph, i.e., there are no multiple edges between two vertices.
- (2) The RPS request probability matrices  $\mathcal{R}_x$  for  $\mathcal{H}(S_{o_d}, o_d) = (\mathcal{V}, \mathcal{E})$  and  $x$  is an element of a set in  $S_{o_d}$ , where,  $\mathcal{R}_x[v_u, v_\ell]$  is the probability that the process at vertex  $v_u \in \mathcal{V}_x$  forwards the client request to the server at vertex  $v_\ell \in \mathcal{V}_x$ , for an edge  $(v_u, v_\ell)$  in  $\mathcal{E}_x$ .
- (3) The RPS blocking periods,  $(\mathcal{B}_x)_{x \in S_{o_d}}$ , where  $\mathcal{B}_x$  is a function over  $\mathcal{V}_x$ , and  $x \in S_{o_d}$  refers to client or server processes. Note that the edges in  $\mathcal{E}_x^i$  form a directed circle in the graph  $\mathcal{H}(S_{o_d}, o_d)$ , where  $x \in S_{o_d}$  and  $i \in [1, 3]$ . A client request of  $x \in \mathcal{V}_x$  to server  $o[d]$ , is blocking  $o[d]$  for  $\mathcal{B}_x(o[d]) = x.B[d]$  time. A client request of  $x \in \mathcal{V}_x$  to server  $relay(x, o_j)$ , blocks that server for a period of  $\mathcal{B}_x(relay(x, o_j)) = x.D[j]$ , if  $j \in [d+1, M]$  and  $\mathcal{B}_x(relay(x, o_j)) = \bar{w}(x, relay(x, o_j), o[d])$  otherwise ( $j \in \text{Re1}(S_{o_d}, o_d) \setminus [d+1, M]$ ). Once the servers return to process  $x \in \mathcal{V}_x$  with an answer, after a period of  $\mathcal{B}_x(x) = \mathcal{T}_x$ , process  $x$  sends a new client request to a server in  $\mathcal{V}_x \setminus \{x\}$ . Note that  $x.B[d]$ ,  $x.D[j]$ ,  $\bar{w}(x, relay(x, o_j), o[d])$  and  $\mathcal{T}_x$  are functions of  $x$  and  $o[d]$ ,  $x$  and  $j$ ,  $x, relay(x, o_j)$  and  $o[d]$ , and respectively,  $x$ .

Note that this definition of an RPS is a special case of the definition given in [23], which is adapted to our purposes. A contention subsystem  $\mathcal{CS}(S_{o_d}, o_d)$  is directly mapped to an RPS  $\mathcal{RP}(S_{o_d}, o_d)$ , by setting  $o[d] = o_d$ ,  $t[n] = t_n$ , a message to be a demand request,  $\mathcal{H}(S_{o_d}, o_d) = \mathcal{H}(S_{o_d}, o_d)$ ,  $(\mathcal{R}_x)_{x \in S_{o_d}} = (\mathcal{R}_s)_{s \in S_{o_d}}$ , and  $(\mathcal{B}_x)_{x \in S_{o_d}} = (\mathcal{B}_s)_{s \in S_{o_d}}$ , where  $d \in [1, M]$  and  $n \in [1, N]$ . Namely, we set  $x.B[d] = s.B[d]$ ,  $x.D[j] = s.D[j]$ ,  $\bar{w}(x, relay(x, o_j), o[d]) = W(x, relay(s, o_j), o_d)$  and  $\mathcal{T}_x = \mathcal{T}_s$ , where  $x \in S_{o_d}$  equals to the respective  $s \in S_{o_d}$  following the mapping that we described above.  $\square$

**Lemma 9.** *The running time of each framework iteration is  $O(M \cdot N^4)$ .*

**Proof.** The running time per iteration of the Baynat and Dallery algorithm [4] is in  $O(|stations| \cdot |classes|^3)$ , where  $|stations|$  and  $|classes|$  are the numbers of the network's stations and classes, respectively. In the context of shared-object systems, the number of stations,  $|stations|$ , corresponds to the number of vertices  $|\mathcal{V}|$  of the contention graph  $\mathcal{H}(S_{o_d}, o_d) = (\mathcal{V}, \mathcal{E})$  and the number of classes to  $S_{o_d}$ 's cardinality, where  $d \in [1, M]$ . Thus, the running time of each iteration is in  $O(|\mathcal{V}| \cdot |S_{o_d}|^3)$ . Notice that  $|\mathcal{V}| = N + N \cdot (M-1) + 1$  and  $|S_{o_d}| = N$ , if  $S_{o_d} = thread$ , and  $|\mathcal{V}| = M - \ell + 1$  and  $|S_{o_d}| = 1$ , if  $S_{o_d} = \{o_\ell\}$ , where  $\ell \in [1, d-1]$ . The result follows by taking the maximum  $|\mathcal{V}|$  and  $|S_{o_d}|$  of these two cases.  $\square$

**Corollary 10.** *Lemmas 7, 8 and 9 imply Theorem 6.*

## 10. Finding an $\varepsilon$ -OSE

We present a procedure (Algorithm 3) for finding  $\varepsilon$ -OSEs. We give a detailed explanation of Algorithm 3 (Section 10.1) and analyze its running time (Lemma 11 of Section 10.5). We also detail the algorithm's functions (sections 10.2, 10.3, and respectively, 10.4), which are *initializeSystemState()*, *updateStates()*, and *recalcB()* and *recalcT()*.

**Algorithm 3:** The procedure for finding an  $\varepsilon$ -OSE.

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1 Input: Number of objects,  $M$  and threads,  $N$ ; jobs  $\{job_i\}_{i \in [1, J]}$  and their arrival rates to threads  $\{\lambda_{i,n}\}_{n \in [1, N], i \in [1, J]}$ ;  $R$  request probability matrix;  $\varepsilon$ ;
2 Variables: The item states are recorded in  $t_n$ ,  $n \in [1, N]$ , and  $o_d$ ,  $d \in [1, M-1]$ , such that  $t_n$  has the form  $((\text{inter-demand period})T[1, M]$ ,
   (delay) $D[1, M]$ , (blocking period)  $B[1, M]$ ) and  $o_d$  is of the form  $((\text{inter-demand period})T[d+1, M]$ , (delay)  $D[d+1, M]$ , (blocking period)
    $B[d+1, M]$ );  $\mathcal{T}_v$ , item  $v$ 's inter-demand period, for every  $v = t_n$  such that  $n \in [1, N]$  and  $v = o_d$  such that  $d \in [1, M-1]$ ;  $loopEnd$  (Boolean) this
   variable is true when the function  $augmThrBlock()$  decides that no OSE can be found and thus the loop should stop.
3 Output:  $(\{t_n\}_{n \in [1, N]}, \{o_d\}_{d \in [1, M-1]}, \{\mathcal{T}_v\}_{v \in \text{allStates}}, loopEnd)$ ;
4 Macros:  $objThrdSet() = \{(tag, i, \tau) \mid (tag = \#o \wedge \mathcal{T}_{o_i} = \tau) \vee (tag = \#t \wedge \mathcal{T}_{t_i} = \tau)\}$ ;
5  $converged(prev, curr) = (\nexists (tag, i, \tau) \in prev, (tag, i, \tau') \in curr : |\tau - \tau'| \geq \varepsilon)$ ;
6  $blocking(n) = A + \sum_{d=1}^M R(t_n, o_d) \cdot t_n.D[d]$ ;
7  $allStates = \{t_n \mid n \in [1, N]\} \cup \{o_d \mid d \in [1, M-1]\}$ ;
8 begin
9    $initializeSystemState(N, M, \{job_i\}_{i \in [1, J]}, \{\lambda_{i,n}\})$ ;
10   $loopEnd \leftarrow \text{false}$ ;
11  repeat
12     $let prevSet \leftarrow objThrdSet()$ ;
13    for  $d = M$  to  $1$  do  $updateStates(\#B, d, thread, object, \{\mathcal{T}_v\}_{v \in \text{allStates}}, R)$ ;
14    foreach  $n \in [1, N]$  do  $(\mathcal{T}_{t_n}, loopEnd) \leftarrow augmThrBlock(\Sigma_i \lambda_{i,n}, blocking(n))$ ;
15    for  $d = 1$  to  $M-1$  do  $updateStates(\#T, d, thread, object, \{\mathcal{T}_v\}_{v \in \text{allStates}}, R)$ ;
16  until  $converged(prevSet, objThrdSet()) \vee loopEnd = \text{true}$ ;
17  return  $(\{t_n\}_{n \in [1, N]}, \{o_d\}_{d \in [1, M-1]}, \{\mathcal{T}_v\}_{v \in \text{allStates}}, loopEnd)$ ;
18 procedure  $initializeSystemState(N, M, \{job_i\}_{i \in [1, J]}, \{\lambda_{i,n}\})$  begin
19   for  $d = M$  to  $1$  do
20     foreach item  $s$  such that  $(s, o_d)$  is an edge in  $\mathcal{G}$  do
21        $s \leftarrow \text{initRecord}(s, d, \{t_n\}_{n \in [1, N]}, \{o_d\}_{d \in [1, M-1]})$ ;
22   for  $n = 1$  to  $N$  do  $\mathcal{T}_{t_n} \leftarrow augmThrBlock(\Sigma_i \lambda_{i,n}, blocking(n))$ ;
23   for  $d = 1$  to  $M-1$  do  $\mathcal{T}_{o_d} \leftarrow \sum_{\ell=d+1}^M R(o_d, o_\ell) \cdot o_d.T[\ell]$ ;
24 procedure  $updateStates(tag, d, thrSet, objSet, (\mathcal{T}_v)_{v \in \text{allStates}}, R)$  begin
25    $CS(thrSet, d) \leftarrow \text{def ContentionSubsystem}(\{t_n\}_{n \in [1, N]}, \{o_d\}_{d \in [1, M-1]}, d, (\mathcal{T}_v)_{v \in \text{allStates}}, R)$ ;
26    $(thrSet[n].T[d], thrSet[n].D[d])_{n \in [1, N]} \leftarrow BDF(CS(thrSet, d))$ ;
27   for  $j = 1$  to  $d-1$  do
28      $CS(objSet[j], d) \leftarrow \text{def ContentionSubsystem}(\{objSet[j]\}, \{o_d\}_{d \in [1, M-1]}, d, (\mathcal{T}_v)_{v \in \text{allStates}}, R)$ ;
29      $(objSet[j].T[d], objSet[j].D[d])_{n \in [1, N]} \leftarrow BDF(CS(thrSet, d))$ ;
30   if  $tag = \#B$  then  $\text{recalc}B(d)$ , else if  $tag = \#T$  then  $\text{recalc}T(d)$ ;

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10.1. The  $\varepsilon$ -OSE solver

The procedure always halts and computes an approximate equilibrium,  $\varepsilon$ -OSE, when such is reachable. Namely, whenever the job arrival and completion rates differ by at most  $\varepsilon$ , the procedure returns the system state in an  $\varepsilon$ -OSE, or indicates that an OSE is not a state that the system can be in. The procedure sets initial values to the system state,  $c[s, o_d]$ , and then uses the proposed methods (sections 6 to 9) for estimating  $c[s, o_d]$  iteratively, until convergence. The decision on when to stop considers the system inter-demand period,  $\{\mathcal{T}_{item}\}_{item \in V \setminus \{o_M\}}$ , and stops whenever there is no  $item \in V \setminus \{o_M\}$  for which the change in  $\mathcal{T}_{item}$  is greater than  $\varepsilon$  since the previous iteration, where  $\mathcal{G} = (V, E)$  is the acquisition graph.

The procedure's input includes the system parameters, i.e., number of threads  $N$  and objects  $M$ , the jobs,  $job_i$ ,  $i \in [1, J]$ , and their arrival rates  $\{\lambda_{i,n}\}_{i \in [1, J], n \in [1, N]}$  to each  $t_n$ ,  $n \in [1, N]$ , as well as the request probability matrix,  $R$ . The algorithm uses the Boolean variable  $loopEnd$ , which is true when the algorithm decides that no OSE can be found. The procedure's output includes the delay  $D$ , inter-demand period  $T$  and blocking period  $B$  between all system items, as well as, the item inter-demand periods  $\mathcal{T}_v$ , for every item  $v \neq o_M$ , and  $loopEnd$ .

The procedure starts with a system state that represents the case in which all queues are empty (see the function  $initializeSystemState()$ ). It then estimates the state of a system in which threads can block one another, and the delay grows as more requests are pending in the queues. The main part of the pseudocode (Algorithm 3) consists of a repeat-until loop (lines 11–17) that follows the procedure's initialization (line 9). Before the procedure can return its output value, the loop has to end either when the  $\varepsilon$ -OSE conditions are satisfied or when the procedure detects that an OSE cannot be reached. Each iteration aims at further improving the  $\varepsilon$ -OSE estimation. The repeat-until loop exits when no item changes by at least  $\varepsilon$  between every two iterations (and thus the system state satisfies the conditions of an  $\varepsilon$ -OSE).

In every iteration, the procedure computes (i) the blocking periods of demand requests for objects,  $s.B[d]$  (the function  $updateStates()$ ), (ii) the thread inter-demand periods,  $\mathcal{T}_{t_n}$  (the function  $augmntThreadBlock()$ ), and (iii) the object inter-demands,  $\mathcal{T}_{o_d}$  (which is the function  $updateStates()$ ), where  $(s, o_d)$  is an edge of the acquisition graph  $\mathcal{G}$ ,  $n \in [1, N]$  and  $d \in [1, M-1]$ . The repeat-until loop repeats the steps (i), (ii) and (iii), which deals with interdependencies using alternating backward and forward iterations. Namely, it resolves the forward dependencies in which  $(s, o_d)$ 's blocking period,  $s.B[d]$ , depends on  $o_\ell$ 's delay by iterating backward, where  $\ell \in (d, M]$ , i.e., starting from  $d = M$  and counting downwards, we can estimate  $s.B[d]$ , because (in a system that its state satisfies the equilibrium conditions) all of  $(s, o_d)$ 's forward dependencies can be resolved. Similarly, it uses forward iterations for resolving backward dependencies with respect to  $o_d$ 's item inter-

demand period,  $\mathcal{T}_{o_d}$ , because all of  $o_d$ 's backward dependencies are resolved. Moreover, the function *augmntThreadBlock()* allows the repeat-until loop to stop whenever the job inter-arrival time becomes less or equal than the time it takes that thread to complete such jobs, i.e., there's no OSE.

The blocking period estimation, step (i), starts from the last system object,  $o_M$ , where there are no dependencies on the delay of subsequent demand requests. For every  $s$  such that  $(s, o_M)$  is an edge of  $\mathcal{G}$ , we calculate the delay,  $s.D[M]$ , and the pairwise inter-demand period,  $s.T[M]$ , of demand requests to  $o_M$  through the *updateStates*(#B,  $d$ , *thread*, *object*,  $\{\mathcal{T}_v\}_{v \in \text{allStates}}$ ,  $R$ ) function (line 13), where  $\text{allStates} = \{t_n \mid n \in [1, N]\} \cup \{o_d \mid d \in [1, M-1]\}$ . Therefore, the procedure can compute the blocking period of demand requests to  $o_{M-1}$ ,  $s.B[M-1]$ , because it has just estimated the dependencies of subsequent demand requests for  $o_M$ . Repeating this process for  $d = M-1, \dots, 1$ , the procedure compute the blocking periods of demand requests to any  $o_d$ ,  $s.B[d]$ , where  $d \in [1, M]$ . Note that this is possible, since in every step  $d$ ,  $d = M-1, \dots, 1$ , of this for loop, we have already computed the demand request delays and the inter-demand periods of every  $o_{d'}$ ,  $o_{d'}.D[d']$ , and respectively,  $o_{d'}.T[d']$ , where  $d' \in [d+1, M]$  (Section 7).

After computing the blocking periods, delays and pairwise inter-demand periods, the procedure estimates the threads' inter-demand periods (Section 8.1), which can be used to estimate the job completion rates. It does this in step (ii), through the function *augmntThreadBlock*( $\Sigma_i \lambda_{i,n}$ , *blocking*( $n$ )) (line 14) and by using the thread idle probability (Section 3), where *blocking*( $n$ ) =  $A + \sum_{d=1}^M R(t_n, o_d) \cdot t_n.D[d]$ . Moreover, note that the *augmntThreadBlock()* function (Section 8.1) allows the repeat-until loop to stop whenever it detects that the inter-arrival time of jobs to a thread becomes less or equal than the time it takes that thread to complete such jobs (i.e., there's no OSE). Note that the repeat-until loop breaks when the Boolean variable *loopEnd* is true (line 14).

Step (iii) uses the *updateStates()* function (line 15) for calculating the object inter-demand periods, after calculating the new estimates for the delay and the pairwise inter-demand periods. The procedure estimates the inter-demand period  $\mathcal{T}_{o_d}$ , for each  $o_d$ ,  $d \in [1, M-1]$ , via the item inter-demand period of demand requests for items that precede  $o_d$  in a job path  $(\bullet, \text{item}_j, o_d, \bullet)$  (Section 8.2). Therefore, the procedure estimates the inter-demand periods for each  $o_d$  in the order of  $d = 1, \dots, M-1$ .

Once the procedure verifies the satisfaction of the  $\varepsilon$ -OSE conditions (Section 5), the repeat-until loop end (line 16) and the procedure returns.

## 10.2. The *initializeSystemState()* function

The procedure *initializeSystemState()* initializes Algorithm 3 assuming that there is no contention, i.e., all queues have zero length in the shared-object system (lines 9 and 18). In the context of shared-object systems, no contention means that the delay of each demand request equals its blocking period,  $s.D[d] = s.B[d]$ , for all items  $s$  and  $o_d$ . Thus, the procedure initializes the blocking periods  $s.B[d]$  through the function *initRecord()* (lines 19–21). It uses the average demand completion period  $f_{s,o_d}$ , as proposed in Section 7.1, which is a random variable with a known distribution. That is,  $s.B[M] = A + R(s, o_d) \cdot R(o_d, o_d) \cdot f_{s,o_d}$ , if  $d = M$  and  $s.B[d] = A + R(s, o_d) \cdot R(o_d, o_d) \cdot f_{s,o_d} + \sum_{\ell=d+1}^M R(d, o_\ell) \cdot d.D[\ell]$ , if  $d \in [1, M-1]$ , where  $s \in \{t_n \mid n \in [1, N]\} \cup \{o_i \mid i \in [1, d-1]\}$ . Namely, the blocking period of a request to access (demand) the last object equals to the acquisition period plus the average demand completion period on that object and the blocking period of a demand to  $o_d$ ,  $d \in [1, M-1]$ , is recursively computed as the sum of the acquisition period,  $A$ , the average demand completion period  $R(s, o_d) \cdot R(o_d, o_d) \cdot f_{s,o_d}$  plus the average blocking period of a subsequent demand to one of the following objects  $d.B[\ell]$ ,  $\ell \in [d+1, M]$ , weighted by the probability of sending such a demand,  $R(d, o_\ell)$ ,  $\ell \in [d+1, M]$ . Moreover, the  $s.T[d]$  pairwise inter-demand periods are set to equal  $s.B[d]$ .

The  $\mathcal{T}_n$  (thread) inter-demand periods are computed (line 22) through the function *augmThrBlock*( $\Sigma_i \lambda_{i,n}$ , *blocking*( $n$ )), where *blocking*( $n$ ) is defined in line 6. Furthermore, the  $\mathcal{T}_{o_j}$  (object) inter-demand periods are set to  $\sum_{\ell=j+1}^M R(o_j, o_\ell) \cdot o_j.T[\ell]$  (line 23). Algorithm 3 iteratively finds the correct values of the pairwise and item inter-demand periods (arbitrary initialization of the system's state is proposed in [23]).

## 10.3. The *updateStates()* function

This function updates the blocking periods and the item inter-demand periods with respect to  $o_d$  (lines 24–30). If the input tag is #B, the function updates the blocking periods  $s.B[d]$  for every  $s \in \{t_n \mid n \in [1, N]\} \cup \{o_j \mid j \in [1, d-1]\}$ , as in Section 7. Otherwise, if the input tag is #T, the function updates the inter-demand period of  $o_d$ ,  $\mathcal{T}_{o_d}$ , as in Section 8.

The procedure *updateStates()* defines the contention subsystem for every set of item sources  $S_{o_d}$  using the function *defContentionSubsystem()* (line 25 if  $S_{o_d} = \text{thread}$  and line 28 if  $S_{o_d} = \{o_j\}$ ,  $j \in [1, d-1]$ ). It then calculates the delay,  $s.D[d]$ , and pairwise inter-demand period,  $s.T[d]$ , for every  $s \in S_{o_d}$  using the *BDF()* function of Section 9.2 (line 26 if  $S_{o_d} = \text{thread}$  and line 29 if  $S_{o_d} = \{o_j\}$ ,  $j \in [1, d-1]$ ). The procedure ends with the computation of the blocking periods or the inter-demand periods, depending on the tag with which the procedure was called.

## 10.4. The *recalcB()* and *recalcT()* functions

We present the exact formulas that give the first three moments of  $s.B[d]$ , i.e., the function *recalcB()*, and  $\mathcal{T}_{o_d}$ , i.e., the function *recalcT()*. We find these formulas using the equations in sections 7, and respectively, 8.

Let  $F_{s,o_d} = A + R(s, o_d) \cdot R(o_d, o_d) \cdot f_{s,o_d}$ , be the sum of the acquisition time and the job completion period times the related probabilities ( $A$  and  $F_{s,o_d}$  can be bound by a constant and thus can be treated as such). The first three moments of the blocking time for  $d = M$  are

$$E(s.B[M]^m) = (F_{s,M})^m, \text{ for } m = 1, 2, 3 \quad (16)$$

and if  $d \in [1, M - 1]$ , we have that

$$E(s.B[d]) = F_{s,o_d} + \sum_{d'=d+1}^M (\Pr[(s, \bullet, d, o_{d'})] \cdot E(d.B[d'])) \quad (17)$$

$$E(s.B[d]^2) = (F_{s,o_d})^2 + \sum_{d'=d+1}^M \Pr[(s, \bullet, d, o_{d'})] (E(d.D[d']^2) + 2F_{s,o_d} \cdot E(d.D[d'])) \quad (18)$$

$$E(s.B[d]^3) = (F_{s,o_d})^3 + \sum_{d'=d+1}^M \Pr[(s, \bullet, d, o_{d'})] (E(d.D[d']^3) + 3(F_{s,o_d})^2 \cdot E(d.D[d']) + 3F_{s,o_d} \cdot E(d.D[d']^2)) \quad (19)$$

Moreover, the first three moments of  $\mathcal{T}_{o_d}$  are

$$E(\mathcal{T}_{o_d}) = \frac{\sum_{s \in \text{arrivals}(o_d)} \omega(s, o_d) \cdot (F_{s,o_d} + E(\mathcal{T}_s))}{\sum_{s \in \text{arrivals}(o_d)} \omega(s, o_d)} \quad (20)$$

$$E(\mathcal{T}_{o_d}^2) = \frac{\sum_{s \in \text{arrivals}(o_d)} \omega(s, o_d) \cdot ((F_{s,o_d})^2 + E(\mathcal{T}_s^2) + 2F_{s,o_d} \cdot E(\mathcal{T}_s))}{\sum_{s \in \text{arrivals}(o_d)} \omega(s, o_d)} \quad (21)$$

$$E(\mathcal{T}_{o_d}^3) = \frac{\sum_{s \in \text{arrivals}(o_d)} \omega(s, o_d) \cdot ((F_{s,o_d})^3 + E(\mathcal{T}_s^3) + 3(F_{s,o_d})^2 E(\mathcal{T}_s) + 3F_{s,o_d} E(\mathcal{T}_s^2))}{\sum_{s \in \text{arrivals}(o_d)} \omega(s, o_d)} \quad (22)$$

We remind that  $\text{arrivals}(o_d) = \text{thread} \cup \{o_j \mid j \in [1, d - 1]\}$  and  $\omega(s, o_d) = R(s, o_d) \cdot s.T[d]$  (Section 8.2).

### 10.5. Running time

Notice that the running times of Algorithm 2 (Baynat–Dallery framework) and Algorithm 3 depend on the number of iterations of these algorithms. Lemma 11 bounds the procedure running time for one iteration.

**Lemma 11.** *The running time of one iteration of Algorithm 3 is in  $O(M^2 \cdot N^4 + M^3)$ .*

**Proof.** We look at the running time of each step of the repeat-until loop to find the algorithm's running time. Steps (i) and (iii) call the function `updateStates()` so at most  $M$ ;  $M$ , and respectively  $M - 1$  times. Note that the function `updateStates()` calls at most  $1 + (M - 1)$  times the function `BDF()`, because the input parameter  $d$ , which denotes the object whose state is to be updated, is at most  $M$  (line 27). The first call is done by setting  $S_{o_d} = \text{thread}$  and (at most)  $M - 1$  calls are done by setting  $S_{o_d} = \{o_j\}$ ,  $j \in [1, d - 1]$ . The `BDF()` function has running time in  $O(M \cdot N^4 \cdot I_f)$  and  $O(M \cdot I_f)$  (Lemma 9), when `BDF()` is called for  $S_{o_d} = \text{thread}$ , and respectively, for  $S_{o_d} = \{o_j\}$ ,  $j \in [1, d - 1]$ , where  $I_f$  denotes the maximum number of framework iterations (Lemma 9). It also holds that the function `augmntThreadBlock()` is called  $N$  times in step (ii) and it's the running time is practically constant (see Section 3 with respect to the findings of Latouche and Ramaswami [16]). Thus, the running time of one iteration of Algorithm 3 is in  $O(M \cdot (M \cdot N^4 \cdot I_f) + N + M \cdot ((M - 1) \cdot M \cdot I_f)) = O(M^2 \cdot N^4 + M^3)$ .  $\square$

## 11. Conclusions

We consider a resource allocation problems that can be modeled as generalized dynamic dining philosophers problems. We formulate questions that are associated with equilibrium situations in such systems, where input and output rates match. We believe that the way we find the equilibrium as well as estimate the delay and throughput in such systems can be the basis for an analysis of further generalizations of the problem studied here, such as the ones that are described in the literature on resource allocation, e.g., non-sequential scheduling, such as parallel resource acquisition (2-phase locking) and resource acquisition that is reactive to contention conditions [14,19,10,11,22]. Another research direction is to consider the approach proposed by Reif and Spirakis [24] that does deterministic object acquisition via FIFO queues. They rather consider resource granting systems for satisfying probabilistically the changing user requests for resource allocation, using local communication between granting and requesting processes.

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