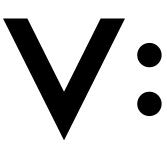
# Università degli Studi della Campania LUIGI VANVITELLI

COURSE OF COMPUTER SYSTEMS MODELING AND SEMANTIC WEB

# Exercises from the course

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November 30, 2021



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#### Abstract

This is a collection of exercises that have been proposed for the Computer Systems Modeling and Semantic Web course in the third year of the Data Analytics international bachelor.

Exercises are inspired to several sources and a possible solution is proposed. Solutions include the use of specific software. We will use the Java Modeling Tools simulator.

### 1 Exercise: the virtual channels<sup>1</sup>

We have a computer network composed of 4 routers with Poisson distributed service times. Router 1, 2 and 4 can process an average of 10 packets per second. Router 3 can process an average of 20 packets per second.

The network is serving 4 virtual channels. The first channel passes through routers 1, 2 and 3, then delivers the packets to destination. The second channel passes through routers 1, 3 and 4, then delivers the packets to destination. The third channel passes through routers 2, 3 and 4, then delivers the packets to destination. The fourth channel passes through router 3, then delivers the packets to destination. The sources of the channels produce packets according to Poisson distributions as well. The rates are 3, 4, 5 and 6 packets per second respectively.

- 1. What are the utilizations of routers?
- 2. What are the average number of packets at the routers?
- 3. What are the response times of the routers?
- 4. Which channel has the highest response time at router 2?
- 5. Which router is the bottleneck of the system?
- 6. What is the average total time in the system for packets using virtual channel 2?

#### 1.1 Solution

We have a network of four interconnected routers that are visited in different ways by packets that are generated at different sources and travel into separate virtual channels. These channels are using the same 4 routers in different ways.

Since packets of all channels have the same service times in each router, the model can be approached analytically.

As question 6 requests a total time in the system, we can model the system as a queuing network. The routers transparently process packets from any source, making no difference between the channels (e.g., there is no priority or quality of service policy). Anyway, questions 4 and 6 suggest that the four channels have to be dealt with separately, in order to compare what is happening for a specific channel, that is, a specific source. This request suggests the definition of 4 classes.

The system can be modeled as in Fig. 1.

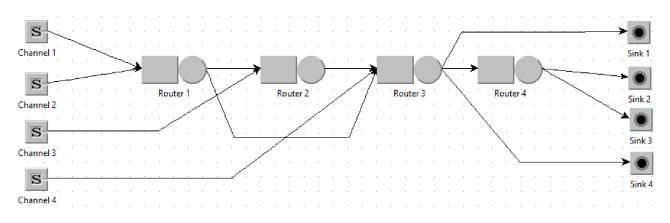


Figure 1: The model

The questions may be answered by applying an analytical approach or by using the JMT simulator.

<sup>&</sup>lt;sup>1</sup>This exercise is based on the exercise presented in [1] in subsection 18.6.1, page 322.

#### **1.2** Analytical solution

For question 1,  $U_k = \lambda_k / \mu_k$ , where  $\mu_k$  are the provided (class-independent) service rates and  $\lambda_k$  should be computed.

As each channel is routed deterministically,  $\lambda_{k,c}$  (where k identifies the router or the source if 0, and c identifies the channel) can be immediately obtained for each router:

 $\begin{array}{l} \lambda_{1,1} = \lambda_{2,1} = \lambda_{3,1} = \lambda_{0,1} = 3 ~ \mathrm{job/s}, \\ \lambda_{1,2} = \lambda_{3,2} = \lambda_{4,2} = \lambda_{0,2} = 4 ~ \mathrm{job/s}, \\ \lambda_{2,3} = \lambda_{3,3} = \lambda_{4,3} = \lambda_{0,3} = 5 ~ \mathrm{job/s}, \\ \lambda_{3,4} = \lambda_{0,4} = 6 ~ \mathrm{job/s}. \end{array}$ 

The total  $\lambda_k = \sum_{c} \lambda_{k,c}$  for each router are:

 $\begin{array}{l} \lambda_1 = \lambda_{1,1} + \lambda_{1,2} = 3 + 4 = 7 \text{ job/s}, \\ \lambda_2 = \lambda_{2,1} + \lambda_{2,3} = 3 + 5 = 8 \text{ job/s}, \\ \lambda_3 = \lambda_{3,1} + \lambda_{3,2} + \lambda_{3,3} + \lambda_{3,4} = 3 + 4 + 5 + 6 = 18 \text{ job/s}, \\ \lambda_4 = \lambda_{4,2} + \lambda_{4,3} = 4 + 5 = 9 \text{ job/s}. \end{array}$ 

Consequently, average utilizations are:  $U_1 = \lambda_1/\mu_1 = 7/10 = 0.7,$  $U_2 = \lambda_2/\mu_2 = 8/10 = 0.8,$ 

 $U_3 = \lambda_3/\mu_3 = 18/20 = 0.9,$  $U_4 = \lambda_4/\mu_4 = 9/10 = 0.9.$ 

This answers question 1, and the problem can be solved, as the system is stable; since  $U_3 = U_4 = 0.9$  is the highest average utilization value, routers 3 and 4 are the bottleneck, and this answers question 5.

In order to answer question 2, we might consider that

$$N_{k} = \sum_{c} N_{k,c} = \sum_{c} \lambda_{k,c} \cdot R_{k,c} = \sum_{c} \frac{\lambda_{k,c} \cdot D_{k,c}}{1 - U_{k}} = \sum_{c} \frac{U_{k,c}}{1 - U_{k}} = \frac{U_{k}}{1 - U_{k}}$$

Using the values for average utilizations, the average numbers of packets are:  $N_1 = U_1/(1 - U_1) = 0.7/0.3 = 2.34$  jobs,  $N_2 = U_2/(1 - U_2) = 0.8/0.2 = 4$  jobs,  $N_3 = U_3/(1 - U_3) = 0.9/0.1 = 9$  jobs,  $N_4 = U_4/(1 - U_4) = 0.9/0.1 = 9$  jobs.

For question 3, it holds that

$$R_k = \frac{N_k}{X} = \frac{N_k}{\sum\limits_{c} X_c} = \frac{N_k}{\sum\limits_{c} \lambda_c} = \frac{N_k}{\lambda_k},$$

as sums only have to consider the channels that actually use router k, so that  $R_1 = N_1/\lambda_1 = 2.34/7 = 0.34$  s,  $R_2 = N_2/\lambda_2 = 4/8 = 0.5$  s,  $R_3 = N_3/\lambda_3 = 9/18 = 0.5$  s,  $R_4 = N_4/\lambda_4 = 9/9 = 1$  s.

For question 4, we have that

$$R_{k,c} = \frac{D_{k,c}}{1 - U_k} = \frac{v_{k,c} \cdot S_{k,c}}{1 - U_k} = \frac{\frac{\lambda_{k,c}}{\lambda_c} \cdot S_{k,c}}{1 - U_k} = \frac{\frac{1}{\mu_k}}{1 - U_k}$$

because there is no loop in the model and there is no dependency on the channel in the final expression, as all average service rates for the routers are independent from the channel. As this is the only question in which an index is asked that explicitly depends on classes, and dependency on channels disappears, one might consider that classes are not needed, and that the system might be modeled by means of a simple queuing network and solved by applying the separable models technique: this is anyway not viable, as routing would not be homogeneous, thus violating the third assumption.

In order to answer question 4 we obtain, for router 2, that is used by channels 1 and 3, the same value found while answering question 3 for  $R_2$ :

$$\begin{split} R_{2,1} &= 1/(\mu_2 \cdot (1-U_2)) = 1/(10 \cdot (1-0.8)) = 0.5 \text{ s}, \\ R_{2,3} &= 1/(\mu_2 \cdot (1-U_2)) = 1/(10 \cdot (1-0.8)) = 0.5 \text{ s}. \end{split}$$

To answer question 6, we have to sum all the average response times for the routers that are used by channel 2, that are routers 1, 3 and 4: the overall average time spent in the systems by packets using channel 2 is  $T = R_1 + R_2 + R_4 = 0.34 + 0.5 + 1 = 1.84$  s.

#### 1.3 Using JMT

When creating the 4 classes, each should be assigned one of the sources shown in Fig. 1 as reference station, setting up the corresponding rate as in Fig. 2.

efine type (C osed Classe	s: If a ClassSwitcl	name and parameters for each <b>h</b> is in the model, then <b>all</b> the at has <b>Fork, ClassSwitch, Sca</b>	closed class	es must have t	he <b>same</b> reference station. ference station is <b>not</b> generated b	y <b>any</b> Source.	Classes:	d Class
<b>iorities:</b> A la Color	arger value implies Name	s a higher priority. Type	Priority	Population	Interarrival Time Distribution		Reference Station	
	Class1	🥥 Open 👻	0		exp(3)	Edit	E Channel 1	-
	Class2	🥥 Open 🛛 👻	0		exp(4)	Edit	E Channel 2	•
	Class3	🥥 Open 👻	0		exp(5)	Edit	Channel 3	•
	Class4	🥥 Open 👻	0		exp(6)	Edit	🗉 Channel 4	-

Figure 2: Classes setup

The channels have to be obtained by setting properly the routing section in the queues for each class. As channels have deterministic paths, each router should be set so that jobs from each class are directed to the right next router. This can be done by choosing a probabilistic routing with 100% probability of taking the right path between the physical connections between the routers. Examples for channels 1 and 2 at router 3 are in Fig. 3 and 4.

tation Name			
ation Name: Router 3			
outer 3 Parameters Definiton			
Queue Section \ Service Section \ R	Suring Section 1	1	
Routing Strategies Class	Routing Strategy	Description	n Ited to stations connected
Class	Probabilities	to the curre	nt one according to the obabilities. If the sum of
Class2	Probabilities	the probabi	lities is different from 1, a /ill be scaled to sum 1.
🥥 Class3	Probabilities	Routing Op	ations
🥥 Class4	Probabilities	- Destinat	1
		Router 4	0.0
		Sink 1	1.0
		Sink 4	0.0

Figure 3: Setup of channel 1 at router 3

题 Editing Router 3 Properties				×
Station Name Station Name: Router 3				
Station Name. Kouler 5				
Router 3 Parameters Definiton				
Queue Section \ Service Section Routing S	ection			
Routing Strategies			Description	
Class	Routing Strategy		connected to the c according to the sp	
🥥 Class1	Probabilities	•	probabilities. If the	sum of the
<b>O</b> Class2	Probabilities	•	probabilities is diffe the values will be s	
Class3	Probabilities	•	Routing Options	
Class4	Probabilities	-	Destination	Probability
Classe			Router 4	1.0
			Sink 1	0.0
			Sink 4	0.0
	Done			

Figure 4: Setup of channel 2 at router 3

As routers process all packets equally for all channels, the service section setup for all classes of each router will be set up so that all classes have the same service rate (10 packets per second for routers 1, 2 and 4, 20 packets per second for router 3, exponentially distributed service times) as in Fig. 5.

Editing Router 3 Properties ×									
Station Name Station Name: Router 3									
· · · · · ·	outing Section \								
Number of Servers	Numbe	er: 1							
Service Time Distributions	1								
Class	Strategy	Service Time Distribution							
Class1	Load Independent 🔹	exp(20)	Edit						
Class2	Load Independent 🔹	exp(20)	Edit						
Class3	Load Independent 🔹	exp(20)	Edit						
Class4	Load Independent 🔹	exp(20)	Edit						
			1						
	[	Done							

Figure 5: Setup of service times for router 3

The queue section for all routers is set to infinite server, and FCFS service policy for all channels.

In order to answer question 1, the 4 utilizations for the 4 routers with respect to all classes must be added in the performance indices panel. Similarly, to answer question 2, the 4 average number of customers for the 4 routers with respect to all classes must be added. Analogously, in order to answer question 3, the 4 response times for the 4 routers with respect to all classes must be added.

To answer question 4, response times for router 2 with respect to classes 1 and 3 must be added, as channels 2 and 4 do not use router 2.

In order to answer question 5, no additional preformance index is needed, as the bottleneck is the router with the highest utilization and utilizations have been computed to answer question 1.

Finally, to answer question 6, the 3 response times for routers 1, 3 and 4 with respect to class 2 must be added and summed.

The list of needed performance indices is in Fig. 6.

Performance Index	Class/Mode		00	C (1)	
		Station/Region/System	Stat.Res.	Conf.Int.	Max Rel.Err.
Utilization				0.99	
Utilization	All Classes	Router 2		0.99	(
Utilization	All Classes	Router 3		0.99	C
Utilization	All Classes	Router 4		0.99	C
Number of Customers	All Classes	Router 1		0.99	C
Number of Customers	All Classes	Router 2		0.99	C
Number of Customers	All Classes	Router 3		0.99	0
Number of Customers	All Classes	Router 4		0.99	0
Response Time	All Classes	▼ → Router 1 →		0.99	0
Response Time	All Classes	▼ → Router 2 ▼		0.99	0
Response Time	All Classes	🕶 Router 3 👻		0.99	0
Response Time	All Classes	Router 4		0.99	0
Response Time	🖉 Class1	Router 2		0.99	0
Response Time	Class3	Router 2		0.99	0
Response Time	Class2	🕶 Router 1 👻		0.99	0
Response Time	Class2	🕶 Router 3 💌		0.99	C
Response Time	Class2	Router 4		0.99	C

Figure 6: Setup of performance indices

After launching the simulation, some of the indices will not satisfy confidence intervals with standard settings. It is sufficient to augment the maximum number of events from 1000000 to 15000000 in the "Define simulation parameters" panel. If the simulation takes too much time to complete, check if numbers of customers indices all converge to a finite value: otherwise, routing might not be set correctly.

In the following, we obviously expect that the obtained results are coherent with the ones obtained by the analytical solution.

We obtain the values shown in Fig. 7 for the utilizations. All values are in the confidence interval. Utilization of router 1 is 0.70, utilization of router 2 is 0.78 (compatible with 0.8 obtained analytically, as simulation error is 0.03), utilization of router 3 is 0.90, while utilization of router 4 is 0.91 (compatible with 0.90, as simulation error is 0.03, and this answers question 1): consequently, the system bottleneck is router 4, but router 3 is basically in the same conditions of average utilization (this answers question 5, and the analytical results confirm that they both are equally the bottleneck).

We obtain the values shown in Fig. 8 for the average numbers of packets. For router 1 we obtain 2.38, for router 2 we obtain 4.03, for router 3 we obtain 9.08, for router 4 we obtain 9.02 (values for router 1 and 3 are not compatible with the ones obtained by the analytical solution, anyway within a small interval): this answers question 2.

 $\mathbf{6}$ 

🚿 Simul	lation Results - esercizi	o-multiclass_MultiChann	elNetwork.jsimg								-	0	x c
Numbe	r of Customers 🗍 Respo	onse Time Utilization											
	utilization for each sele	ected class at each select n the station (may be gre		ueing stations this is the average u	utiliza	ation of e	each ser	/er. The	e utiliza	tion of	a delay	statio	n is the
	Station Name:	Router 1	Class Name:	All		0.726	_		_	_			
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	61440		0.635	-						
	Min:	0.6920	Max:	0.7175		0.544 0.453							
	Average value: 0.7	7047		Abort Measure	_	0.363							
$\checkmark$						0.272							
				Hide instantaneous values		0.181 0.091							
	Right-click to save it. Click on green bars to	o see the simulation time	e, the sample average (blue), and	d the sample values (green).		0.000	1	2	3	4	5	6	7 10^3
	Station Name:	Router 2	Class Name:	All	1	0.855			_		_		
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	40960		0.748							10000
	Min:	0.7637	Max:	0.8045		0.641 0.535							
	Average value: 0.7			Abort Measure		0.428							
$\checkmark$						0.321							
				Hide instantaneous values		0.214 0.107							
	Right-click to save it. Click on green bars to		e, the sample average (blue), and	d the sample values (green).		0.000	0.7	1.4	2.1	2.8	3.5	4.2	4.9
													10^3
	Station Name:	Router 3	Class Name:	All		0.951							
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	48640		0.832 0.713							
	Min:	0.8845	Max:	0.9130		0.594							
	Average value: 0.8	3987		Abort Measure		0.475							
$\mathbf{\nabla}$				I liste in standard and a standard	1	0.357 0.238							
	Right-click to save it.			Hide instantaneous values		0.119							
		o see the simulation time	e, the sample average (blue), and	d the sample values (green).		0.000	0.4	0.8	1.2	1.6	2	2.4	2.8 10^3
	Station Name:	Router 4	Class Name:	All	75	ן0.941		_					
	Conf.Int/Max Rel.Err:		Analyzed samples:			0.824							
	Min:	0.8876	Max:	0.9311		0.706 0.588							
	Average value: 0.9			Abort Measure		0.471							
$\checkmark$	<b>_</b>			] [	-	0.353							
				Hide instantaneous values		0.235 0.118							
	Right-click to save it. Click on green bars to	o see the simulation time	, the sample average (blue), and	the sample values (green)		0.000	0.5	1	1.5	2	2.5	3	3.5
	green burs t		, compre arerage (orac), and			U	0.5	'	1.5	2	2.5	5	10^3
													1
			Simu	lation Complete (Time Elapsed: 1-	49.5s								

Figure 7: Average utilizations

🧭 Simula	ation Results - eserciz	zio-multiclass_MultiChannelNetwork	jsimg			- 🗆 X
Number	of Customers Resp	oonse Time Utilization \				
	r of Customers	; for each selected class at each selec	ted station.			
	Station Name:	Router 1	Class Name:	All		3.481
	Conf.Int/Max Rel.Err	: 0.99 / 0.03	Analyzed samples:	573440		3.045
	Min:	2.3118	Max:	2.4468		2.175
	Average value: 2	.3793		Abort Measure		1.740
						1.305
	Right-click to save it			Hide instantaneous values		0.435
		to see the simulation time, the samp	ole average (blue), and	the sample values (green).		0.000 0 6 12 18 24 30 36 42 10 <sup>3</sup>
	Station Name:	Router 2	Class Name:	All	1	5.713]
	Conf.Int/Max Rel.Err		Analyzed samples:			4.999
	Min:	3.9396	Max:	4.1172		4.285
	Average value: 4			Abort Measure		2.857
	Attract					2.143
				Hide instantaneous values		1.428 <sup>-</sup> 0.714 <sup>-</sup>
	Right-click to save it Click on green bars	t. to see the simulation time, the samp	ole average (blue), and	the sample values (green).		0.000 0 21 42 63 84 105 126 147
		-, ,				10^3
	Station Name:	Router 3	Class Name:	All		11.21
	Conf.Int/Max Rel.Err	: 0.99 / 0.03	Analyzed samples:	9175040		9.805
	Min:	8.8558	Max:	9.3091		7.004
	Average value: 9	.0824		Abort Measure		5.603
				Hide instantaneous values		4.202 <sup>1</sup> 2.801 <sup>1</sup>
	Right-click to save it	t.		The instantaneous values		1.401
		to see the simulation time, the samp	ole average (blue), and	the sample values (green).		0.000 0 37 74 111 148 185 222 259 10^3
	Station Name:	Router 4	Class Name:	All	1	12.56]
	Conf.Int/Max Rel.Err		Analyzed samples:			
	Min:	8.7721	Max:	9.2604		9.4181
	Average value: 9	.0162		Abort Measure		6.2791
$\mathbf{V}$	<b>J</b>					4.709
				Hide instantaneous values		3.139 <sup>1</sup> 1.570 <sup>1</sup>
	Right-click to save it Click on green bars	t. to see the simulation time, the samp	ole average (blue), and	the sample values (green).		0.000 50 100 150 200 250 300 350
						10^3 👻
	1.00		Simu	lation Complete (Time Elapsed: 14	9.59	s)

Figure 8: Average numbers of customers

Response times for the routers with respect to all classes are in Fig. 9. Response times for router 1, 2, 3 and 4 are respectively 0.34 s, 0.50 s, 0.50 s and 1.00 s: this answers question 3.

umbe		_	Network.jsimg								
	r of Customers Respo	onse Time \Utilization \									
	nse Time response time for each	n selected class at each sel	ected station. In a Fork/Join se	ection this index refers to tasks and	not to custor	ners.					
	Station Name:	Router 1	Class Name:	All	0.418	_					
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	368640	0.365			===		=	
	Min:	0.3284	Max:	0.3456	0.261						
	Average value: 0.3	3370		Abort Measure	0.209						
9	Right-click to save it. Click on green bars to	o see the simulation time,	the sample average (blue), and	Hide instantaneous values	0.157 0.104 0.052 0.000 0	8 16	24	32	40		56
	Station Name:	Router 2	Class Name:	All	<b>0.718</b>						10^3
	Conf.Int/Max Rel.Err:		Analyzed samples:		0.628	$\sim$				1	
	Min:	0.4906	Max:	0.5192	0.538 -		+++		<del> </del>	╤	
	Average value: 0.5			Abort Measure	0.359						
	Right-click to save it. Click on green bars to	o see the simulation time,	the sample average (blue), and	the sample values (green).	0.090 0.000 0	13 26	39	52	65		91 10^3
	Station Name:	Router 3	Class Name:	All	0.590	<u></u>			<u>l</u>		
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	5570560	0.516	╤┲┲		1 1711 7		huhl	<u>,</u>
	Min:	0.4876	Max:	0.5080	0.369						
-	Average value: 0.4	1978		Abort Measure	0.295 <sup>1</sup> 0.2211						
Ø	Right-click to save it.		the sample average (blue), and	Hide instantaneous values	0.148 <sup>-</sup> 0.074 <sup>-</sup>	45 90	125	190	225	270	215
	Click on green bars to		the sample average (blue), and	d the sample values (green).	0.148 0.074 0.000 0	45 90	135	180	225		315 10^3
			the sample average (blue), and Class Name:		0.148 <sup>-</sup> 0.074 <sup>-</sup> 0.000 0	45 90	135	180	225		
	Click on green bars to	o see the simulation time, Router 4		d the sample values (green).	0.148 0.074 0.000 0	45 90	135	180	225		
	Click on green bars to Station Name:	o see the simulation time, Router 4	Class Name:	d the sample values (green).	0.148 0.074 0.000 0 1.384 1.211 1.038 0.865	45 90	135	180	225 :		
<i>"</i>	Click on green bars to Station Name: Conf.Int/Max Rel.Err:	Router 4 0.99 / 0.03 0.9681	Class Name: Analyzed samples:	d the sample values (green). All 3932160	0.148 0.074 0.000 0 1.384 1.211 1.038	45 90	135	180	225		

Figure 9: Average response times - question 3

Response times for router 2 with respect to channel 1 and 3 are in the upper part of Fig. 10 (channels 2 and 4 do not use it). Obviously they have the same value of 0.50 s, as we know from previous considerations: this answers question 4.

As for the lower part of Fig. 10, response times for routers 2, 3 and 4 with respect to channel 2 are respectively 0.34 s, 0.51 s and 0.99 s, for an average total time in the system for packets using virtual channel 2 of 1.84 s: this answers question 6.

Station Name: Router 2 Class Name: Class 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Min:       0.4922       Max:       0.5161         Image: Construction of the standard of t
Image: Solid station Name:       Router 1       Class Name:       Class 2       0.388       0.484
We have the count of the sample values       Product measures         Hide instantaneous values       0.209         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.719         Station Name:       Router 2       Class Name:       Class 3         Conf.Int/Max Rel Err.       0.90 / 0.03       Analyzed samples:       0.55360         Min:       0.4918       Max:       0.5136         Average value:       0.5027       Abort Measure       0.300         Hide instantaneous values       0.300       0.99 / 0.03       Analyzed samples:       0.300         Station Name:       Router 1       Class Name:       Class 2       0.300       0.300         Station Name:       Router 1       Class Name:       Class 2       0.300       0.325         Min:       0.3254       Max:       0.3454       0.336       0.326         Min:       0.3254       Max:       0.3454       0.360       0.116       0.380         Min:       0.3254       Max:       0.3519       0.300       0.15       0.520       0.500       0.16       0.13       0.650       0.650       0.16       0.13       0.650       0.16       0.13
Night-click to save it.       0.000       13       26       39       52       65       76       91         Image: Station Name:       Router 2       Class Name:       Class Name:       Class Name:       0.000
Right-click to save it.       0.000       13       26       39       52       65       76       91         10'3       Station Name:       Router 2       Class Name:       Class 3       0.000       13       26       39       52       65       76       91       10'3         Image: Conf.Int/Max Rel.Err.       0.99 / 0.03       Analyzed samples       653360       0.359       0.499       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399       0.399
10:3         Station Name:       Router 2       Class Name:       Class 3         Conf.int/Max RelErr:       0.99 / 0.03       Analyzed samples:       655360         Min:       0.4918       Max:       0.5136         Average value:       0.5027       Abort Measure         Hide instantaneous values       0.6000       19       38       57       76       95       114       133         Cick on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.366       0.362       0.269       0.269       0.270       0.036       0.368       0.160       0.036       0.046       0.066
Station Name:       Router 2       Class Name:       Class 3       0.719         Conf.Int/Max RelErr:       0.97 / 0.03       Analyzed samples:       65360       0.316         Min:       0.4918       Max:       0.5136       0.449         Average value:       0.5027       Abort Measure       0.369       0.169         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.369       0.180         Station Name:       Router 1       Class Name:       Class 2       0.369         Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       133120       0.276         Min:       0.3254       Max:       0.3454       0.369       0.076         Min:       0.3254       Max:       0.3454       0.369       0.027         Min:       0.3254       Max:       0.3454       0.369       0.026       0.076<
Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       65360         Min:       0.4918       Max:       0.5136         Min:       0.4918       Max:       0.5136         Average value:       0.5027       Abort Measure         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.369         Station Name:       Router 1       Class Name:       Class2         Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       133120         Min:       0.3254       Max:       0.3454         Min:       0.4945       Max:       0.5197         Average value:       0.5071       Abort Measure       0.4567         Min:       0.4945       Max:       0.5197         Average value:       0.5071       Abort Measure       0.5567         Min:       0.4945       Max
Min:       0.4918       Max:       0.5136         Average value:       0.5027       Abort Measure       0.359         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.369       0.000         Station Name:       Router 1       Class Name:       Class2       0.386         Conf.Int/Max Rel.Er:       0.99 / 0.03       Analyzed samples:       133120       0.322         Nin:       0.3354       Max:       0.344       0.349         Nin:       0.3354       Max:       0.344         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.889       0.322         Nin:       0.3354       Max:       0.3454       0.3454         0.040       0.3354       Abort Measure       0.369         Nin:       0.499 / 0.03       Analyzed samples:       133120       0.049         0.040       0.355       10       15       20       25       30       35         Station Name:       Router 3       Class Name:       Class2       0.650       0.049       0.049       0.049       0.049       0.049       0.049       0.049       0.049
Average value:       0.5027       Abort Measure         Hide instantaneous values       0.369       0.000         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.369         Station Name:       Router 1       Class Name:       Class 2         Conf.Int/Max Rel.Er:       0.99 / 0.03       Analyzed samples:       133120         Min:       0.3254       Max:       0.3454         Average value:       0.354       Abort Measure       0.000         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.629         Station Name:       Router 3       Class Name:       Class 2         Conf.Int/Max Rel.Er:       0.99 / 0.03       Analyzed samples:       19200         Min:       0.4445       Max:       0.5197         Nort       0.5071       Abort Measure       0.5597         Min:       0.5071       Abort Measure       0.157         Min:
Hide instantaneous values       0.269 0.800 0.000 0       19       38       57       76       95       114       133 10^3         Station Name:       Router 1       Class Name:       Class2       0.366 0.322 0.276       0.360 0.322 0.276       0.360 0.322 0.276         Min:       0.3254       Max:       0.3454       0.3454         Average value:       0.3354       Abort Measure       0.466 0.000 0       0.15       20       25       30       35         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.629 0.000 0       0.5       10       15       20       25       30       35         Station Name:       Router 3       Class Name:       Class2       0.629 0.550 0.550       0.629 0.550       0.60       0.
Right-click to save it.       0.000       19       38       57       76       95       114       133         Image: Station Name:       Router 1       Class Name:       Class 2       0.366       0.322       0.366       0.322       0.322       0.322       0.3354         Min:       0.3254       Max:       0.3454       0.3454       0.336       0.366       0.322       0.366       0.326       0.366       0.326       0.366       <
Right-Click to save it.       0.000       19       38       57       76       95       114       133         10'3       10'3       10'3       10'3       10'3       10'3         10'0       19       38       57       76       95       114       133       10'3         10'3       10'3       Astronomic constraints       0.3254       Max:       0.3454       0.325       0.220       0.184       0.322       0.220       0.184       0.325       0.230       0.184       0.046       0.046       0.046       0.046       0.046       0.046       0.000       5       10       15       20       25       30       35       10'3       10'3         10'1       15       20       25       30       35       10'3       15       0'3       135       10'3       15       0'3       15       10'3       15       0'3       10'3       10'3       10'3       10'3       10'3       10'3       10'3       114       133       10'3       13120       10'3       114       133       10'3       10'3       15'3       10'3       12'3       10'3'3       10'3'3       10'3'3       10'3'3       10'3'3       10'3'3'3'3'3'3'
Image: Station Name:       Router 1       Class Name:       Class 2       0.368       0.322         Image: Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       133120       0.3254         Image: Right-click to save it.       0.3354       Abort Measure       0.184         Image: Right-click to save it.       0.164       0.000       5       10       15       20       25       30       35         Image: Router 3       Class Name:       Class 2       0.629       0.046       0.000       5       10       15       20       25       30       35         Image: Router 3       Class Name:       Class 2       0.629       0.550       0.472       0.550       0.472       0.550       0.472       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.326       0.157       0.326       0.157       0.326       0.157       0.079       0.090       0.30       60       90       120       150       180       210         Image: Right-click to save it.       Click on green bars to see the simulation time, the sample average (bl
Station Name:       Router 3       Class Name:       Class Name:       Class Name:       Class 2         Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       13120       0.322         Min:       0.3254       Max:       0.3454         Average value:       0.354       Abort Measure         Hide instantaneous values       0.092         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.046         0.092       0.03         Min:       0.4945         Min:       0.4945         Min:       0.5071         Abort Measure       0.314         0.032       0.09
Conf.Int/Max Rel.Err:       0.39 / 0.03       Analyzed samples:       133120       0.322         Min:       0.3254       Max:       0.3454         Average value:       0.3354       Abort Measure         Hide instantaneous values       0.184         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.629         Station Name:       Router 3       Class Name:       Class2         Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       819200         Min:       0.4945       Max:       0.5197         Min:       0.4945       Max:       0.5197         Average value:       0.5071       Abort Measure         Hide instantaneous values       0.314         0.323       0.324         0.4945       Max:       0.5197         0.304       0.336       0.157         Average value:       0.5071       Abort Measure         Right-click to save it.       0.157         Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.336
Min:       0.3254       Max:       0.3454         Average value:       0.3354       Abort Measure       0.1844         Hide instantaneous values       0.092       0.1844         O.092       0.046       0.092         O.000       5       10       15       20       25       30       35         Station Name:       Router 3       Class Name:       Class2       0.629       0.472       0.472       0.393       0.043         Min:       0.4945       Max:       0.5197       Abort Measure       0.550       0.472       0.393       0.314       0.394       0.394       0.472       0.393       0.314       0.043       0.000       5       10       15       20       25       30       35       10^43         Min:       0.4945       Max:       0.5197       Abort Measure       0.393       0.314       0.393       0.314       0.326       0.157       0.393       0.314       0.326       0.157       0.393       0.314       0.315       0.315       0.314       0.315       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.314       0.31
Average value:       0.3354       Abort Measure         Hide instantaneous values       0.184         Right-click to save it.       0.104         Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.164         Station Name:       Router 3         Conf.Int/Max Rel.Err:       0.99 / 0.03         Min:       0.4945         Min:       0.4945         Min:       0.4945         Kight-click to save it.       0.5071         Hide instantaneous values       0.157         Right-click to save it.       0.15071         Abort Measure       0.167         0.197       0.000         30       60       90       120       150       180       210
Hide instantaneous values       0.138 0.092 0.046 0.000 0 5 10 15 20 25 30 35 10^3         Station Name:       Router 3       Class Name:         Conf.Int/Max Rel.Err.       0.99 / 0.03         Min:       0.4945         Min:       0.4945         Min:       0.5197         Average value:       0.5071         Hide instantaneous values       0.157 0.314 0.314 0.314 0.306 0.315 0.079         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).
Right-click to save it.       0.046       0.000       5       10       15       20       25       30       35         Station Name:       Router 3       Class Name:       Class2       0.050       0.046       0.000       5       10       15       20       25       30       35         Station Name:       Router 3       Class Name:       Class2       0.050       0.472       0.046       0.000       0.550       0.472       0.046       0.472       0.033       0.046       0.472       0.033       0.046       0.472       0.033       0.046       0.046       0.046       0.046       0.472       0.033       0.046       0.472       0.033       0.046       0.472       0.033       0.046
Right-click to save it.       0.000       5       10       15       20       25       30       35         Station Name:       Router 3       Class Name:       Class2       0.000       5       10       15       20       25       30       35         Min:       0.4945       Max:       0.5197       0.334       0.314       0.334       0.314       0.314       0.236       0.157       0.334       0.314       0.236       0.157       0.000       30       60       90       120       150       180       210
Station Name:       Router 3       Class Name:       Class2       0.629       0.550         Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       819200       0.472       0.393         Min:       0.4945       Max:       0.5197       0.393       0.314       0.314         Average value:       0.5071       Abort Measure       0.314       0.236       0.157         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       10^43       0.009       120       150       180       210
Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       819200         Min:       0.4945       Max:       0.5197         Average value:       0.5071       Abort Measure         Hide instantaneous values       0.3141         Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.500
Conf.Int/Max Rel.Err:       0.99 / 0.03       Analyzed samples:       819200         Min:       0.4945       Max:       0.5197         Average value:       0.5071       Abort Measure         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.157
Min:       0.4945       Max:       0.5197         Average value:       0.5071       Abort Measure       0.334         Hide instantaneous values       0.157       0.157         Right-click to save it.       Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.000       30       60       90       120       150       180       210
Hide instantaneous values       0.236         Right-click to save it.       0.157         Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.236
Hide instantaneous values       0.157         Right-click to save it.       0.079         Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).       0.000
Right-click to save it. Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).
Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).
10^3
Station Name: Router 4 Class Name: Class2 1.399
Conf.Int/Max Rel.Err: 0.99 / 0.03 Analyzed samples: 2048000
Min: 0.9620 Max: 1.0088 0.875
Average value: 0.9854 Abort Measure 0.700
Hide instantaneous values 0.525
0175
Right-click to save it. Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).
Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).
Click on green bars to see the simulation time, the sample average (blue), and the sample values (green).

Figure 10: Average response times - questions 4 and 6  $\,$ 

## 2 Exercise: CPU-bound and I/O-bound<sup>2</sup>

A system consists of two devices: a CPU device with exponential service rate 2 jobs/s and an I/O device with exponential service rate 1 job/s. There are two different types of jobs: CPU-bound jobs and I/O-bound jobs.

CPU-bound jobs arrive at the CPU from outside according to a Poisson process of rate 0.2 jobs/s. After serving at the CPU, three things can happen to a CPU-bound job:

- 1. with probability 0.3, the job leaves the system;
- 2. with probability 0.65, the job returns to the CPU queue to repeat the process;
- 3. with probability 0.05, the job goes to the I/O device queue, serves there once, and immediately returns to the CPU queue to repeat the process.

The I/O-bound jobs arrive at the I/O from outside the network according to a Poisson process with rate 0.25 jobs/s. After serving at the I/O, there are three things that can happen to an I/O-bound job:

- 1. with probability 0.4, the job leaves the system;
- 2. with probability 0.5, the job returns to the I/O queue to repeat the process;
- 3. with probability 0.1, the job goes to the CPU device queue; each time the job serves at the CPU device, it has a 0.05 probability of returning to the CPU device and a 0.95 probability of returning to the I/O queue.

Our goal is to answer the following questions:

- 1. what is the expected time in system of CPU-bound jobs?
- 2. what is the average number of CPU-bound jobs at the CPU?
- 3. if the service policy of the CPU is processor sharing and the service policy of the I/O is shortest job first, how do we expect the behavior of the CPU-bound and I/O bound number of customers at the CPU and the I/O and their total time spent in the system will change? Why? Verify if your guess is confirmed by results;
- 4. in order to use this system for real time applications, the CPU is scheduled with a discriminatory processor sharing (DPS) policy that allocates twice the CPU to CPU-bound jobs with respect to I/O-bound jobs. The deadline for CPU-bound jobs is 3 seconds: is this choice sufficient to satisfy this requirement? Comment results, and compare them to previous cases. If it is not sufficient, what choice may be sufficient?

#### 2.1 Solution

The two devices, namely the CPU and the I/O device, are used by both the types of jobs, and can be represented by two queuing stations. As the routing probabilities are given and depend on the type of job, a classed queuing network with a class per type is a viable model for the system. Both stations are characterized by exponentially distributed service times, that are provided in the form of service rates  $\mu_{k,c}$  equal for both classes at each station, so that an analytical solution may be applied if the system is stable.

The system can be modeled as in Fig. 11.

<sup>&</sup>lt;sup>2</sup>This exercise is based on the exercise presented in [1] in subsection 18.6.3, page 326.

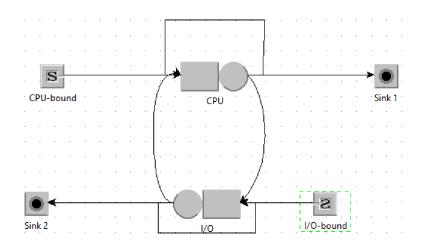


Figure 11: The model

#### 2.2 Analytical solution

The two questions are about CPU-bound jobs, so

$$R_{c} = \sum_{k} R_{k,c} = \sum_{k} \frac{D_{k,c}}{1 - \sum_{c'} U_{k,c'}} = \sum_{k} \frac{v_{k,c} \cdot s_{k,c}}{1 - \sum_{c'} U_{k,c'}} = \sum_{k} \frac{\frac{\lambda_{k,c}}{\lambda_{c} \cdot \mu_{k,c}}}{1 - \sum_{c'} U_{k,c'}}$$

The equations to find  $\lambda_{1,CPU-bound}$  and  $\lambda_{2,CPU-bound}$  are obtained by inspecting the model and are:

 $\begin{cases} \lambda_{1,CPU-bound} = \lambda_{0,CPU-bound} + \lambda_{1,CPU-bound} \cdot p_{1,1,CPU-bound} + \lambda_{2,CPU-bound} \cdot p_{2,1,CPU-bound} = 0.2 + 0.65\lambda_{1,CPU-bound} + \lambda_{2,CPU-bound} + \lambda_{2,CPU-bou$ 

$$\begin{cases} 0.35\lambda_{1,CPU-bound} = \lambda_{2,CPU-bound} + 0.2\\ \lambda_{2,CPU-bound} = 0.05\lambda_{1,CPU-bound}\\ \end{cases}$$
$$\begin{cases} 0.3\lambda_{1,CPU-bound} = 0.2\\ \lambda_{2,CPU-bound} = 0.05\lambda_{1,CPU-bound}\\ \lambda_{1,CPU-bound} = 0.666 \ jobs/s\\ \lambda_{2,CPU-bound} = 0.033 \ jobs/s \end{cases}$$

Analogously, the equations to find  $\lambda_{1,I/O-bound}$  and  $\lambda_{2,I/O-bound}$  are obtained by inspecting the model and are:

 $\begin{cases} \lambda_{1,I/O-bound} = \lambda_{1,I/O-bound} \cdot p_{1,1,I/O-bound} + \lambda_{2,I/O-bound} \cdot p_{2,1,I/O-bound} = 0.05\lambda_{1,I/O-bound} + 0.1\lambda_{2,I/O-bound} \\ \lambda_{2,I/O-bound} = \lambda_{0,I/O-bound} + \lambda_{1,I/O-bound} \cdot p_{1,2,I/O-bound} + \lambda_{2,I/O-bound} \cdot p_{2,2,I/O-bound} = 0.25 + 0.95\lambda_{1,I/O-bound} + 0.5\lambda_{1,I/O-bound} +$ 

$$\begin{cases} 0.95\lambda_{1,I/O-bound} = 0.1\lambda_{2,I/O-bound} \\ 0.5\lambda_{2,I/O-bound} = 0.25 + 0.95\lambda_{1,I/O-bound} \\ \lambda_{1,I/O-bound} = 0.105\lambda_{2,I/O-bound} \\ 0.5\lambda_{2,I/O-bound} = 0.25 + 0, 1\lambda_{2,I/O-bound} \\ \lambda_{1,I/O-bound} = 0.066 \ jobs/s \\ \lambda_{2,I/O-bound} = 0.625 \ jobs/s \end{cases}$$

We can compute now the average utilizations for the devices by the CPU-bound tasks as  $U_{1,CPU-bound} =$  $\frac{\lambda_{1,CPU-bound}}{\mu_{1,CPU-bound}} = \frac{0.666}{2} = 0.3331 \text{ and } U_{2,CPU-bound} = \frac{\lambda_{2,CPU-bound}}{\mu_{2,CPU-bound}} = \frac{0.033}{1} = 0.0331, \text{ and by the I/O-bound tasks}$ as  $U_{1,I/O-bound} = \frac{\lambda_{1,I/O-bound}}{\mu_{1,I/O-bound}} = \frac{0.066}{2} = 0.0331 \text{ and } U_{2,I/O-bound} = \frac{\lambda_{2,I/O-bound}}{\mu_{2,I/O-bound}} = \frac{0.625}{1} = 0.6251$ , concluding that the system is stable and can be solved analytically.

Applying the formula found for  $R_c$  to CPU-bound tasks we obtain

$$R_{CPU-bound} = R_{1,CPU-bound} + R_{2,CPU-bound} = 2.626 + 0.482 = 3.108 \, s_{2,CPU-bound} = 2.626 + 0.482 = 3.108 \, s_{2,CPU-bound} = 3.108 \, s_$$

since

$$R_{1,CPU-bound} = \frac{\frac{\lambda_{1,CPU-bound}}{\overline{\lambda_{0,CPU-bound} \cdot \mu_{1,CPU-bound}}}}{1 - U_{1,CPU-bound} - U_{1,I/O-bound}} = \frac{\frac{0.666}{0.2 \cdot 2}}{1 - 0.333 - 0.033} = 2.626 \ s$$

0 000

and

$$R_{2,CPU-bound} = \frac{\frac{\lambda_{2,CPU-bound}}{\overline{\lambda_{0,CPU-bound} \cdot \mu_{2,CPU-bound}}}}{1 - U_{2,CPU-bound} - U_{2,I/O-bound}} = \frac{\frac{0.033}{0.2 \cdot 1}}{1 - 0.033 - 0.625} = 0.482 \ s$$

that answers question 1.

In order to answer question 2, we can consider that

$$N_{k,c} = X_c \cdot R_{k,c} = \frac{X_{k,c}}{v_{k,c}} R_{k,c} = \frac{\lambda_{k,c}}{\frac{\lambda_{k,c}}{\lambda_c}} R_{k,c} = \lambda_c \cdot R_{k,c}$$

that, applied to the CPU for CPU-bound tasks, gives an average number of tasks equal to

 $N_{1,CPU-bound} = \lambda_{CPU-bound} \cdot R_{1,CPU-bound} = 0.2 \cdot 2.626 = 0.5252.$ 

As the shortest job first policy is used for the I/O device, question 3 cannot be answered by means of the analytical methods presented in the course. Anyway, from a qualitative point of view, we may expect that the effect on the average number of CPU-bound jobs at the CPU will not change significantly, due to the fact that the fraction of I/O-bound jobs that uses the CPU, and that may take advantage of the processor sharing policy with respect to CPU-bound jobs, is small and that they come from the I/O device, that has a lower service rate: we also expect that the average number of I/O-bound jobs at the CPU will be lower, because they will be served faster. For the average number of jobs at the I/O device, we expect a small improvement, because shorter workloads will be promoted to be executed first and will not suffer the operations of longer workloads. For the same reason, we expect shorter average time in the system for both the kind of jobs, with a higher improvement for I/O-bound jobs because they are prevalent in the workload of the I/O device. These hypotheses may be verified by simulation.

Analogously, the analytical approach is not suitable to answer question 4.

#### $\mathbf{2.3}$ Using JMT

When creating the 2 classes, each should be assigned one of the sources shown in Fig. 11, setting up the correspinding rate as in Fig. 12.

Classes (	Characteristics						Add Class
		ne and parameters for each s in the model, then <b>all</b> the			he <b>same</b> reference station		Classes: 2
Open Clas		has Fork, ClassSwitch, Sca			ference station is <b>not</b> generated b	y <b>any</b> Source.	
Color	Name	Туре	Priority	Population	Interarrival Time Distribution		Reference Station
	CPU-bound	🥥 Open 👻	C		exp(0.2)	Edit	🗉 CPU-bound 🗸 🗙
	I/O-bound	🥥 Open 👻	C		exp(0.25)	Edit	🗉 I/O-bound 🗸 🗙

Figure 12: Classes setup

The routing section in the queues can be easily set probabilistically, as described by the specification for each class. Examples for both type of jobs at the CPU are in Fig. 13 and 14.

💹 Editing CPU Properties				×
Station Name				
Station Name: CPU				
CPU Parameters Definiton				
Queue Section Service Section Routing	Section			
Routing Strategies			Description	
Class	Routing Strategy		-	stations connected
CPU-bound	Probabilities	_	to the current one	
CPO-bound	Probabilities		specified probabili	
🥥 I/O-bound	Probabilities	-	the probabilities is the values will be s	different from 1, all
	L		the values will be s	
			Routing Options	
			Destination	Probability
			CPU	0.65
			1/0	0.05
			Sink 1	0.3
	Done			
	Done			

Figure 13: Setup of CPU-bound jobs routing at the CPU

💹 Editing CPU Properties		×
Station Name		
Station Name: CPU		
CPU Parameters Definiton		
$\int$ Queue Section $\setminus$ Service Section $\setminus$ Routing S	ection	
Routing Strategies		Description
Class	Routing Strategy	Jobs are routed to stations connected
CPU-bound	Probabilities	to the current one according to the
		<ul> <li>specified probabilities. If the sum of</li> <li>the probabilities is different from 1, all</li> </ul>
🧟 I/O-bound	Probabilities	the values will be scaled to sum 1.
		- Resting Oction
		Routing Options
		Destination Probability CPU 0.05
		I/O 0.95
		Sink 1 0.0
	Done	

Figure 14: Setup of I/O-bound jobs routing at the CPU

As devices process all jobs with the same rates, the service section setup for all classes of each queuing station will be set up so that all classes have the same service rate (2 jobs per second for the CPU and 1 job per second for the I/O device, exponentially distributed service times) as in Fig. 15.

Editing CPU Properties	Editing CPU Properties     X											
Station Name Station Name CPU												
CPU Parameters Definiton Queue Section Service Section R Number of Servers	outing Section \ Numbe	ar: 1 💌										
Service Time Distributions												
Class CPU-bound	Strategy Load Independent 🔹	Service Time Distribution exp(2)	Edit									
🥥 I/O-bound	Load Independent 🔹	exp(2)	Edit									
	I/O-bound Load Independent exp(2) Edit											
~		Done										

Figure 15: Setup of service times for the CPU

The queue section for all queuing station is set to infinite server, and FCFS service policy for all classes. In order to answer question 1, the system response time for class CPU-bound must be added in the performance indices panel. Similarly, to answer question 2, the average number of customers for the CPU routers with respect to class CPU-bound must be added.

The list of needed performance indices is in Fig. 16.

prmance Indices e performance indices to be	collected and plotted by the sim	ulation engine.		Se	lect an index
Performance Index	Class/Mode	Station/Region/System	Stat.Res.	Conf.Int.	Max Rel.Err.
Response Time	CPU-bound	▼ 🕞 System ▼		0.99	0.
Number of Customers	CPU-bound	• CPU •		0.99	0.
	lect samples in a CSV file for add :ono\JMT	itional statistical analysis. This option m	ay produce a file with	3	Delimiter:

Figure 16: Setup of performance indices

After launching the simulation, we obviously expect that the obtained results are coherent with the ones obtained by the analytical solution.

We obtain the value shown in Fig. 17 for the expected time in system of CPU-bound jobs. The value is in the confidence interval. The result is 3.18, not compatible with 3.10 obtained analytically but sufficiently close, as simulation error is 0.03.

We obtain the value shown in Fig. 18 for the average numbers of CPU-bound jobs at the CPU. The value is in the confidence interval. The result is 0.53, as obtained analytically.

🧭 Simul	ation Results - eserci	zio-multiclass_CPU-bound_IO-bou	und.jsimg								-		×
Number	of Customers Syste	m Response Time											
-	<b>Response Time</b> response time of the e	entire system for each selected clas	s.										
	Station Name:	Network	Class Name:	CPU-bound		3.297						_	
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	51200		2.931 2.564							
	Min:	3.0861	Max:	3.2708		2.198							
	Average value: 3.	1785		Abort Measure		1.832							
$\mathbf{\nabla}$						1.465 1.099							
				Hide instantaneous values		0.733							
	Double click on this Right-click to save it.	graph to open it in a new windows			0	D.366							
		o see the simulation time, the sam	ple average (blue), a	nd the sample values (green).	(	0000.c	37	74	111	148	185	222	259 10^3
			Si	imulation Complete (Time Elapsed: 1.	.7s)								

Figure 17: System response time for class CPU-bound

🧭 Simu	lation Results - eserc	izio-multiclass_CPU-bound_IO-bo	und.jsimg							-		×
Number	r of Customers \Syste	em Response Time \										
	er of Customers number of customers	s for each selected class at each sel	ected station.									
	Station Name:	CPU	Class Name:	CPU-bound	0.556	Ē						=
	Conf.Int/Max Rel.Err	: 0.99 / 0.03	Analyzed samples:	573440								
	Min:	0.5214	Max:	0.5454	0.432							
	Average value: 0	.5334		Abort Measure	0.309							
					0.247							
				Hide instantaneous values								
			5.									
	Right-click to save it Click on green bars		nple average (blue), a	nd the sample values (green).	0.000	91	182	273	364	455	546	637
		for each selected class at each selected station.  CPU Class Name: CPU-bound 0.556 0.494 0.494 0.492 0.5214 Max: 0.5454 0.5454 0.309 0.247 0.309 0.247 0.185 0.123 0.662 0.000										
			S	imulation Complete (Time Elapsed: 1.	7s)							

Figure 18: Average number of customers at CPU for CPU-bound jobs

In order to answer question 3, the average number of I/O-bound jobs at the CPU and of I/O-bound and CPU-bound at the I/O, and the system response time for I/O-bound jobs must be computed, as shown in Fig. 19 and Fig. 20.

🚿 Simu	lation Results - eserci	zio-multiclass_CPU-bound_IO-bo	und-schedulingnona	analitico.jsimg						-		x í
Numbe	r of Customers \ Syste	m Response Time \										
	er of Customers number of customers	for each selected class at each sele	ected station.									
	Station Name:	I/O	Class Name:	I/O-bound	2.365							
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	1310720	2.070 1.774					1		
	Min:	1.7677	Max:	1.8539	1.478							
	Average value: 1.8	8108		Abort Measure	1.183 <sup>-</sup> 0.887 <sup>-</sup>	ſ						
				Hide instantaneous values	0.591							
	Right-click to save it.				0.296							
	Click on green bars t	o see the simulation time, the sam	ple average (blue), a	nd the sample values (green).	0.000 <sup>4</sup> 0	0.3	0.6	0.9	1.2	1.5	1.8	2.1
				we to the	0.0741	~						10^6
	Station Name:	CPU	Class Name:	I/O-bound	0.065			_				
	Conf.Int/Max Rel.Err: Min:	0.0509	Analyzed samples: Max:	0.0532	0.055			$\geq$	-			₹
	Average value: 0.0		IVIdX.	Abort Measure	0.046 0.037							
$\checkmark$	Average value.	JJ21			0.028							
				Hide instantaneous values	0.018 <sup>-</sup> 0.009 <sup>-</sup>							
	Right-click to save it.	o see the simulation time, the sam	ple average (blue), a	nd the sample values (green).	0.000	137	274	411	548	685	822	959
			p.o	(g ).		137	274	411	540	005	022	10^3
	Station Name:	I/O	Class Name:	CPU-bound	0.128	<						
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	122880	0.112							
	Min:	0.0947	Max:	0.0990	0.080							
	Average value: 0.0	0969		Abort Measure	0.064							
				Hide instantaneous values	0.048 <sup>-</sup> 0.032 <sup>-</sup>							
	Right-click to save it.			The instantaneous values	0.016							
		o see the simulation time, the sam	ple average (blue), ar	nd the sample values (green).	0.000-	0.3	0.6	0.9	1.2	1.5	1.8	2.1
												10^6 👻
			Si	mulation Complete (Time Elapsed: 4	.8s)							

Figure 19: Average number of customers at CPU for I/O-bound jobs and at I/O for CPU-bound and I/O-bound jobs

¢	🔰 Simul	lation Results - eser	izio-multiclass_CPU-bound_IO-bou	nd-schedulingnona	nalitico.jsimg							-		×
ſī	Number	of Customers Syst	em Response Time											
	•	Response Time response time of the	entire system for each selected clas	5.										
		Station Name:	Network	Class Name:	I/O-bound	8.53							_	
		Conf.Int/Max Rel.Er	: 0.99 / 0.03	Analyzed samples:	450560	7.46 6.39								
		Min:	7.3031	Max:	7.5758	5.33	- I r							
		Average value:	.4395		Abort Measure	4.26								
					Hide instantaneous values	2.13								
		Right-click to save	t.			1.06								
		Click on green bars	to see the simulation time, the sam	ble average (blue), ar	d the sample values (green).	0.00	0	0.3	0.6	0.9	1.2	1.5	1.8	2.1 10^6
				Sii	nulation Complete (Time Elapsed: 4.	8s)								

Figure 20: System response time for class I/O-bound

The service disc pline of the CPU must be set to PS for both classes, that is accessible in the Preemptive Scheduling set in the Queue Section tab, and the service discipline of the I/O must be set to SJF for both classes. The new results are in Fig. 21 and Fig. 22.

🧭 Simu	lation Results - eserciz	zio-multiclass_CPU-bound_IO-bo	und-schedulingnona	analitico.jsimg							-		) ×
Number	of Customers Syste	m Response Time \											
	er of Customers number of customers	for each selected class at each sel	ected station.										
	Station Name:	CPU	Class Name:	CPU-bound		0.568							
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	368640	11	0.497 0.426							
	Min:	0.5127	Max:	0.5413	11	0.355							
	Average value: 0.5	5270		Abort Measure		0.284							
	Right-click to save it. Click on green bars t	o see the simulation time, the sam	nple average (blue), ai	Hide instantaneous values		0.213 0.142 0.071 0.000 0	59	118	177	236	295	354	413 10^3
	Station Name:	1/0	Class Name:	I/O-bound	1	1.454]		_					
					┦	1.272							
	Conf.Int/Max Rel.Err:		Analyzed samples:	1146880	$\left\{ \right\}$	1.090							
	Min:	1.3441	Max:		1	0.908 0.727							
$\checkmark$	Average value: 1.3	3714		Abort Measure		0.545							
	Right-click to save it. Click on green bars t	o see the simulation time, the san	nple average (blue), ai	Hide instantaneous values		0.363 0.182 0.000 0	0.2	0.4	0.6	0.8	ĺ	1.2	1.4 10^6
	Station Name:	CPU	Class Name:	I/O-bound		0.056							_
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	81920	11	0.049 0.042							
	Min:	0.0498	Max:	0.0528	1	0.035							
	Average value: 0.0	0513		Abort Measure		0.028							
$\mathbf{v}$						0.021 0.014							
	Right-click to save it.			Hide instantaneous values		0.007							
		o see the simulation time, the sam	nple average (blue), a	nd the sample values (green).		0.000	92	184	276	368	460	552	644 10^3
	Station Name:	I/O	Class Name:	CPU-bound		0.108	<u> </u>						
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	122880		0.095							
	Min:	0.0802	Max:	0.0848		0.068							
	Average value: 0.0	0825		Abort Measure		0.054							
$\mathbf{\nabla}$						0.041 0.027							
	Right-click to save it.			Hide instantaneous values		0.014							
		o see the simulation time, the sam	nple average (blue), a	nd the sample values (green).		0.000 0	0.3	0.6	0.9	1.2	1.5	1.8	2.1
													10^6
			Si	imulation Complete (Time Elapsed: 5	5.0s)	)							

Figure 21: Average number of customers with PS and SJF policies

Results are summarized and compared in the following table:

	FCFS+FCFS	PS+SJF
N <sub>CPU,CPU-bound</sub>	0.527	0.527
N <sub>I/O,I/O-bound</sub>	1.811	1.371
N <sub>CPU,I/O</sub> -bound	0.052	0.051
$N_{I/O,CPU-bound}$	0.097	0.083
$R_{CPU-bound}$	3.126	3.048
$R_{I/O-bound}$	7.440	5.727

and confirm our hypotheses.

	r of Customers Syste	m Response Time									
	Response Time	entire system for each selected cl	ass.								
	Station Name:	Network	Class Name:	CPU-bound	3.299						
	Conf.Int/Max Rel.Err:	0.99 / 0.03	Analyzed samples:	81920	3.079 <sup>-</sup> 2.859 <sup>-</sup>						-
	Min:	2.9652	Max:	3.1307	2.639						
	Average value: 3.0	0479		Abort Measure	2.419 2.199						
					1.979						
				Hide instantaneous values	1.759						
					1.539						
~					1.319						
					1.100 <sup>-</sup> 0.880 <sup>-</sup>						
					0.660						
	Double click on this	graph to open it in a new window	10		0.440						
	Right-click to save it.		/5.		0.220						
								· · · ·			
	Click on green bars t	o see the simulation time, the sai	nple average (blue), a	nd the sample values (green).	0.000	59	118 1	177 236	295	354	413 10
	Station Name:	Network	mple average (blue), a	nd the sample values (green).	5.941	59	118 1	177 236	295	354	
		Network		I/O-bound	5.941 5.545	59	118 1	177 236	295	354	
	Station Name:	Network	Class Name:	I/O-bound	5.9411 5.545 5.149 4.753	59		177 236	295	354	
	Station Name: Conf.Int/Max Rel.Err: Min:	Network 0.99 / 0.03 5.5964	Class Name: Analyzed samples:	I/O-bound : 163840 5.8574	5.941 5.545 5.149 4.753 4.357	59			295	354	
	Station Name: Conf.Int/Max Rel.Err:	Network 0.99 / 0.03 5.5964	Class Name: Analyzed samples:	I/O-bound : 163840	5.941 5.545 5.149 4.753 4.357 3.961	59			295	354	
	Station Name: Conf.Int/Max Rel.Err: Min:	Network 0.99 / 0.03 5.5964	Class Name: Analyzed samples:	I/O-bound : 163840 5.8574	5.941 5.545 5.149 4.753 4.357 3.961 3.565	59			295	354	
	Station Name: Conf.Int/Max Rel.Err: Min:	Network 0.99 / 0.03 5.5964	Class Name: Analyzed samples:	I/O-bound           163840           5.8574           Abort Measure	5.941 5.545 5.149 4.753 4.357 3.961	59			295	354	
<u> </u>	Station Name: Conf.Int/Max Rel.Err: Min:	Network 0.99 / 0.03 5.5964	Class Name: Analyzed samples:	I/O-bound           163840           5.8574           Abort Measure	5.9411 5.545 5.149 4.753 4.357 3.961 3.565 3.169	59			295	354	
0	Station Name: Conf.Int/Max Rel.Err: Min:	Network 0.99 / 0.03 5.5964	Class Name: Analyzed samples:	I/O-bound           163840           5.8574           Abort Measure	5.941 5.545 5.149 4.753 4.357 3.961 3.565 3.169 2.772 2.376 1.980	59		77 236	295	354	
2	Station Name: Conf.Int/Max Rel.Err: Min:	Network 0.99 / 0.03 5.5964	Class Name: Analyzed samples:	I/O-bound           163840           5.8574           Abort Measure	5.941 5.545 5.149 4.753 4.357 3.961 3.565 3.169 2.772 2.376 1.980 1.584	59		77 236	295	354	
2	Station Name: Conf.Int/Max Rel.Err: Min: Average value: 5:	Network 0.99 / 0.03 5.5964 7269	Class Name: Analyzed samples: Max:	I/O-bound           163840           5.8574           Abort Measure	5.941 5.545 5.149 4.753 4.753 3.961 3.565 3.169 2.772 2.376 1.980 1.584 1.188	59		77 236	295	354	
7	Station Name: Conf.Int/Max Rel.Err: Min: Average value: 5.	Network 0.99 / 0.03 5.5964 7269 graph to open it in a new window	Class Name: Analyzed samples: Max:	I/O-bound           163840           5.8574           Abort Measure	5.941 5.545 5.149 4.753 4.753 4.357 3.961 3.565 3.169 2.772 2.376 1.980 1.584 1.188 0.792 0.396	59		77 236	295	354	
0	Station Name: Conf.Int/Max Rel.Err: Min: Average value: 5. Double click on this ; Right-click to save it.	Network 0.99 / 0.03 5.5964 7269 graph to open it in a new window	Class Name: Analyzed samples: Max:	I/O-bound       163840       5.8574       Abort Measure       Hide instantaneous values	5.941 5.545 5.149 4.753 4.357 3.961 3.565 3.169 2.772 2.376 1.980 1.584 1.188 0.792				295	354	

Figure 22: System response times with PS and SJF policies

To answer question 4, it is sufficient to change the queue policy to DPS, with weights 2.0 and 1.0 for CPUbound and I/O bound jobs, respectively. With this setting, simulation produces the values in column DPS in the following table, that extends the previous one:

	FCFS+FCFS	PS+SJF	DPS+SJF
N <sub>CPU,CPU-bound</sub>	0.527	0.527	0.524
N <sub>I/O,I/O-bound</sub>	1.811	1.371	1.377
N <sub>CPU,I/O-bound</sub>	0.052	0.051	0.063
N <sub>I/O,CPU-bound</sub>	0.097	0.083	0.082
$R_{CPU-bound}$	3.126	3.048	2.980
$R_{I/O-bound}$	7.440	5.727	5.718

As first, checking  $R_{CPU-bound}$  we note that the value is 2.980 s, that is less than the 3 s requirement: consequently, this choice is not sufficient, because that value is affected by a 3% error, thus it is 2.980  $\pm$  0.03, that gives an upper bound of 3.01, and anyway would be too close to the deadline to be viable in practice, considering that it is an average value of a distribution. We also note that, notwithstanding the higher priority (that is assigning, with DPS, twice the CPU time to CPU-bound jobs with respect to I/O jobs), the improvement in the average number of CPU-bound jobs at the CPU is negligible, as well as the average number of I/O-bound ones, with respect to the PS case, as the contribution of the I/O bound ones to the CPU workload is small. The average number of I/O-bound jobs at the I/O is also unaltered, while the average number of CPU-bound ones is significantly higher. The impact of the new setting is also further, even if slightly, improving the value of  $R_{I/O-bound}$ .

## References

Harchol-Balter, M. (2013). Performance modeling and design of computer systems: Queueing theory in action. Cambridge University Press. doi: 10.1017/CBO9781139226424