QED Q's

Telephone Call/Contact Centers

Service Engineering

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Supporting Material (Downloadable)

M. "Call Centers: Research Bibliography with Abstracts." Version 7, December 2006.

Gans, Koole, and M.: "Telephone Call Centers: Tutorial, Review and Research Prospects." *MSOM, 2003*. (Sec. 3-4, possibly 2.)

Brown, Gans, M., Sakov, Shen, Zeltyn, Zhao: "Statistical Analysis of a Telephone Call Center: A Queueing-Science Perspective." JASA, 2005.

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Whitt's website: both the ED and QED regimes.

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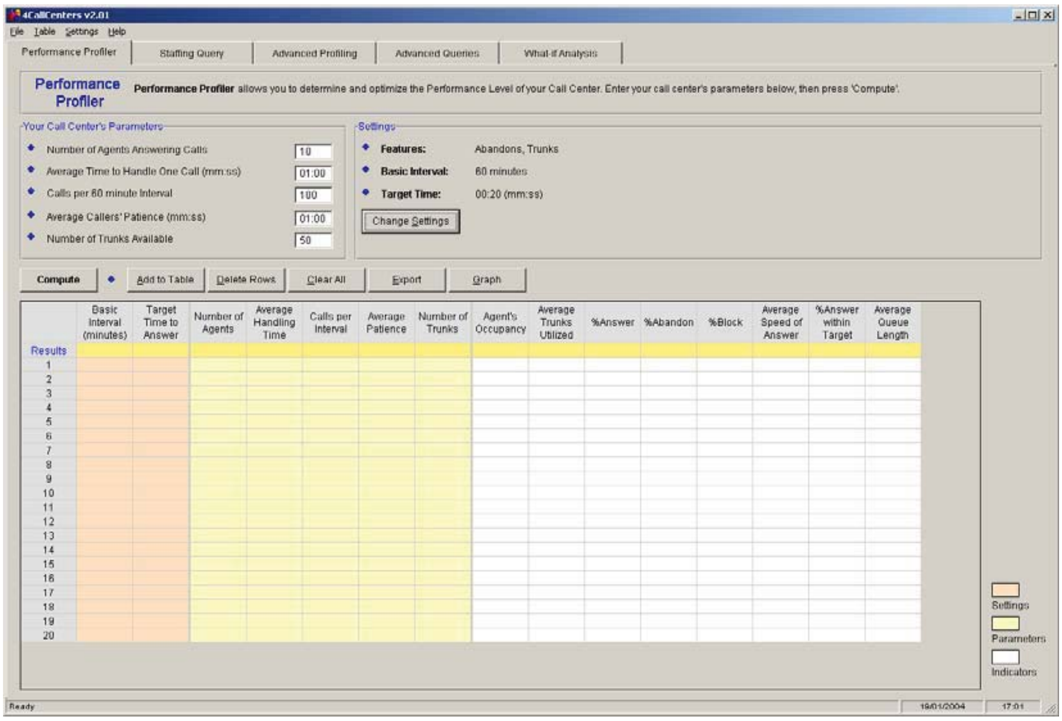
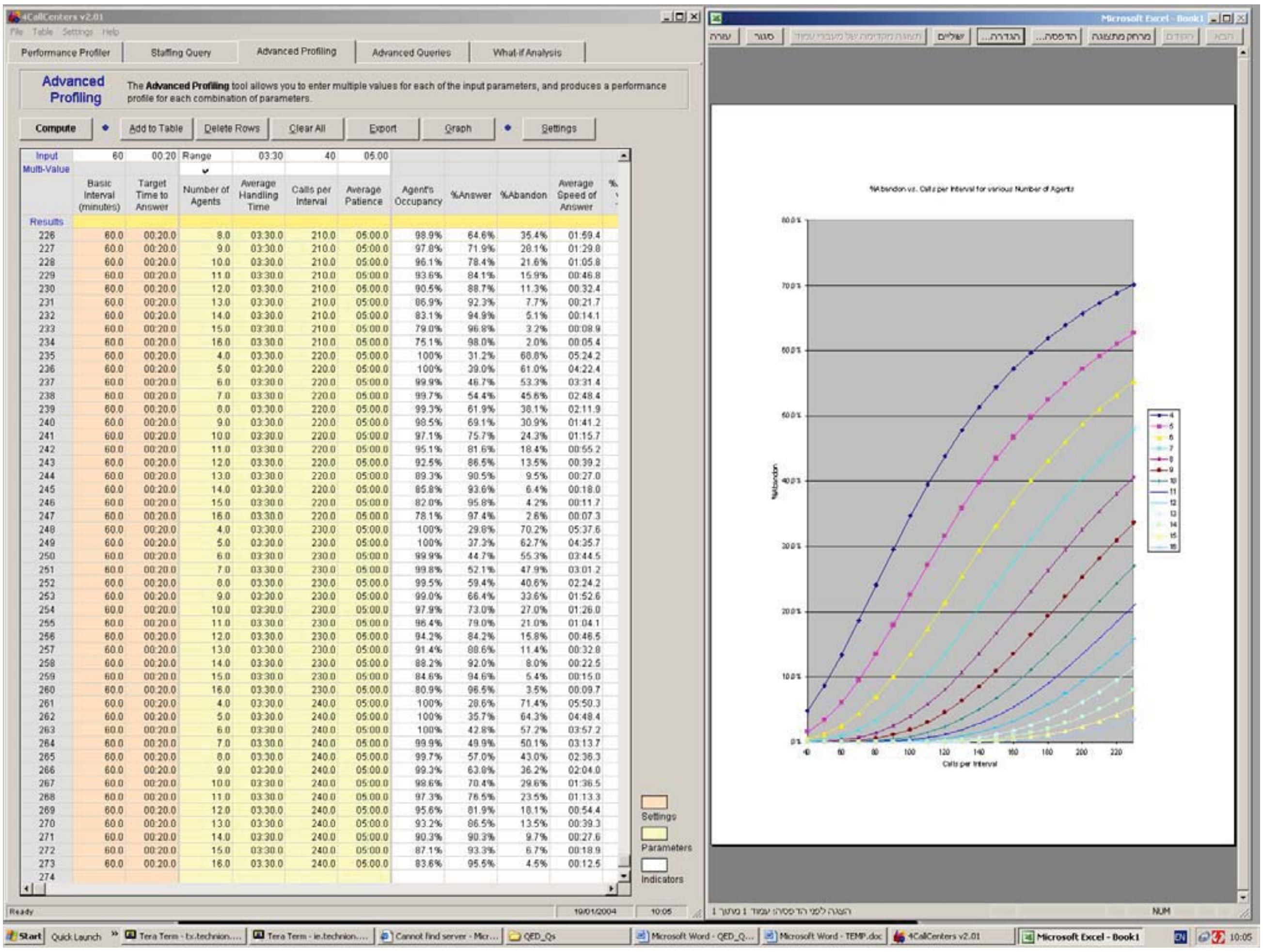
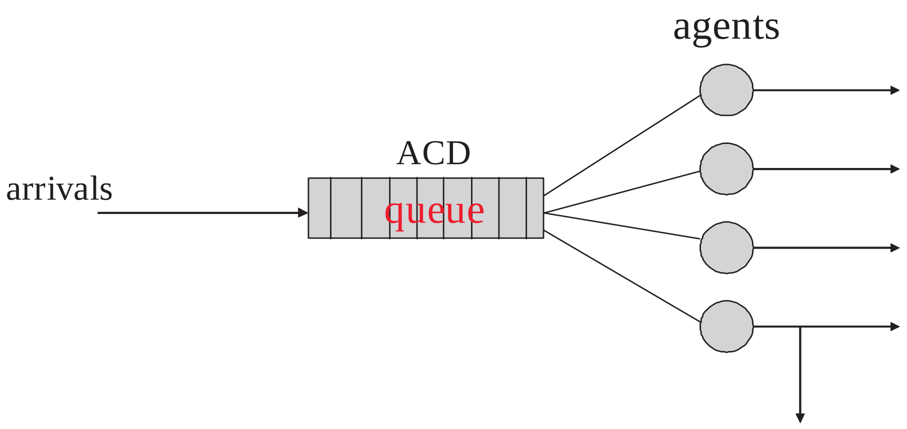
4CallCenters: Personal Tool for WFM

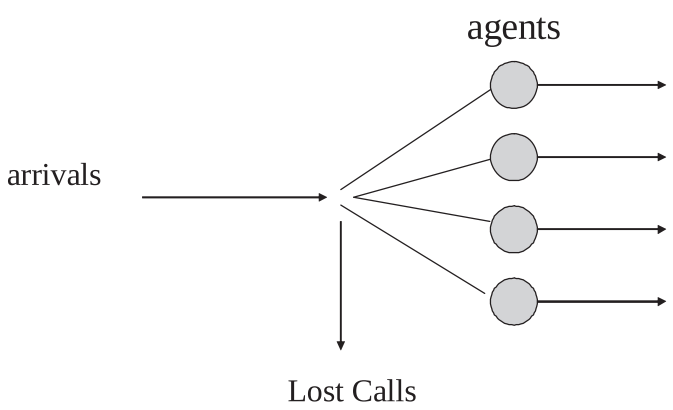




Erlang-C (M/M/N): # Agents



Erlang-B (M/M/N/N): # Trunks



“First National City Bank Operating Group”

“By tradition, the method of meeting increased work load in banking is to increase staff. If an operation could be done at a rate of 80 transactions per day, and daily load increased by 80, then the manager in charge of that operation would hire another person; it was taken for granted…” (Harvard Case)

1:1 Staffing - Classical IE (Erlang-C)

8 transactions per hour ⇒ **E(S)** = **7:30 minutes** (=**M**)

λ/hr	N Agents	ρ = OCC	L_q = Que	W_q = ASA
8	2	50%	0.3	2:30
16	3	67%	0.9	3:20
24	4	75%	1.5	3:49
32	5	80%	2.2	4:09

λ/hr	N	ρ = OCC	L_q = Que	W_q = ASA
72	10	90%	60	5:01
120	16	93.8%	11	5:29
400	51	98%	42	6:18
640	81	98.8%	70	6:32
1,280	161	99.4%	145	6:48
2,560	321	99.7%	299	7:00
3,600	451	**99.8%**	423	**7:04**
↓	↓	↓	↓	↓
∞	∞	**1**	∞	**7:30 !**

$\Rightarrow$ **Efficiency-Driven Operation** **(Heavy-Traffic)**

Intuition: at 100% utilization, N servers = 1 fast server

Indeed $\overline{W_q} \approx \overline{W_q} \mid W_q > 0 = \frac{1}{N} \cdot \frac{\rho_N}{1-\rho_N} \cdot E(S) \rightarrow E(S) = 7{:}30$ **!**

since $\rho_N = \frac{\lambda_N \times E(S)}{N} = \frac{8(N-1) \times 7.5/60}{N} = \frac{N-1}{N} = 1 - \frac{1}{N}$

$N(1-\rho_N) = 1 \quad , \quad \rho_N \rightarrow 1 .$

What can be achieved

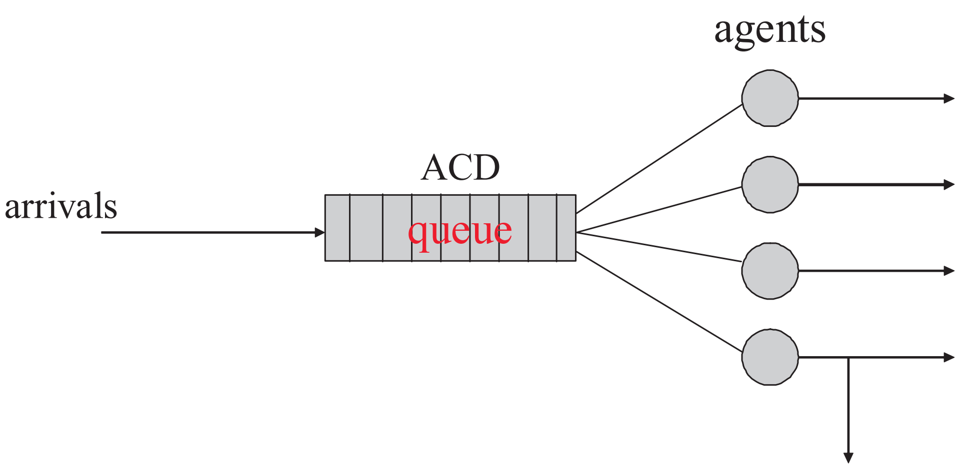
At what cost

Copy of Summary Interval - Order PK

Date: 7/7/97
Split/Skill: Order PK

Time	Avg Speed Ans (W)	Avg Aban Time	ACD Calls (λ)	Avg ACD Time (1/μ)	Avg ACW Time	Aban Calls (#Aban)	% ACD Time	% Ans Calls	Avg Pos Staff (N)	Calls Per Pos	%Serv Lev	%Aux Time	%ACW Time	%ACD Time (P)
Totals	:00:02	:00:28	10456	:03:47	:00:25	46	53	98	70	149		8		
12:00 AM*	:00:00	:00:00	26	:04:31	:00:02	1	76	51	7	4	51	2	16	61
12:30 AM*	:00:03	:04:10	14	:07:27	:00:33	1	89	52	5	3	48	1	26	63
1:00 AM*	:00:00		9	:04:54	:11:29	0	91	90	1	7	90	0	26	65
5:30 AM*			0			0	0		0	0		33	0	0
6:00 AM*	:00:00		12	:03:21	:00:19	0	21	100	7	2	100	9	2	19
6:30 AM*	:00:00		27	:02:51	:00:20	0	32	100	14	2	100	5	3	29
7:00 AM*	:00:00		62	:03:34	:00:15	0	38	100	21	3	100	13	4	34
7:30 AM*	:00:00		93	:03:11	:00:34	0	36	100	30	3	100	7	4	32
8:00 AM*	:00:00		120	:03:37	:00:40	0	39	100	47	3	100	8	6	33
8:30 AM*	:00:00		193	:03:04	:00:14	0	44	100	61	3	100	10	7	37
9:00 AM*	:00:01		293	:03:25	:00:25	0	54	99	75	4	97	9	7	47
9:30 AM*	:00:02	:00:06	381	:03:45	:00:22	2	60	97	91	4	93	8	8	52
Peak → 10:00 AM*	:00:02	:00:01	416	:03:49	:00:26	1	63	97	94	4	96	5	8	55
10:30 AM*	:00:00		349	:03:35	:00:33	0	52	99	96	4	99	6	8	44
11:00 AM*	:00:00		352	:03:50	:00:27	0	51	100	102	3	100	7	8	45
11:30 AM*	:00:00		349	:03:44	:00:18	0	49	100	97	4	100	8	5	45
12:00 PM*	:00:01		354	:03:59	:00:18	0	52	95	95	4	95	8	5	47
12:30 PM*	:00:00		336	:03:38	:00:21	0	52	99	97	3	99	9	8	46
1:00 PM*	:00:00		347	:03:53	:00:32	0	51	99	98	4	99	11	6	44
1:30 PM*	:00:00		368	:03:52	:00:14	0	56	99	99	4	99	11	7	60
2:00 PM*	:00:01		393	:03:55	:00:17	0	51	100	106	4	100	10	5	46
2:30 PM*	:00:00		403	:03:58	:00:13	0	54	100	112	4	100	10	4	50
3:00 PM*	:00:00	:00:04	410	:04:02	:00:16	1	57	98	110	4	98	8	5	51
3:30 PM*	:00:00		347	:03:59	:00:14	0	60	100	100	3	100	7	5	45
4:00 PM*	:00:00		382	:03:48	:01:37	0	64	100	98	4	100	6	7	47
4:30 PM*	:00:00		379	:03:41	:00:19	0	55	99	97	4	99	8	5	50
5:00 PM*	:00:00		411	:03:53	:00:19	0	53	100	109	4	100	9	5	46
5:30 PM*	:00:01		387	:03:58	:00:19	0	58	99	98	4	99	10	6	51
6:00 PM*	:00:01	:00:21	371	:03:28	:00:25	1	53	98	91	4	96	9	6	47
6:30 PM*	:00:00		280	:03:26	:00:13	0	41	100	90	3	100	8	4	37
7:00 PM*	:00:00		289	:03:24	:00:17	0	42	100	78	3	100	9	5	38

Erlang-C = M/M/N



Rough Performance Analysis

Peak 10:00 – 10:30 a.m., with 100 agents

400 calls

3:45 minutes average service time

2 seconds ASA (Average Speed of Answer)

Rough Performance Analysis

Peak 10:00 – 10:30 a.m., with 100 agents

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2 seconds ASA

Offered load $R = \lambda \times E(S)$

$= 400 \times 3{:}45 = 1500$ min./30 min.

$= 50$ Erlangs

Occupancy $\rho = R/N$

$= 50/100 = 50\%$

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$= 50$ Erlangs

Occupancy $\rho = R/N$

$= 50/100 = 50\%$

⇒ **Quality-Driven Operation** (Light-Traffic)

⇒ Classical Queueing Theory

Above: $R = 50$, $N = R + 50$, ≈ **all served immediately**.

Rule of Thumb: $N = \lceil R + \delta R \rceil$, $\delta > 0$ service-grade.

Quality-driven: 100 agents, 50% utilization

$\Rightarrow$ **Can** increase offered load - **by how much?**

Erlang-C **N=100 E(S) = 3:45 min.**

$\underline{\lambda}$**/hr**	$\underline{\rho}$	**E(W_q) = ASA**	**% Wait = 0**
800	50%	0	100%

Quality-driven: 100 agents, 50% utilization

$\Rightarrow$ **Can** increase offered load - **by how much?**

Erlang-C **N=100 E(S) = 3:45 min.**

$\underline{\lambda}$/hr	$\underline{\rho}$	$E(W_q)$ = ASA	% Wait = 0
800	50%	0	100%
1400	87.5%	0:02 min.	88%
1550	96.9%	0:48 min.	35%
1580	98.8%	2:34 min.	15%
1585	**99.1%**	**3:34 min.**	12%

Quality-driven: 100 agents, 50% utilization

$\Rightarrow$ **Can** increase offered load - **by how much?**

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1585	**99.1%**	**3:34 min.**	12%

$\Rightarrow$ **Efficiency-driven Operation (Heavy Traffic)**

$$\overline{W_q} \approx \overline{W_q} \mid W_q > 0 = \frac{1}{N} \cdot \frac{\rho_N}{1-\rho_N} \cdot E(S) \to E(S) = 3{:}45\ \textbf{!}$$

$$N(1-\rho_N) = 1 \quad , \quad \rho_N \to 1$$

Above: R = 99, N = R + 1, $\approx$ **all delayed**.

Rule of Thumb: $N = \lceil R + \gamma \rceil$, $\gamma > 0$ **service grade**.

Changing N (**Staffing**) in Erlang-C

			E(S) = 3:45	
λ/hr	N	OCC	ASA	% Wait = 0
1585	100	99.1%	3:34	12%

Changing N (**Staffing**) in Erlang-C

			E(S) = 3:45	
λ/hr	N	OCC	ASA	% Wait = 0
1585	100	99.1%	3:34	12%
1599	**100**	99.9%	**59:33**	0%

Changing N (**Staffing**) in Erlang-C

E(S) = 3:45

λ/hr	N	OCC	ASA	% Wait = 0
1585	100	99.1%	3:34	12%
1599	**100**	99.9%	**59:33**	0%
1599	**100+1**	98.9%	**3:06**	13%
1599	102	98.0%	1:24	24%
1599	105	**95.2%**	0:23	**50%**

Changing N (**Staffing**) in Erlang-C

E(S) = 3:45

λ/hr	N	OCC	ASA	% Wait = 0
1585	100	99.1%	3:34	12%
1599	**100**	99.9%	**59:33**	0%
1599	**100+1**	98.9%	**3:06**	13%
1599	102	98.0%	1:24	24%
1599	105	**95.2%**	0:23	**50%**

⇒ **New Rationalized Operation**

Efficiently driven, in the sense that OCC > 95%;

Quality-Driven, 50% answered **immediately**

QED Regime = Quality- and Efficiency-Driven Regime

Above: R = 100, N = R + 5, 50% delayed.

$\sqrt{\cdot}$ **Safety-Staffing** $\mathbf{N} = \lceil R + \beta\sqrt{R}\,\rceil, \quad \beta > 0$.

QED Theorem (**Halfin-Whitt**, 1981)

Consider a sequence of M/M/N models, **N=1,2,3,…**

Then the following **3 points of view** are equivalent:

- Customer $\lim_{N\to\infty} P_N\{\text{Wait} > 0\} = \alpha, \qquad 0 < \alpha < 1;$
- Server $\lim_{N\to\infty} \sqrt{N}(1-\rho_N) = \beta, \qquad 0 < \beta < \infty;$
- Manager $N \approx R + \beta\sqrt{R}, \qquad R = \lambda \times \mathrm{E(S)}$ large;

Here $$\alpha = \left[1 + \frac{\beta\phi(\beta)}{\varphi(\beta)}\right]^{-1},$$

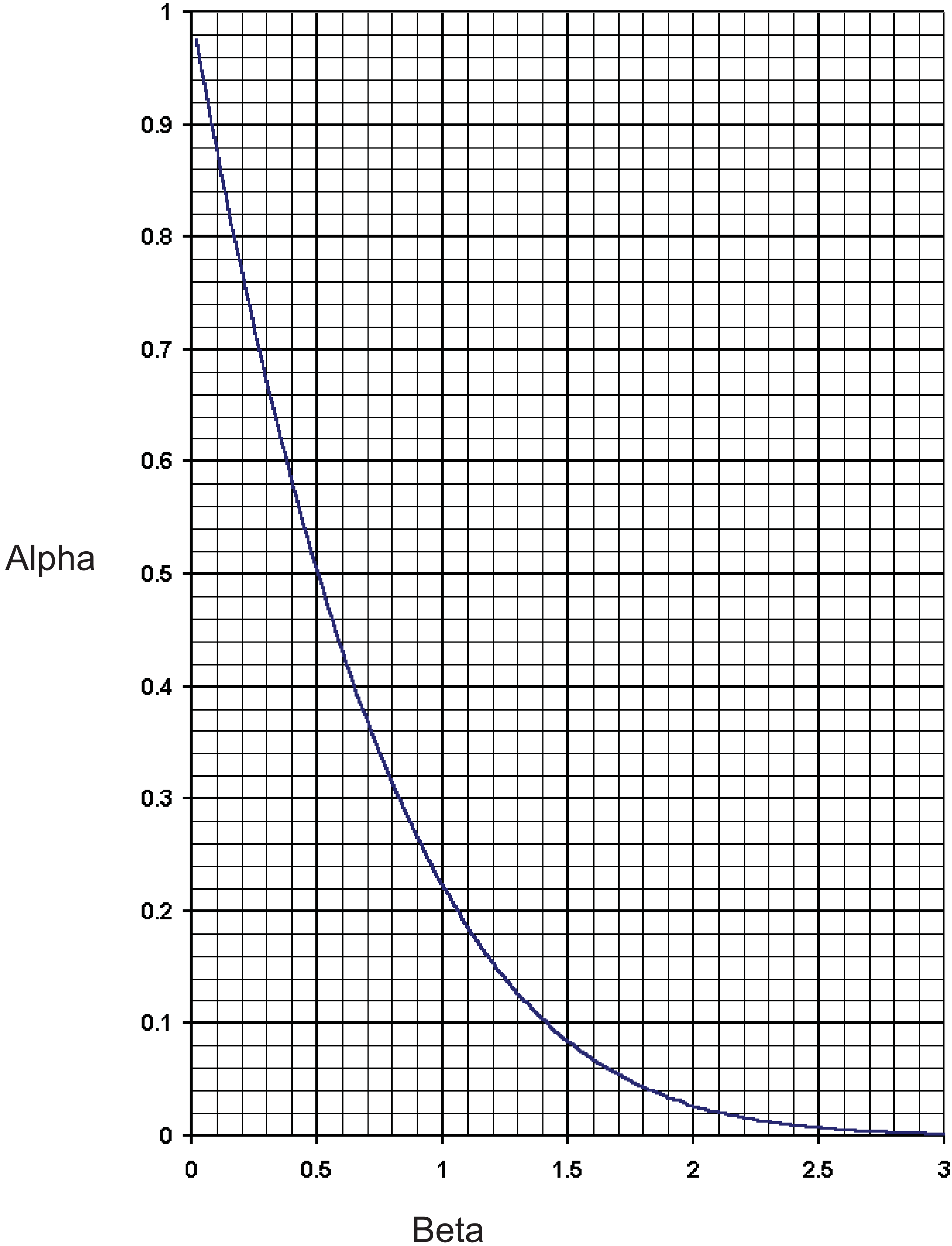
where $\varphi(\cdot)/\phi(\cdot)$ is the standard normal density/distribution.

Extremes:

Everyone waits: $\alpha = 1 \quad \Leftrightarrow \quad \beta = 0$ **Efficiency-driven**

Quality-driven $\alpha = 0 \quad \Leftrightarrow \quad \beta = \infty$ **No one waits**:

The Halfin-Whitt Delay Function



$\sqrt{\cdot}$ Safety-Staffing: Performance

$R = \lambda \times E(S)$ Offered load (Erlangs)

$N = R + \underbrace{\beta\sqrt{R}}$ β = "service-grade" > 0

$= R + \Delta$ $\sqrt{\cdot}$ safety-staffing

Expected Performance:

$$\%\ \text{Delayed} \approx P(\beta) = \left[1 + \frac{\beta\phi(\beta)}{\varphi(\beta)}\right]^{-1}, \quad \beta > 0$$ Erlang-C

$$\text{Congestion index} = E\left[\frac{\text{Wait}}{E(S)} \,\middle|\, \text{Wait} > 0\right] = \frac{1}{\Delta}$$ ASA

$$\%\left\{\frac{\text{Wait}}{E(S)} > T \,\middle|\, \text{Wait} > 0\right\} = e^{-T\Delta}$$ TSF

$$\text{Servers' Utilization} = \frac{R}{N} \approx 1 - \frac{\beta}{\sqrt{N}}$$ Occupancy

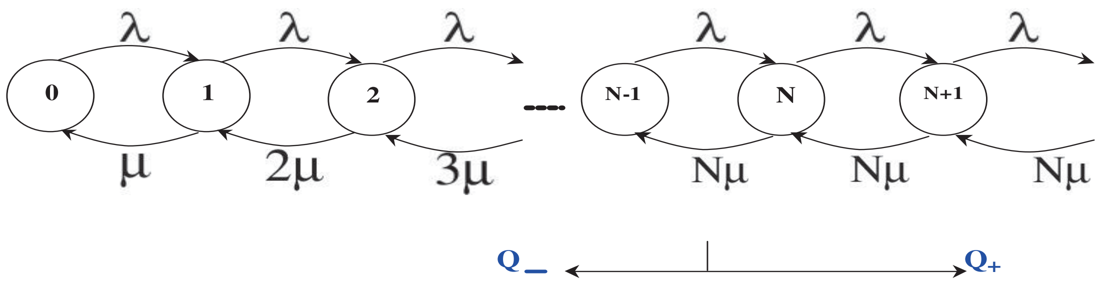
QED : Some Intuition (Assume $\mu = 1$)

M/**M**/N: $W_N \mid W_N > 0 \overset{d}{=} \exp\left(\text{mean} = \frac{1}{N}\frac{1}{1-\rho_N}\right)$

$$\sqrt{N}\, W_N \mid W_N > 0 \overset{d}{=} \exp\left(\sqrt{N}\,(1-\rho_N)\right) \Rightarrow \exp(\beta)$$

But why $P(W_N > 0) \to \alpha, \quad 0 < \alpha < 1$?

M/M/N (Erlang-C) with Many Servers: $N \uparrow \infty$



$Q(0) = N$: all servers busy, no queue.

Recall $$E_{2,N} = \left[1 + \frac{T_{N-1,N}}{T_{N,N-1}}\right]^{-1} = \left[1 + \frac{1-\rho_N}{\rho_N E_{1,N-1}}\right]^{-1}.$$

Here $$T_{N-1,N} = \frac{1}{\lambda_N E_{1,N-1}} \sim \frac{1}{N\mu \times h(-\beta)/\sqrt{N}} \sim \frac{1/\mu}{h(-\beta)\sqrt{N}}$$

which applies as $\sqrt{N}(1-\rho_N) \to \beta, \ -\infty < \beta < \infty.$

Also $$T_{N,N-1} = \frac{1}{N\mu(1-\rho_N)} \sim \frac{1/\mu}{\beta\sqrt{N}}$$

which applies as above, but for $0 < \beta < \infty$.

Hence, $$E_{2,N} \sim \left[1 + \frac{\beta}{h(-\beta)}\right]^{-1}, \text{ assuming } \beta > 0.$$

Rules of Thumb: Operational Regimes

$R = \lambda \times E(S)$ units of work per unit of time (load)

Efficiency-driven $(\%\{\text{Wait} > 0\} \to 100\%)$

$N = \lceil R + \gamma \rceil, \quad \gamma > 0$ service grade

Quality-driven $(\%\{\text{Wait} > 0\} \to 0)$

$N = \lceil R + \delta R \rceil, \quad \delta > 0$

QED Regime $(\%\{\text{Wait} > 0\} \to \alpha, \ 0 < \alpha < 1)$

$N = \lceil R + \beta\sqrt{R} \rceil, \quad \beta > 0$ $\sqrt{\cdot}$ **Safety-Staffing**

Determine Regimes (Strategy), Parameters (Economics)

Strategy: Managers, Agents (Unions), Customers

Economics: Minimize agent salaries + waiting cost

Strategy: Sustain Regime under Pooling

Base: $\lambda = 300/\text{hr}$, AHT = 5 min, N = 30 agents

$$R = 300 \times \frac{5}{60} = 25, \quad OCC = 83.3\% \quad ASA = 15 \text{ sec}$$

$$y = (N - R)/\sqrt{R} = (30 - 25)/\sqrt{25} = 1, \quad P(1) = 22\%$$

4 CC: $\lambda = 1200$, AHT = 5, R = 100; N=?

Quality-Driven: maintain OCC at 83.3%.

N = 120, ASA = .5 sec, y = (120 – 100)/10 = 2

Efficiency-Driven: maintain ASA at 15 sec.

N = 107, OCC = 95%, y = 0.8

QED: maintain %{Wait>0}) at 22% (y at 1).

$$N = 100 + 1 \cdot \sqrt{100} = 110, \quad OCC = 91\%, \quad ASA = 7 \text{ sec}$$

9 CC: $\lambda = 2700$, AHT = 5, R = 225

Q: N = 270

E: N = 233

QED: $N = 225 + 1 \cdot \sqrt{225} = 240$, OCC = 94%, ASA = 4.7 sec

Strategy: Sustain Regime under Pooling

Economies of Scale

Base case: M/M/N with parameters λ, μ, N

Scenario: $\lambda \to m\lambda$ $(R \to mR)$

	Base Case	Efficiency-driven	Quality-driven	Rationalized
Offered load	$R = \frac{\lambda}{\mu}$	mR	mR	mR
Safety staffing	Δ	Δ	$m\Delta$	$\sqrt{m}\Delta$
Number of agents	$N = R + \Delta$	$mR + \Delta$	$mR + m\Delta$	$mR + \sqrt{m}\Delta$
Service grade	$\beta = \frac{\Delta}{\sqrt{R}}$	$\frac{\beta}{\sqrt{m}}$	$\beta\sqrt{m}$	$\boxed{\beta}$
Erlang-C = P{Wait>0}	$P(\beta)$	$P\left(\frac{\beta}{\sqrt{m}}\right) \uparrow 1$	$P(\beta\sqrt{m}) \downarrow 0$	$\boxed{P(\beta)}$
Occupancy	$\rho = \frac{R}{R+\Delta}$	$\frac{R}{R+\frac{\Delta}{m}} \uparrow 1$	$\boxed{\rho = \frac{R}{R+\Delta}}$	$\frac{R}{R+\frac{\Delta}{\sqrt{m}}} \uparrow 1$
$\text{ASA} = \text{E}\left[\frac{\text{Wait}}{\text{E}(S)} \,\middle\vert\, \text{Wait} > 0\right]$	$\frac{1}{\Delta}$	$\boxed{\frac{1}{\Delta} = \text{ASA}}$	$\frac{1}{m\Delta} = \frac{\text{ASA}}{m}$	$\frac{1}{\sqrt{m}\Delta} = \frac{\text{ASA}}{\sqrt{m}}$
$\text{TSF} = \text{P}\left\{\frac{\text{Wait}}{\text{E}(S)} > T \,\middle\vert\, \text{Wait} > 0\right\}$	$e^{-T\Delta}$	$\boxed{e^{-T\Delta} = \text{TSF}}$	$e^{-mT\Delta} = (\text{TSF})^m$	$e^{-\sqrt{m}T\Delta} = (\text{TSF})^{\sqrt{m}}$

See: Whitt's "How multi-server queues scale with …demand"

Economics: Quality vs. Efficiency

(**Dimensioning**: with S. Borst and M. Reiman)

Quality	**D**(t)	delay cost	(t = delay time)
Efficiency	**C**(N)	staffing cost	(N = # agents)

Optimization: N* minimizes Total Costs

- **C >> D** : Efficiency-driven
- **C << D** : Quality-driven
- **C** $\approx$ **D** : Rationalized - QED

Satisfization: N* minimal s.t. Service Constraint

Eg. %Delayed < α .

- $\alpha \approx 1$: Efficiency-driven
- $\alpha \approx 0$: Quality-driven
- $0 < \alpha < 1$: Rationalized - QED

Framework: Asymptotic theory of M/M/N, $\mathbf{N} \uparrow \infty$

Economics: $\sqrt{\cdot}$ Safety-Staffing

Optimal $$\mathbf{N}^* \approx \mathbf{R} + y^*\left(\frac{d}{c}\right)\sqrt{\mathbf{R}}$$

where **d** = delay/waiting costs

c = staffing costs

Here $$y^*(\mathbf{r}) \approx \left(\frac{r}{1 + r\left(\sqrt{\pi/2} - 1\right)}\right)^{1/2}, \qquad 0 < r < 10$$

$$\approx \left(2\ln\frac{r}{\sqrt{2\pi}}\right)^{1/2}, \qquad r \text{ large.}$$

Performance measures: $\Delta = y^*\sqrt{R}$ safety staffing

$$P\{\text{Wait} > 0\} \approx \mathbf{P}(y^*) = \left[1 + \frac{y^*\phi(y^*)}{\varphi(y^*)}\right]^{-1}$$ **Erlang-C**

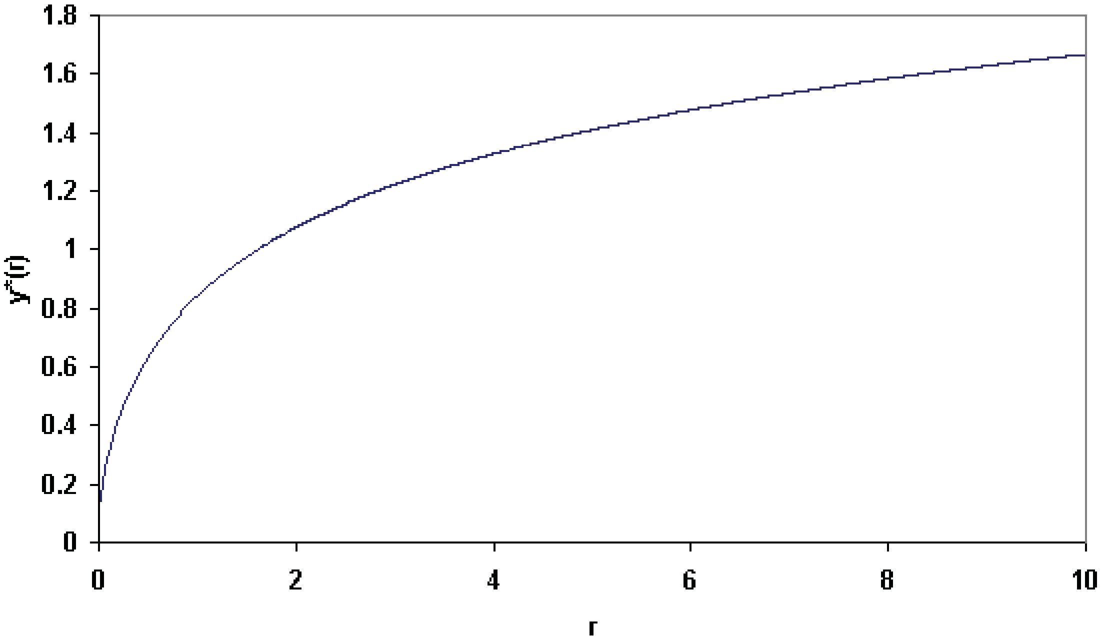
$$\text{TSF} = P\left\{\frac{\text{Wait}}{E(S)} > T \,\middle|\, \text{Wait} > 0\right\} = e^{-T\Delta}$$

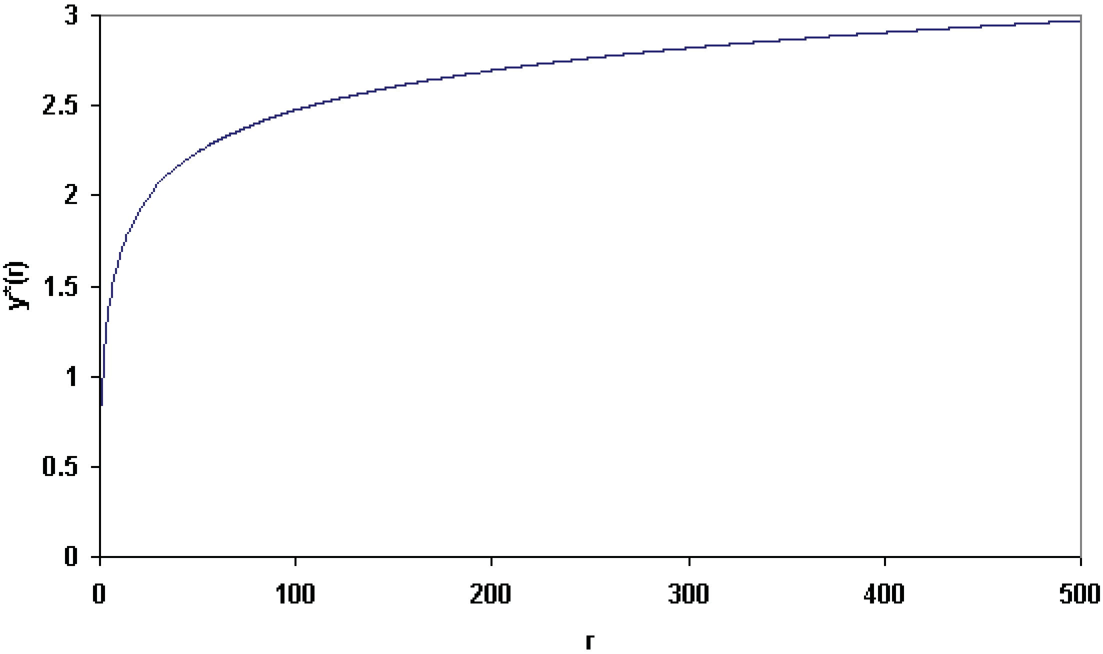
$$\text{ASA} = E\left[\frac{\text{Wait}}{E(S)} \,\middle|\, \text{Wait} > 0\right] = \frac{1}{\Delta}$$

$$\text{Occupancy} = 1 - \frac{\Delta}{N} \approx 1 - \frac{y^*}{\sqrt{N}}$$

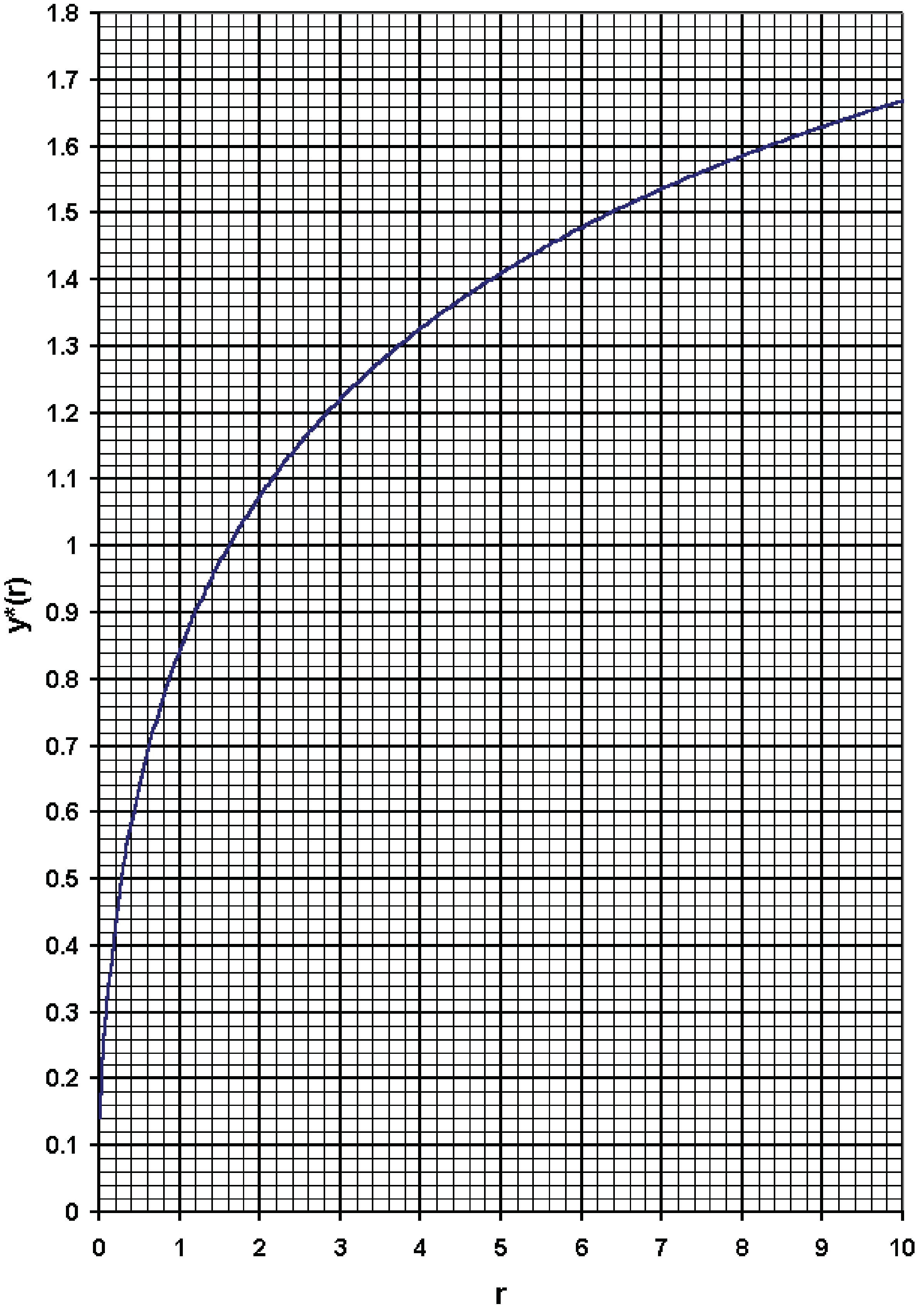
Square-Root Safety Staffing: $N = R + y^{*}(r)\sqrt{R}$

r = cost of delay / cost of staffing





$y^*(r)$, **r = cost of delay / cost of staffing**



Rules-of-Thumb in an "Erlang-C World"

R = Offered Load (not small)

Efficiency-Driven: $N = R + 2$ (or 3, or…);

Expect that essentially **all** customers are delayed in queue, that average delay is about 1/2 (or 1/3, or…) average service-time, and that agents utilization is extremely high (close to 100%).

Quality-Driven: $N = R + (10\% - 20\%) R$

Expect essentially **no** delays of customers.

QED: $N = R + 0.5\sqrt{R}$

Expect that about **half** of the customers are not delayed in queue, that average delay is about one-order less than average service-time (seconds vs. minutes), and that agents utilization is high (90-95%).

Can determine regime scientifically:

Strategy: Retain performance levels under Pooling (4CC demo)

Economics: Minimize agent salaries + congestion cost, or

Satisfization: Least Number of Agents s.t. Constraints

Scenario Analysis: 80:20 Rule (Large Call Center)

Prevalent std: at least 80% customers wait less than 20 sec.

Formally: %(Wait > 20 sec.) < 0.2

- Base Case: $\lambda = 100$ calls per min (avg)
  M = 4 min. service time (avg)
  R = 400 Erlangs offered load (large)

$y^*(\frac{d}{c}) = 0.53$, by %{Wait > 20 sec.} = $P(y^*)\, e^{-1.67y^*} = 0.2$

Hence: $N^* = 400 + 0.53\sqrt{400} = 411$, by $\sqrt{\cdot}$ safety-staffing

And $\frac{d}{c} = (y^*)^{-1}(0.53) = 0.32$, by inverting y^*

Low valuation of customers' time, at $\frac{1}{3}$ of servers' time, yet

reasonable 80:20 performance? enabled by scale!

- What if $\frac{d}{c} = 5$?

N* = 429 agents (vs. 411 before)

Agents' accessibility (idelness) = 7% (vs. 3% before)

Hence, 1 out of 100 waits over 20 sec. (vs. 1 out of 5)

Scenario Analysis: "Reasonable" Service Level ?

Theory: The least N that guarantees %{Wait > 0} < ε is close to $N^* = R + P^{-1}(\varepsilon)\sqrt{R}$ (again $\sqrt{\cdot}$ safety-staffing).

Example: λ = 1,800 calls at peak hour (avg)

M = 4 min. service time (avg)

$$R = 1800 \times \frac{4}{60} = 120 \quad \text{Erlangs offered-load}$$

Service level constraint: 1 out of 100 delayed (avg), namely 99% answered immediately.

$$\Rightarrow N^* = R + P^{-1}(0.01)\sqrt{R} = 120 + 2.38\sqrt{120} = 146 \text{ agents}$$

$$\Rightarrow \frac{d}{c} = (y^*)^{-1}(2.38) = 75:$$ very high service index

Valuation of customers' time as being worth 75-fold of agents' time seems reasonable only in extreme circumstances:

- Cheap servers (IVR)
- Costly delays (Emergency)

Note: **Satisfization easier to model but Costs easier to grasp.**