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Waiting Experience in Open-Shop Service Networks: Improvements via Flow Analytics & Automation

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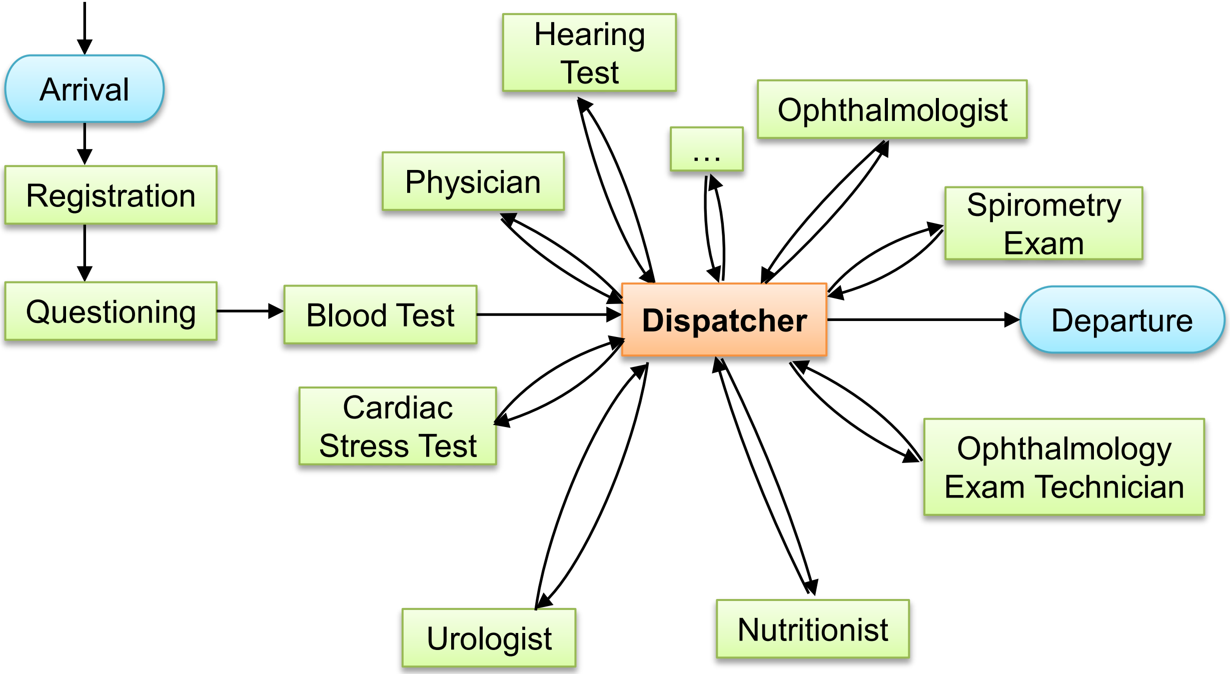
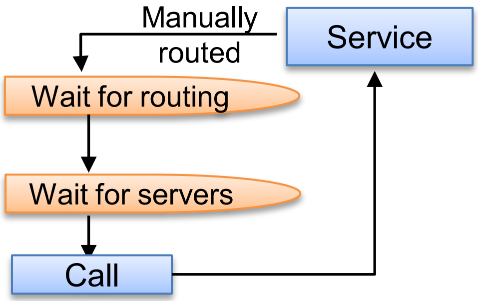
Open-Shop Service Network

Clinic's Open-Shop Service Network





Performance Evaluation

- **Macro, system-level**: total wait
- **Micro, station-level**:
  - **Global**: percentage of excessive waits
  - **Local**: dynamics of waits
  - COVID-19 era: physical distancing constraints

Background: IT Upgrade

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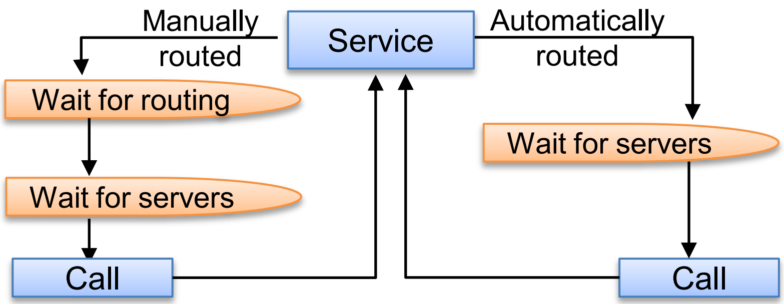
- Automated Customer Routing System (ACRS)
  - Only for EHS male customers
- SMS-Based Customer Paging System (SCPS)
  - Routing message: when customers are routed to next stations
  - Calling message: when servers call customers to examination rooms



Research Questions:
- To understand the (potential) operational benefits and drawbacks of IT in open-shop networks
- To explore how the clinic's new IT capabilities can improve customers' waiting experience

Outline

Impact of IT on open-shop networks

Stylized Model

Data-driven simulation

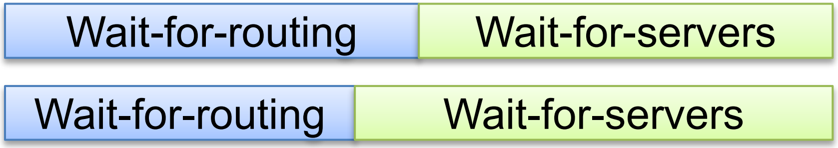
Literature Review

- **Priority and Routing Policies in Networks**
  - **Priority Policy**: Pinedo (2016), Hall (2012), …
  - **Routing Policy**: Averbakh et al. (2006), Chou and Lin (2017), Baron et al. (2017).
  - **Self-Interested Routing**: Arlotto et al. (2018).
- **Performance of Multi-Stage Services**
  - **Peak-End Rule**: Varey and Kahneman (1992), Fredrickson and Kahneman (1993).
  - **Multi-Stage Services**: Lee et al. (2012), Tong et al. (2016), Dixon and Thompson (2016), Das Gupta et al. (2016), …
  - **Open-Shop System**: Shtrichman et al.(2001), Baron et al. (2014, 2017).
- **IT and Healthcare Operations**: Bhargava and Mishra (2014), Lu et al. (2018), Westphal et al. (2020), …
- **Buffer Strategies**: Mandelbaum and Reiman (1998), Song et al. (2015), …

Impact of IT on Macro-Level Waits

Observation 1. (Impact of ACRS on Macro-Level Wait)

The ACRS redistributes the wait among wait-for-routing and wait-for-server times but *does not shorten* the total wait.



Observation 2. (Impact of SCPS on Macro-Level Wait)

The SCPS reduced calling frequencies and call times, but the reduction had *negligible impact* on improving waits.

Impact of ACRS – Descriptive Statistics

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Table 1. Descriptive Statistics of Male EHS Customers in Manually- and Auto-Routed Days

	System time (minutes)											
Days	Wait-for-routing		Wait-for-server		Call		Service		Break		Total	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Manual routing	12.89	10.05	101.55	35.95	3.54	4.04	68.18	14.69	2.22	8.29	188.38	41.20
Automated routing	5.07	6.02	107.45	36.78	4.17	5.29	66.71	15.52	1.34	5.65	184.75	39.96

Impact of ACRS – DID Analysis

Dependent variable:	Model 1 RoutingWT		Model 2 ServersWT		Model 3 TotalWT	
Auto	4.211***	(1.323)	-8.999**	(3.584)	-4.587	(3.754)
Gender	0.112	(1.283)	-22.375***	(4.326)	-21.129***	(4.531)
Auto×Gender	-11.906***	(1.501)	9.006**	(4.082)	-1.547	(4.276)
No. of stations	1.189***	(0.413)	4.074***	(1.399)	5.293***	(1.466)
Workload	0.214***	(0.064)	-0.314*	(0.176)	-0.050	(0.184)
Queue length						
Blood test			2.016***	(0.364)	1.851***	(0.381)
Breast surgeon			5.409***	(0.872)	5.611***	(0.913)
Cardiac stress test			5.881***	(0.323)	5.990***	(0.338)
Cardiologist			-0.589	(5.929)	-1.636	(6.211)
Gynecologist			4.516***	(0.948)	5.233***	(0.993)
Hearing test			5.249***	(0.477)	4.685***	(0.500)
Nutritionist			26.215***	(9.314)	27.665***	(9.756)
Ophthalmologist			3.583***	(0.353)	3.163***	(0.370)
Ophthalmology			2.141***	(0.395)	1.696***	(0.414)
Physician 1			4.302***	(0.384)	4.091***	(0.402)
Physician 2			0.676	(2.878)	-1.171	(3.015)
Questioning			1.707	(1.538)	0.830	(1.611)
Review with cardiologist			4.578*	(2.503)	4.902	(2.622)
Spirometry			4.500***	(0.510)	3.721***	(0.534)
Urologist			-0.088	(6.798)	-0.098	(7.121)
No. of servers (multi-servers stations)						
Blood test			4.466***	(1.404)	4.961***	(1.471)
Cardiac stress test			-3.884***	(1.002)	-4.460***	(1.050)
Physician 1			-0.526	(0.973)	-1.540	(1.019)
Review with cardiologist			3.082	(2.058)	2.873	(2.156)
Observations	742		742		742	
Adjusted R^2	0.264		0.696		0.685	

Notes. Standard errors are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

- Only male EHS customers are automatically routed.
- **Treatment** group: male EHS customers
- **Control** group: female EHS customers

- Model 1: *negative* correlation between $Auto \times Gender$ and wait-for-routing time
- Model 2: *positive* correlation between $Auto \times Gender$ and wait-for-servers time
- Model 3: *no significant* correlation between $Auto \times Gender$ and total wait

Impact of SCPS- Station Performance

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Table 2. Impact of the SCPS on Number of Calls and Call Time per Customer at Stations

	Number of calls per customer					Call time per customer					
	Year 2016		Year 2019		p-value	Year 2016		Year 2019		% change in call time	p-value
	Mean	Std	Mean	Std		Mean	Std	Mean	Std		
Blood test	2.26	1.83	1.45	1.02	<0.001	00:30	01:22	00:14	00:42	-52.55%	<0.001
Breast surgeon	1.86	1.38	1.25	0.73	<0.001	00:35	01:51	00:28	02:02	-19.41%	0.316
Cardiac stress test	2.62	2.25	1.76	1.46	<0.001	00:48	01:44	00:36	01:30	-25.25%	<0.001
Cardiologist	2.11	1.97	1.68	1.01	0.010	01:17	02:49	00:49	01:59	-36.68%	0.044
Gynecologist	1.83	1.59	1.55	1.38	0.003	00:54	02:27	00:43	02:20	-19.92%	0.222
Hearing test	1.89	1.72	1.59	1.03	<0.001	00:59	02:10	00:49	01:45	-16.90%	0.042
Ophthalmologist	1.60	1.24	1.80	1.76	<0.001	00:34	01:46	00:29	01:18	-13.10%	0.245
Ophthalmology	1.97	1.71	1.71	1.36	<0.001	00:54	01:59	00:37	02:23	-32.32%	<0.001
Physician	2.54	2.61	1.79	1.60	<0.001	01:15	03:20	00:34	01:38	-54.82%	<0.001
Review with cardiologist	1.70	1.41	1.61	0.83	0.370	00:38	01:35	00:26	01:28	-30.59%	0.115
Spirometry	2.85	2.54	1.45	1.16	<0.001	00:43	01:35	00:32	01:32	-25.73%	0.001

Impact of SCPS - Simulation

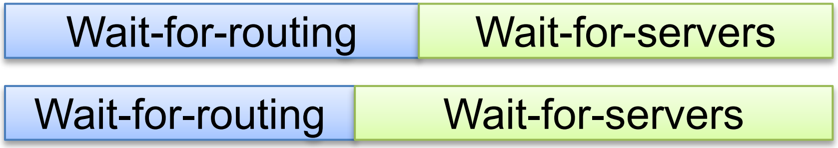
Table 3. Overall effects of the SCPS in simulations

Data	Call time (min)	Macro-level wait (min)		Micro-level > 20 min (%)	Operating hours
		Mean	std		
Year 2016 empirical data	6.94	101.18	49.52	14.10%	6.95
After 29.75% reduction in call time	4.87	102.06	54.25	12.76%	6.77

Impact of IT on Macro-Level Waits

Observation 1. (Impact of ACRS on Macro-Level Wait)

The ACRS redistributes the wait among wait-for-routing and wait-for-server times but *does not shorten* the total wait.



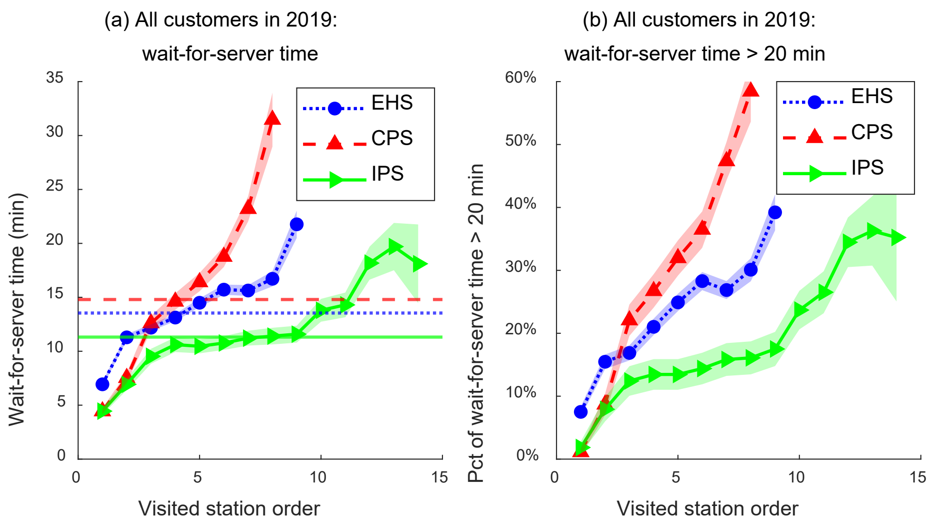
Observation 2. (Impact of SCPS on Macro-Level Wait)

The SCPS reduced calling frequencies and call times, but the reduction had *negligible impact* on improving waits.

Dynamics of Local Micro-Level Measures

Observation 3.

Under the current routing and priority policies, the micro-level performance measures, wait-for-server and the probability of excessive waits per station, increase as the service process progresses.



Station-level FCFS priority policy ignores customers *system-level* information.

Priority policies that consider *system-level* information

Unintended Idleness (UI)

- **Unintended idleness (UI):** both customer and server are waiting unproductively.
- **Server UI**
  - The probability of each server to experience UI.
  - Average server UI are 37.83% and 40.46% in manually- and auto-routed days.
- **Customer UI**
  - The percentage of customers whose waiting could be reduced by delaying their routing decisions by a few minutes.
  - Probability that routing decisions could be improved if the decisions are delayed for 3 minutes is 2.92% and 3.86% in manually- and auto-routed days.

Postpone routing decisions → buffer strategy

Observation 4.

The ACRS's immediacy may lead to information loss for decision-making, which reduces the system's flexibility and causes unintended idleness for both servers and customers.

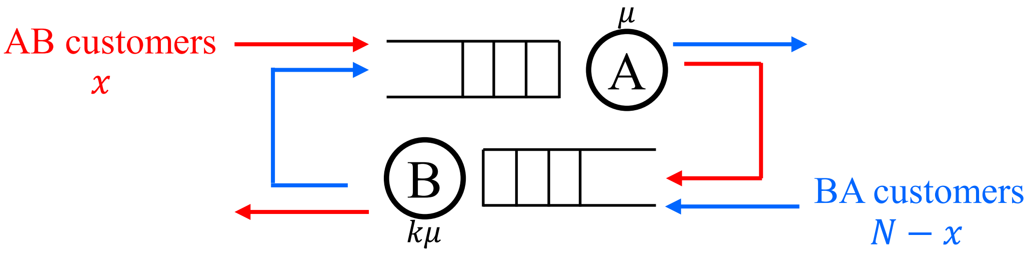
Outline

Impact of IT on open-shop networks:
- Negligible impact on macro-level wait.
- Deterioration of micro-level waits:
  - FCFS priority policy
  - Immediacy of ACRS

- System-level priority policies
- Postpone routing decisions

Stylized Model

Two-Station Open-Shop Network



- Deterministic service times: $^1/_\mu, ^1/_{k\mu}, k > 1$
- N Customers
- Dispatcher's **routing decision**: x customers route AB
- **Performance measures**
  - Macro-level: total wait
  - Micro-level:
    - Wait at last (second) stations
    - Percentage of excessive waits at stations
- **Priority policy:** station-level FCFS vs. advanced customer priority (ACP) policy

FCFS Priority Policy

Proposition 1. [Macro-level total wait under the FCFS policy]
Given a routing policy of x AB customers and $N-x$ BA customers, customers' average total wait in the network is

$$t_F(x) = \begin{cases} \frac{N-1}{2\mu} & if\ x=0 \\ \frac{-(1+k)x^2+(2N-k+1)x-N(2-(N-1)k)}{2N\mu k} & if\ 1 \le x \le \frac{N-1}{k} \\ \frac{x^2+(3k-2N-1)x+(k^2-k+1)N^2+(1-2k-k^2)N}{2N\mu k(k-1)} & If\ \frac{N-1}{k} \le x \le N-k \\ \frac{kN^2-(2+k)N+2x}{2N\mu k} & If\ x > N-k \end{cases},$$

where the error term $\varepsilon = -\frac{(k-1)a^2+(2N-2x-k-1)a}{2\mu k} - \frac{(N-x)(N-x-k-1)}{2k\mu(k-1)}$ and $a = \left\lfloor \frac{N-x-1}{k-1} \right\rfloor$.

Proposition 2. [Micro-level wait under the FCFS policy]
Given a routing policy of x AB customers and $N-x$ BA customers,
(i) Average station-level waits at customers' first and second stations are $t_{F,1}(x) = \frac{(k+1)x^2+(1-k-2N)x+N(N-1)}{2Nk\mu}$ and

$$t_{F,2}(x) = \begin{cases} \frac{(N-1)(k-1)}{2k\mu} & if\ x=0 \\ \frac{-2(1+k)x^2+4Nx+N^2k-N-Nk-N^2}{2N\mu k} & if\ 1 \le x \le \frac{N-1}{k} \\ \frac{(N-x)\left((k^2-2)x-(1-N)k^2-(2N+1)k+2N\right)}{2N\mu k(k-1)} + \frac{\varepsilon}{N} & If\ \frac{N-1}{k} \le x \le N-k \\ \frac{N-x}{2N\mu k}\left((k+1)x-(N+k-Nk+1)\right) & If\ x > N-k \end{cases}$$

(ii) The percentage of station-level excess waits $p_F(x,L)$ is nondecreasing in x for $x < \frac{X_1}{k}$ or $x \ge X_1$, and nonincreasing in x for $\frac{X_1}{k} \le x < X_1$, where $X_1 \equiv N - k\mu L - 1$.

Advanced Customer Priority Policy

Proposition 3. [Macro-level total wait under the ACP policy]
Given a routing policy of x AB customers and $N-x$ BA customers, for $k \in \{2,3,\ldots\}$, customers' average total wait in the network is

$$t_A(x) = \begin{cases} \frac{N-1}{2\mu} & if\ x = 0 \\ \frac{kN^2-(2+k)N+2x}{2N\mu k} & if\ 1 \le x \le N \end{cases}.$$

Proposition 4. [Micro-level wait under the ACP policy]
Given a routing policy of x AB customers and $N-x$ BA customers,

(i) Average station-level waits at customers' first and second stations are

$$t_{A,1}(x) = \begin{cases} \frac{N(N-1)}{2Nk\mu} & if\ x = 0 \\ \frac{(1-k)x^2+(k-1)(2N+1)x+(N+1)(N-2k)}{2N\mu k} & if\ 1 \le x < N-k \\ \frac{(1-k)x^2+(k-2N+2Nk+1)x+N(N-2k-1)}{2N\mu k} & if\ N-k \le x \le N \end{cases}$$ and $$t_{A,2}(x) = \begin{cases} \frac{(N-1)(k-1)}{2k\mu} & if\ x = 0 \\ \frac{(k-1)x^2+(2N-k-2Nk+3)x+2k-3N+N^2k+Nk-N^2}{2N\mu k} & if\ 1 \le x \le N-k \\ \frac{(k-1)(N^2-2Nx+N+x^2-x)}{2N\mu k} & if\ N-k+1 \le x \le N \end{cases}.$$

(ii) The percentage of station-level excess waits $p_A(x, L)$ has the following properties:

- For $L \le \frac{N-1}{k\mu}$, $p_A(x, L)$ is weakly decreasing in x for $x \le X_1 + 1$, and weakly increasing in x for $x > X_1 + 1$.
- For $L > \frac{N-1}{k\mu}$, $p_A(0, L) > p_A(x, L)$, and $p_A(x, L)$ is weakly increasing in x for $x \ge 1$.

Comparison: FCFS vs. ACP

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Proposition 5. [Comparison of macro- and micro-level waits under FCFS and ACP policies]

Suppose the population size is large (i.e., $N > k^2 + 2k - 3$), comparing to the FCFS policy, the ACP policy weakly reduces

(i) The average macro-level wait: $t_A(x) \leq t_F(x)\ \forall x$.

(ii) The average wait at the second (last) station: $t_{A,2}(x) \leq t_{F,2}(x)\ \forall x$.

(iii) The micro-level approximated percentage of excessive waits, $\tilde{p}_A(x, L) \leq \tilde{p}_F(x, L)$,

- Under any routing decision, when $k = 2$ and $L \leq \frac{N-1}{2\mu}$, or when $k \geq 3$ and $\frac{k^2-2}{k\mu} \leq L \leq \frac{N-k}{k\mu}$ or $\frac{(k-1)N-k}{k\mu(k-1)} \leq L \leq \frac{N-1}{2\mu}$.
- Under certain routing decision, when $k = 2$, $x \geq \mu L + 1$ for $L > \frac{N-1}{2\mu}$; when $k \geq 3$, $x \leq \tilde{X}_1$ and $x \geq \tilde{X}_2$ for $L < \frac{k-1}{\mu}$, $\tilde{X}_0 \leq x \leq \tilde{X}_1$ and $x \geq \tilde{X}_2$ for $\frac{k-1}{\mu} < L < \frac{k^2-2}{k\mu}$, $x \geq \tilde{X}_2$ for $\frac{N-k}{k\mu} < L < \frac{(k-1)N-k}{k\mu(k-1)}$, $x \leq \tilde{X}_3$ and $x \geq \mu L + 1$ for $\frac{N-1}{2\mu} < L < \frac{(k-1)(N-1)}{k\mu}$, $x \geq \mu L + 1$ for $L \geq \frac{(k-1)(N-1)}{k\mu}$, where $\tilde{X}_0 \in \left(1, \frac{X_1}{k}\right]$, $\tilde{X}_1 \in \left(\frac{X_1}{k}, X_1\right]$, $\tilde{X}_2 \in (X_1, N - \mu L]$, and $\tilde{X}_3 \in (1, N - \mu L]$.

Macro-Level: Total Wait

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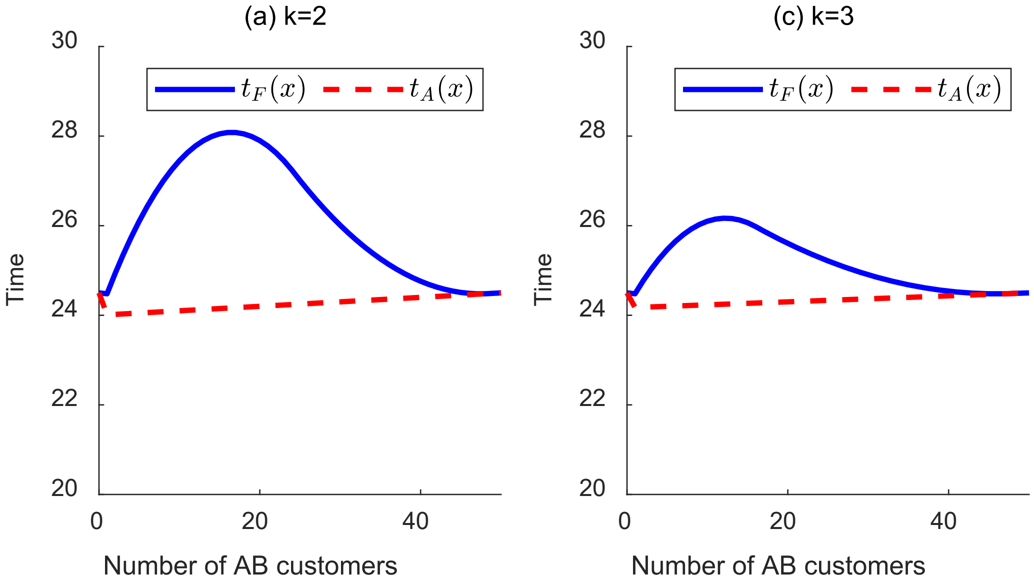
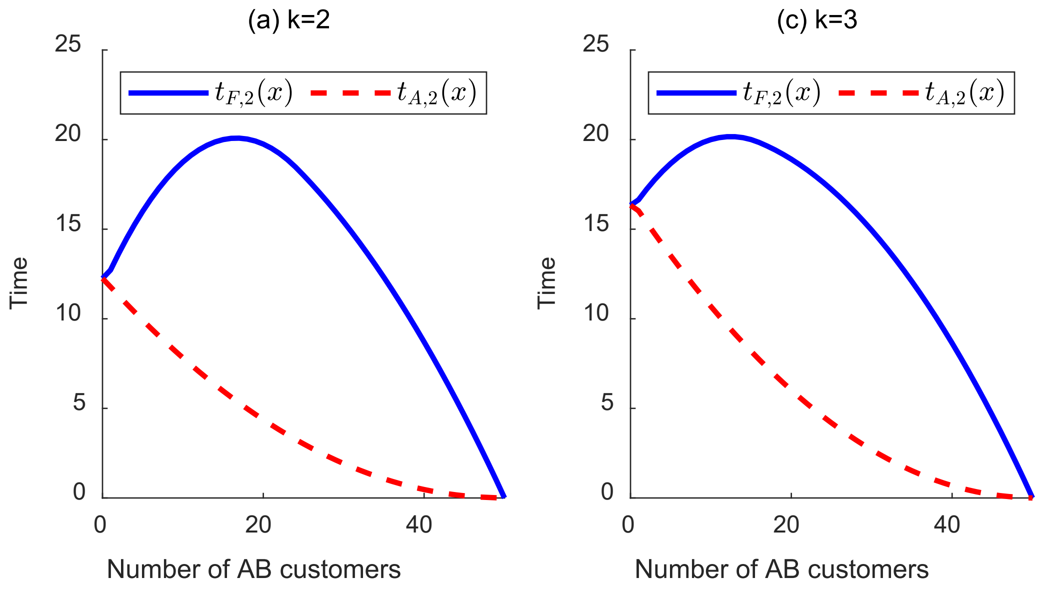


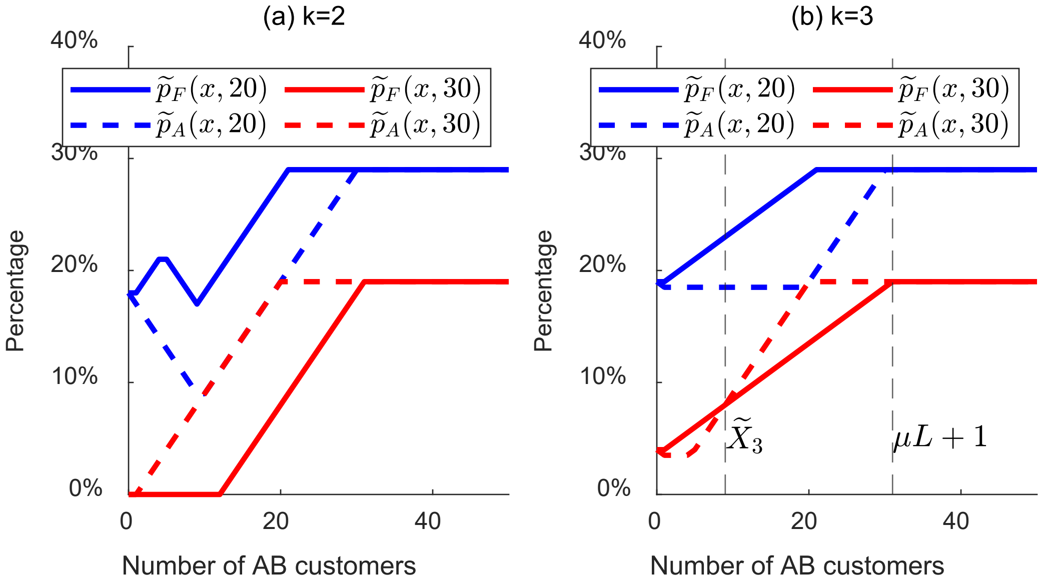
Advanced customer priority (ACP) policy outperforms the FCFS policy from the macro perspective.

Local Micro-Level: Wait at Last Station



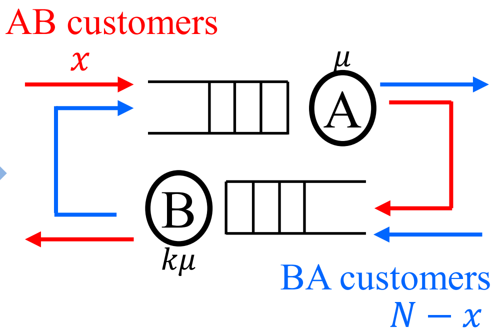
Advanced customer priority (ACP) policy reduces customers' waits at their last station.

Global Micro-Level: Excessive Waits



Advanced customer priority (ACP) policy reduces the percentage of station-level excessive waits under certain circumstances.

Outline



Impact of IT on open-shop networks:

- Negligible impact on macro-level wait.
- Deterioration of micro-level waits:
  - FCFS priority policy
  - Immediacy of ACRS

Two-Station Open-Shop Network

- ACP outperforms FCFS
- Buffer strategy

Data-driven simulation

$k\mu$

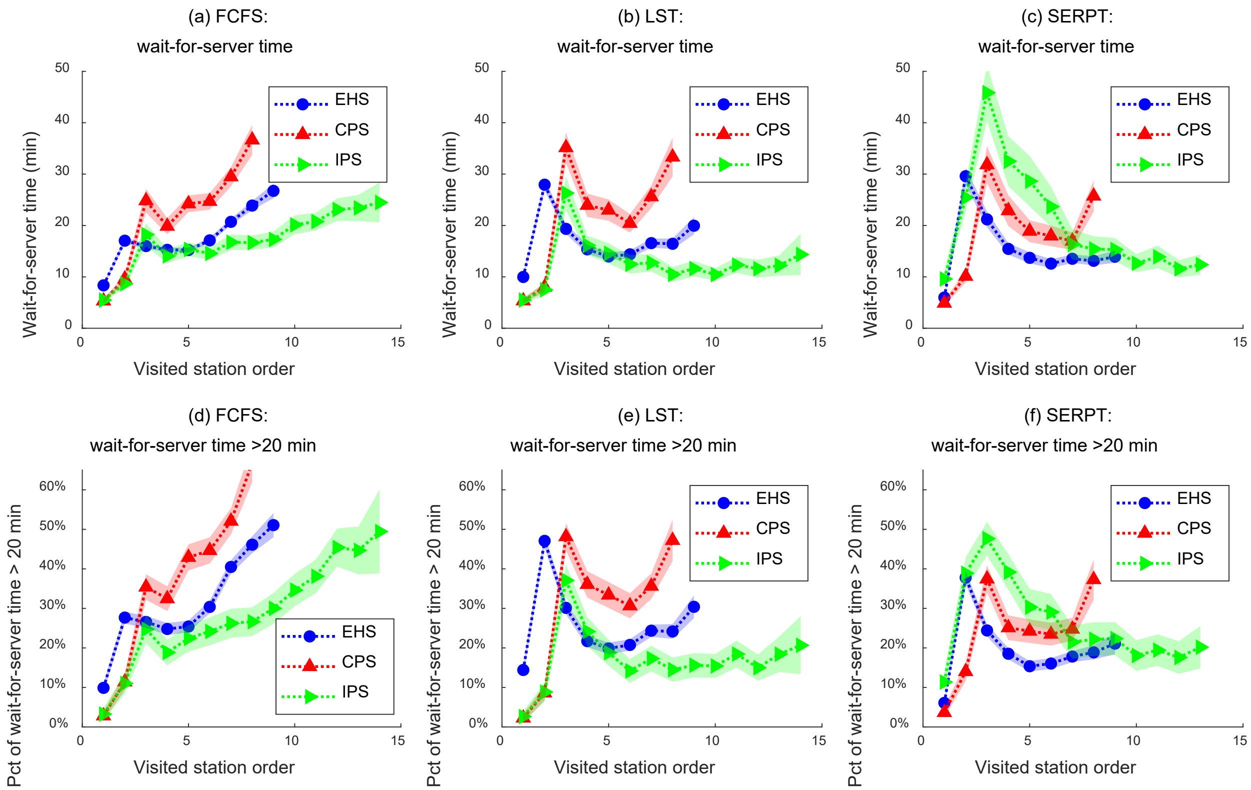
- System-level priority policies
- Postpone routing decisions

Simulation: Macro-Level Wait

Priority Policies		Performance Measures					
		Macro-level wait (min)					
		Wait-for-routing		Wait-for-server		Total	
		Mean	Std	Mean	Std	Mean	Std
Station-level	First-come-first-served (FCFS)	11.38	10.10	103.37	54.18	114.75	58.17
Advanced customers priority (ACP) policy	Longest system time first (LST)	11.38	10.10	99.96	56.47	111.34	58.29
	Shortest expected remaining processing time first (SEPRT)	11.38	10.10	90.88	72.41	102.26	75.97

ACP policies effectively shorten the average overall wait.

Simulation: Micro-Level Wait



ACP policies reduce delays as customers progress towards the end of their visits.

Simulation: Buffer Strategy

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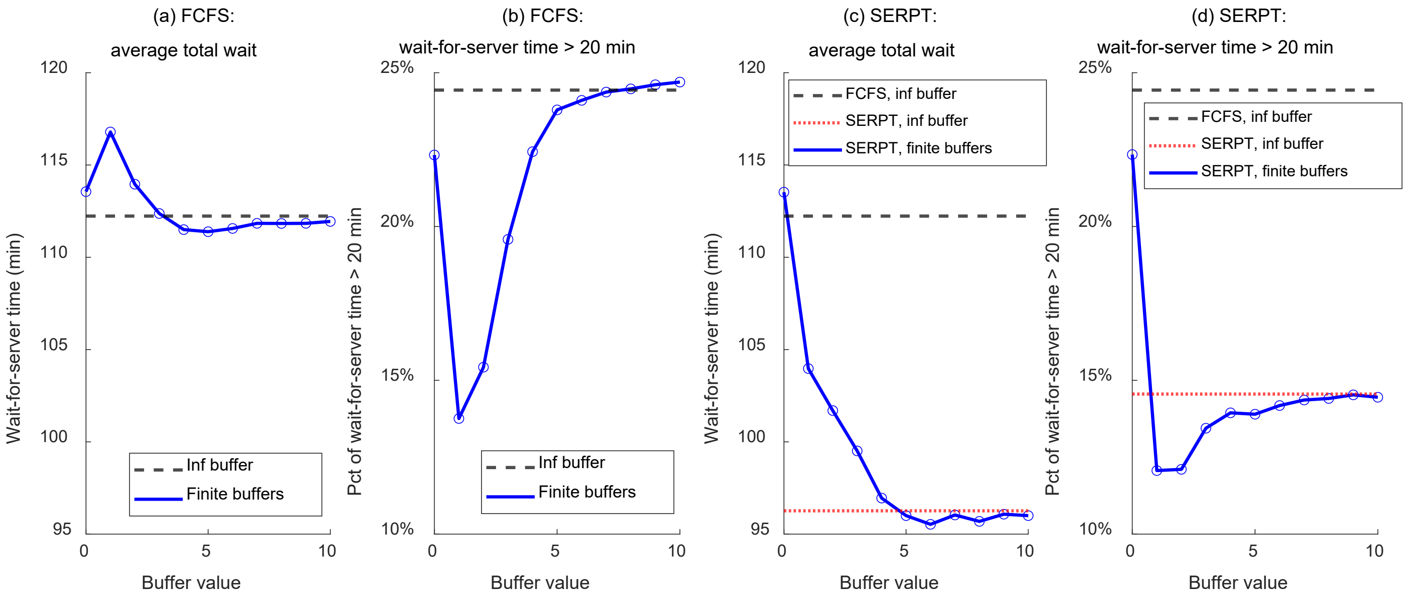
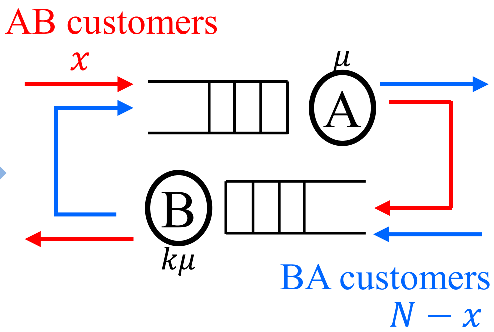
Customers are routed to stations only if stations' queue lengths are below the buffer value.



ACP policies with finite buffer improve both macro- and micro-level performance measures.

Summary



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- ACP outperforms FCFS
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Data-driven simulation: priority-based buffer strategy improves both macro- and micro-level measurements

- System-level priority policies
- Postpone routing decisions