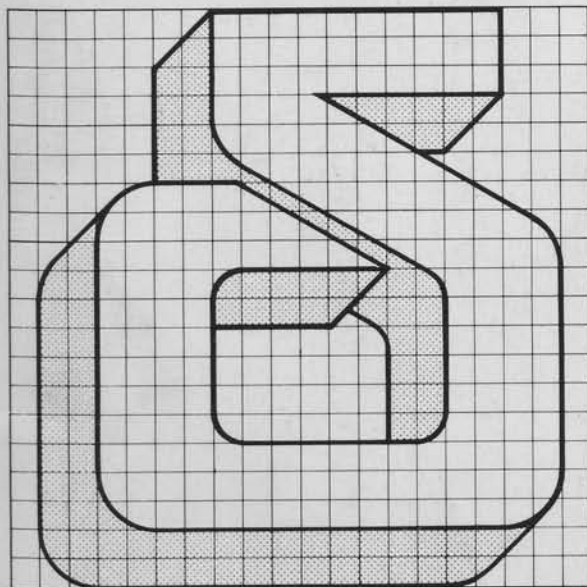
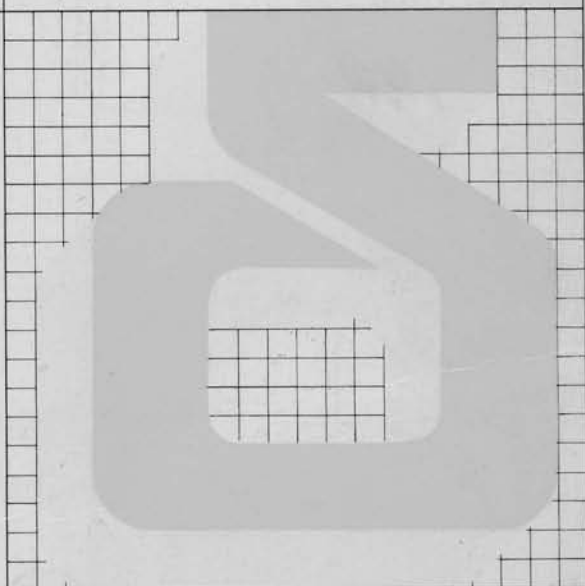




Delft Progress Report

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Symposium 'Traffic and Control'
dedicated to the Scientific Work of
Prof. dr. ir. L. Kosten



Quarterly

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Papers presented at the Symposium
dedicated to the scientific work
of Prof. dr. ir. L. Kosten
on the occasion of his retirement

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Prof. dr. ir. L. Kosten

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Preface

The present issue of Delft Progress Reports is intended as an homage to prof.dr.ir. L. Kosten on the occasion of his retirement from the Delft University of Technology, 31 August 1980. It contains the collection of papers presented at the Symposium on Traffic and Control, Delft, 4 November 1980, to commemorate Kosten's outstanding contributions to applied scientific research. The authors have gracefully presented their respective papers to highlight Kosten's initiating role in such diverse areas as traffic in telephone systems, computers, simulation, and more recently, traffic in computer networks. In doing so, they also pointed at Kosten's particular style of working: an applied mathematician with the constructive approach of an engineer.

Kosten was born on 29 August 1911. He graduated cum laude from the Electrical Engineering Department of the Delft University of Technology in 1933. He obtained his Doctor's degree from the Delft University in 1942, also cum laude; his thesis still has an excellent reputation. In the period 1937 - 1940 he was employed by the Municipal Telephone Company of The Hague, from 1940 until 1956 by the State Post, Telegraph and Telephone Company PTT, lastly as head of the newly established mathematics department. Since 1956 he has been senior professor at the Delft University of Technology, Department of General Sciences, Subdepartment of Mathematics, where he vigorously pursued his research interests and initiated the development of courses in queuing theory, operations research, numerical analysis, and simulation. Under his supervision, some 70 students graduated from the University so that he certainly was one of those outstanding faculty members who shaped the education of the so-called "mathematical engineer". Kosten became also well-known as one of the initiators and organizers of the International Teletraffic Congresses which are held since 1955.

It is gratifying to acknowledge Kosten's scientific work by a symposium and a special issue both concerned with his research interests. The Honourary Committee of the Symposium on Traffic and Control consisted of prof.dr.ir. W.Th. Bähler (who supervised both Kosten's Master's thesis and his Doctor's thesis), ir. N. Rodenburg (President of the N.V. Philips, Eindhoven), and Mr. H. Reinoud (previously Director General of the PTT, The Hague). On the Organizing Committee were prof.ir. D.H. Wolbers (Dean of the Subdepartment of Mathematics), prof.ir. J.L. de Kroes (Department of Electrical Engineering),

prof.dr.ir. J.W. Cohen (Department of Mathematics, State University of Utrecht),
ir. O.B. de Gans and ir. T.C.A. Mensch (Subdepartment of Mathematics). The
contributors to this issue are close friends and collaborators of Kosten
who devoted much of their time and energy in the same research areas. Generous
support to the Symposium was also given by the State Post, Telegraph and
Telephone Company PTT. With all these contributions, it is a pleasure to dedicate
the present issue of Delft Progress Reports to Kosten on the occasion of
his retirement.

F.A. Lootsma

Chairman of the Organizing Committee

Sensitivity and Insensitivity

J.W. Cohen

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Summary

In the late thirties, early forties the insensitivity of the stationary state probabilities for the classical Erlang and for the Engset model were discussed by Vaulot, Palm and Kosten. This phenomenon, rediscovered several times, has attracted much attention in the last ten years, particularly in the analysis of data processing networks. The present paper reviews sensitivity and insensitivity properties for the basic models of teletraffic.

Keywords

Erlang loss formula, Engset loss formula, generalized Engset formula, networks, processor sharing, gradings, sensitivity, insensitivity, product form.

1. Introduction

The presentation of a doctoral thesis at a Dutch University consists of the thesis itself and of a number of so called "Stellingen", i.e. statements or theorems concerning various scientific topics.

"Stelling" 8 of L. Kosten's thesis [1] reads in English translation:

"The statement of Conny Palm that congestion probabilities are in general independent of the holding (i.e. service) time distribution, is incorrect, [2]".

In present day terminology the statement would be phrased with the expression: "... congestion probabilities are in general insensitive to the type of service time distribution".

It is this use of the words: "sensitivity" and "insensitivity" in Teletraffic and Queueing Theory which motivates the title of the present lecture.

Lecturing on "Sensitivity and Insensitivity" at the symposium on the occasion of Prof. Kosten's retirement might suggest the impression that author's emotional feelings concerning Prof. Kosten's contributions to Teletraffic Theory would form the main theme of the present lecture. This suggestion is not intended. At another place [3] where the author has sketched some of the basic ideas in Prof. Kosten's work he already expressed admiration for his work and, in particular, his originality.

Let me finish my remarks about this possible interpretation of the title by stating that the organization of the present symposium should be considered as a token of the sensitivity of the Dutch Operations Research Community concerning Prof. Kosten's influence on the development of Teletraffic Theory.

In the late thirties, early forties the concepts of sensitivity and insensitivity were only discussed by Vulot [19], Palm [2] and Kosten [1]. During the fifties and sixties there was a continuing interest in this phenomenon, but in particular the recent developments of computer networks and the analysis of traffic streams in such networks have led to a thorough analysis of the phenomenon; for an extensive review of the literature we refer to [4], see also [12].

2. The Erlang and the Engset Formula

i. The Erlang Model

Consider a system with N servers.

Customers arrive according to a stationary Poisson process with arrival rate

λ ; arrivals which meet at least one idle server are served immediately; if a customer meets all servers busy, he disappears and never returns. The service times of successively arriving customers are independent, and identically distributed with absolutely continuous distribution $B(\cdot)$, they are also independent of the arrival process. Denote by x_t the number of customers in the system at time t , and by $\tau_{\lambda_i}(t)$, $i=1, \dots, x_t$ the attained service times at time t of the customers then present, here λ_i , $i=1, \dots, x$ is some permutation of $1, \dots, x$ if $x_t = x$.

The process $\{x_t, \tau_{\lambda_i}(t), i=1, \dots, x_t\}$ possesses a unique stationary distribution given by

$$(2.1) \Pr\{x_t = x, \tau_{\lambda_i}(t) < \tau_i; i=1, \dots, x_t\} = p(x) \left\{ \prod_{i=1}^x \int_0^{\tau_i} \frac{1-B(\tau)}{\beta} d\tau \right\}, x=1, \dots, N,$$

$$\Pr\{x_t = 0\} = p(0),$$

with

$$(2.2) p(x) = \frac{\frac{a^x}{x!}}{1 + a \frac{a^2}{2!} + \dots + \frac{a^N}{N!}}, x=0, \dots, N,$$

where

$$(2.3) a = \lambda\beta, \beta = \int_0^{\infty} t dB(t).$$

ii. The Engset Model

Next consider again a system with N servers and with M sources, $M \geq N$. Every source can originate requests for service by one of the N servers. If there is an idle server at the moment that a source makes a request, the request is served, the distribution of its service time is again denoted by $B(\cdot)$ and assumed to be absolutely continuous. When the request of a source has been fully served the source becomes idle and stays idle for a stochastic time, the idle time of the source; its distribution, assumed to be absolutely continuous, is indicated by $A(\cdot)$. If there is no idle server at the moment that a source originates a request, then this request is lost, not served, and its source starts a new idle time. The idle times per source and of all sources are independent, identically distributed variables, independent of the family of service times which are also independent, identically distributed variables.

Denote by x_t the number of busy sources at time t , $x_t \leq N$, let $\tau_{\lambda_i}(t)$, $i=1, \dots, x_t$,

be the attained service times at time t , and $\sigma_{\mu_j}(t)$, $j=1, \dots, M-x_t$ the past idle times of the $M-x_t$ idle sources at time t ; here λ_i , $i=1, \dots, x$ is some permutation of $1, \dots, x$, and similarly μ_j , $j=1, \dots, M-x$ of $1, \dots, M-x$ for $x_t = x$.

The process $\{x_t, \tau_{\lambda_i}(t), \sigma_{\mu_j}(t), i=1, \dots, x_t; j=1, \dots, M-x_t\}$ possesses a unique stationary distribution which is given by

$$(2.4) \Pr\{x_t = x, \tau_{\lambda_i}(t) < \tau_i, \sigma_{\mu_j}(t) < \sigma_j; i=1, \dots, x; j=1, \dots, M-x\} \\ = p(x) \left[\prod_{i=1}^x \int_0^{\tau_i} \frac{1-B(\tau)}{\beta} d\tau \right] \left[\prod_{j=1}^{M-x} \int_0^{\sigma_j} \frac{1-A(\sigma)}{\alpha} d\sigma \right], x=0, \dots, N, M \geq N,$$

an empty product being one by definition, here

$$(2.5) p(x) = \frac{\binom{M}{x} \rho^x}{\sum_{k=0}^N \binom{M}{k} \rho^k}, \quad x=0, \dots, N,$$

where

$$\rho = \beta/\alpha, \quad \beta = \int_0^{\infty} t dB(t), \quad \alpha = \int_0^{\infty} t dA(t).$$

The "time congestion" of the system is given by $p(N)$, whereas it can be shown that the "call congestion" i.e. the probability that an originated request cannot be served due to N busy servers, is given by

$$(2.6) \frac{\binom{M-1}{N} \rho^N}{\sum_{k=0}^N \binom{M-1}{k} \rho^k}, \quad M > N.$$

For the first system discussed above the time congestion is equal to the call congestion and given by (2.2) with $x=N$.

The relation (2.2) for the stationary distribution of the number of busy servers is known as the Erlang formula, whereas the similar relation (2.5) for the case of a finite source group is known as the Engset formula (for a derivation see e.g. [4], [20]).

Obviously both these relations are only dependent on the first moments of the distributions involved. This is the so-called "insensitivity" property, for the first time discussed by Palm [2] for the Erlang as well as the Engset situation but in the latter case with $A(\cdot)$ the negative exponential distribution; see also [5], where Kosten discusses the Engset model by a magnificent application of the "supplementary variable" technique.

It should be noted that the relation (2.4) for $M=N$ shows a remarkable symmetry if $A(\cdot)$ and $B(\cdot)$, α and β , x and $M-x$ are interchanged (note that in (2.5) ρ^x can be replaced by $\beta^x \alpha^{M-x}$ without affecting this expression).

3. Insensitivity, Generalizations

Actually the Erlang formula can be considered under mild conditions as a special case of the Engset formula, by letting $M \rightarrow \infty$, $\alpha \rightarrow \infty$ and $M/\alpha \rightarrow \lambda$.

We, therefore, start from the Engset model in considering generalizations.

There are three types of generalizations to be considered:

- i. individual source characteristics;
- ii. networks;
- iii. generalized processor sharing.

ad i. Individual source characteristics

In the Engset model discussed in the preceding section all sources have the same idle time distribution $A(\cdot)$, and the requests originated by the sources all have the same service time distribution $B(\cdot)$.

In the case of individual source characteristics every source j has its own idle time distribution $A_j(\cdot)$ and the requests stemming from this source have the service time distribution $B_j(\cdot)$; again it is assumed that all idle times and service times are independent. This model has been discussed in [6], [7], see also [8].

An important special case is brought forward by the model with N servers and two source groups 1 and 2 consisting of M_1 and M_2 sources, respectively, with $M_1 + M_2 \geq N$ and such that sources belonging to the same group have identical characteristics, $A_i(\cdot)$, $B_i(\cdot)$, $i=1,2$.

In the notation of section 2 with quantities referring to source group 1(2) indexed 1(2) the expression for the stationary distribution reads

$$\begin{aligned}
 (3.1) \quad & \Pr\{x_t^{(1)} = x^{(1)}, x_t^{(2)} = x^{(2)}, \tau_{\lambda i(1)}^{(1)} < \tau_{i(1)}^{(1)}, \tau_{\lambda i(2)}^{(2)} < \tau_{i(2)}^{(2)}, \\
 & i(1) = 1, \dots, x^{(1)}; i(2) = 1, \dots, x^{(2)}, \\
 & \sigma_{j(1)}^{(1)} < \sigma_{j(1)}^{(1)}, \sigma_{j(2)}^{(2)} < \sigma_{j(2)}^{(2)}, j(1) = 1, \dots, M_1 - x^{(1)}; j(2) = 1, \dots, M_2 - x^{(2)}\} = \\
 & = p(x^{(1)}, x^{(2)}) \prod_{i(1)=1}^{x^{(1)}} \left\{ \int_0^{\tau_{i(1)}^{(1)}} \frac{1-B_1(\tau)}{\beta_1} d\tau \right\} \prod_{i(2)=1}^{x^{(2)}} \left\{ \int_0^{\tau_{i(2)}^{(2)}} \frac{1-B_2(\tau)}{\beta_2} d\tau \right\} \times
 \end{aligned}$$

$$\times \prod_{j(1)=1}^{M_1-x^{(1)}} \left\{ \int_0^{\sigma_{j(1)}^{(1)}} \frac{1-A_1(\sigma)}{\alpha_1} d\sigma \right\} \prod_{j(2)=1}^{M_2-x^{(2)}} \left\{ \int_0^{\sigma_{j(2)}^{(2)}} \frac{1-A_2(\sigma)}{\alpha_2} d\sigma \right\},$$

for $0 \leq x^{(1)} \leq M_1$, $0 \leq x^{(2)} \leq M_2$, $x^{(1)} + x^{(2)} \leq N$, here

$$(3.2) \quad p(x^{(1)}, x^{(2)}) = \binom{M_1}{x^{(1)}} \binom{M_2}{x^{(2)}} \rho_1^{x^{(1)}} \rho_2^{x^{(2)}} C,$$

C being determined by the condition

$$1 = \sum_{u=0}^{M_1} \sum_{v=0}^{M_2} p(u, v).$$

$u + v \leq N$

Again the stationary distribution $p(x^{(1)}, x^{(2)})$ of the number of customers served is insensitive to the idle time and service time distributions.

Another remarkable property of (3.1) and (3.2) is that these relations have the "product form" (except for the normalization constant C).

The generalization of (3.1), (3.2) to K source groups is straightforward. It should be noted that by using (3.1) and (3.2) the formula for the call congestion (2.6) can be easily derived (cf. [4]).

ad ii. Networks

Consider the Engset model of section 2 with $M = N$. In section 2 we have already noted the symmetry in the expression for the stationary distribution, this symmetry is actually easily explained.

Consider a system consisting of two nodes 1 and 2 and at every node M servers are present. This two node system contains M requests, and each request can be at one of the nodes. If it is at node 1(2) it is served there for a stochastic time with distribution $B_1(\cdot)$ ($B_2(\cdot)$), and when such a request has obtained its complete service at node 1(2) it enters node 2(1) for a service time with distribution $B_2(\cdot)$ ($B_1(\cdot)$). Every request has the same behaviour and their service times are independent.

By identifying the source group in the Engset model with node 1, the service point with node 2 (note $N=M$), $A(\cdot)$ with $B_1(\cdot)$ and $B(\cdot)$ with $B_2(\cdot)$ it is seen that actually both models are identical.

In fact we have here the "closed model with M requests", it is a basic

model for the traffic flow in a system consisting of a CPU and I/O device, but it may also be considered as a data handling network consisting of two nodes.

The generalization is a closed network consisting of P nodes with M requests and service time distribution $B_j(\cdot)$ at node j , $j=1, \dots, P$, all service times being independent. However, the routing of the requests through the network has to be specified. This is obtained by specifying the routing matrix

$$(3.3) \quad \Pi_{hk}, \quad h, k \in \{1, \dots, P\},$$

with

$$(3.4) \quad \Pi_{hk} \geq 0, \quad \sum_{k=1}^P \Pi_{hk} = 1, \quad h=1, \dots, P,$$

here Π_{hk} is the conditional probability that a request enters node k for service when it has been fully served at node h .

It will be assumed that the matrix (Π_{hk}) of transition probabilities defines an irreducible aperiodic Markov chain on the set $\{1, \dots, P\}$, so that the set of equations

$$(3.5) \quad z_k = \sum_{h=1}^P z_h \Pi_{hk}, \quad k=1, \dots, P,$$

$$\sum_{k=1}^P z_k = 1,$$

possesses a unique nonnegative solution $z_k = \mu_k$, $k=1, \dots, P$.

Denote by $x_t(j)$ the number of requests present at node j at time t and by $\tau_t(\lambda(j, i))$ the attained service times of these requests at time t , where $\lambda(j, i)$, $i=1, \dots, x_t(j)$, is a permutation of $1, \dots, x_t(j)$. Then under the assumptions made above concerning Π_{hk} and with $B_j(\cdot)$ absolutely continuous the process $\{x_t(j), \tau_t(\lambda(j, i)), i=1, \dots, x_t(j), j=1, \dots, P\}$ possesses a unique stationary distribution given by

$$(3.6) \quad \Pr\{x_t(j) = x_j, \tau_t(\lambda(j, i)) < \tau(\lambda(j, i)), i=1, \dots, x_j, j=1, \dots, P\} =$$

$$D \prod_{j=1}^P \frac{\{\mu_j \beta_j\}^{x_j}}{x_j!} \prod_{j=1}^P \int_0^{\tau(\lambda(j, i))} \frac{1 - B_j(\tau)}{\beta_j} d\tau,$$

for

$$0 \leq x_j \leq M, \quad \sum_{j=1}^P x_j = M,$$

an empty product being zero by definition; D , the normalization constant, is determined by

$$(3.7) \quad D \sum_{x_1=0}^M \dots \sum_{x_p=0}^M \frac{(\mu_j \beta_j)^{x_j}}{x_j!} = 1,$$

$$x_1 + \dots + x_p = M$$

and

$$\beta_j = \int_0^{\infty} t dB_j(t).$$

Again it is seen from (3.6) and (3.7) that the stationary distribution of $x_t(j)$, $j=1, \dots, P$ is insensitive to the type of $B_j(\cdot)$.

The next generalization of this model is the model for which every request has its individual routing matrix $\Pi_{hk}^{(n)}$, $n=1, \dots, M$ and its own service time distribution $B_j^{(n)}$, $n=1, \dots, M$ at node j ; for this model cf. [4], see also [9] for even more complex models.

ad iii. Generalized processor sharing

Consider again the Engset model of section 2 but with the following service discipline, viz. if the number of busy servers is $x_t = x$ then everyone of these x requests present obtains during $t \div t + \Delta t$ an amount of service equal to

$$(3.8) \quad f(x) \Delta t$$

with

$$(3.9) \quad 0 \leq f(x) < \infty, \quad x f(x) \leq c, \quad x > 0.$$

Hence the attained service of a request increases with a rate $f(x)$, if x sources are busy. For the Engset model of section 2 $f(x) = 1$, $x = 1, \dots, N$ and the "service capacity" c equals N .

If $f(x) = 1/x$ then the service discipline is known as "processor sharing", for general $f(\cdot)$ satisfying (3.9) it is known as "generalized processor sharing", because the requests present at the service facility share with rate $f(\cdot)$ the processing capacity.

Denote again for the system with M sources by x_t the number of busy sources at time t and by $\tau_{\lambda_i}(t)$, $i=1, \dots, x_t$ the "attained" service of request λ_i at time t , further $\sigma_{\mu_j}(t)$ is again the past idle time. Note that in general

$t - \tau_{\lambda_i}(t)$ is (for general $f(x)$) not the moment at which the service of request λ_i started.

Again the process $\{x_t, \tau_{\lambda_i}(t), \sigma_{\mu_j}(t), i=1, \dots, x_t; j=1, \dots, M-x_t\}$ possesses a unique stationary distribution; it is given by

$$(3.10) \Pr\{x_t = x, \tau_{\lambda_i}(t) < \tau_i, \sigma_{\mu_j}(t) < \sigma_j; i=1, \dots, x; j=1, \dots, M-x\} =$$

$$p(x) \left[\prod_{i=1}^x \left\{ \int_0^{\tau_i} \frac{1-B(\tau)}{\beta} d\tau \right\} \prod_{j=1}^{M-x} \left\{ \int_0^{\sigma_j} \frac{1-A(\sigma)}{\alpha} d\sigma \right\} \right], x=0, \dots, M,$$

where

$$(3.11) p(x) = \frac{\binom{M}{x} \rho^x \phi(x)}{\sum_{k=0}^M \binom{M}{k} \rho^k \phi(k)}, x=0, \dots, M,$$

$$(3.12) \phi(x) = \left\{ \prod_{h=1}^x f(h) \right\}^{-1}, x=0, \dots, M,$$

an empty product being zero by definition.

Again the stationary distribution $p(\cdot)$ of busy sources is insensitive.

Denote by $\underline{v}$ the sojourn time of a request at the service node, then it can be shown cf. [4] that

$$(3.13) E\{\underline{v}\}/\beta = \frac{\sum_{x=0}^{M-1} \binom{M-1}{x} \rho^x \phi(x+1)}{\sum_{x=0}^{M-1} \binom{M-1}{x} \rho^x \phi(x)},$$

so that in general $E\{\underline{v}\} \neq \beta$. Obviously the righthand side of (3.13) represents the average rate by which a request is processed.

Another interesting result is obtained when the average sojourn time $\underline{v}$ is considered under the condition that it is known that the "required" service time of a request is equal to s . Under mild conditions it can be shown cf. [4] that

$$(3.14) E\{\underline{v} \mid \tau = s\} = s \frac{\sum_{x=0}^{M-1} \binom{M-1}{x} \rho^x \phi(x+1)}{\sum_{x=0}^{M-1} \binom{M-1}{x} \rho^x \phi(x)},$$

i.e. it equals the product of s and the average service rate.

A rather surprising result is obtained if we take

$$(3.15) f(x) = \frac{1}{M+1-x}, x=1, \dots, M,$$

then

$$\phi(x) = \frac{(M-x)!}{M!},$$

and consequently from (3.11)

$$(3.16) \quad p(x) = \frac{\frac{\rho^x}{x!}}{\sum_{x=0}^M \frac{\rho^x}{x!}}, \quad x = 0, \dots, M;$$

i.e. for the service rate given by (3.15) the stationary distribution of the number of busy sources in the Engset model with M sources is identical with that of the classical Erlang model with M servers: another "insensitivity" phenomenon but now with respect to the service discipline.

Next we consider the classical Erlang model with "processor sharing", so we have a Poissonian arrival stream, and a customer who meets at his arrival $N+1$ customers in the system is lost (for reasons which will become apparent below we take here $N+1$ instead of N). For this model the stationary distribution is given by

$$(3.17) \quad \Pr\{x_t = x, \tau_{\lambda_i}(t) < \tau_i, i = 1, \dots, x\} =$$

$$p(x) \prod_{i=1}^x \left\{ \int_0^{\tau_i} \frac{1-B(\tau)}{\beta} d\tau \right\}, \quad x = 0, \dots, N+1,$$

$$(3.18) \quad p(x) = \frac{\frac{\rho^x}{x!} \phi(x)}{\sum_{k=0}^{N+1} \frac{\rho^k}{k!} \phi(k)}, \quad x = 0, \dots, N+1.$$

Consider the special case:

$$(3.19) \quad \text{for } x = 1, \dots, N \text{ is } f(x) = 1 \text{ so that } \phi(x) = 1,$$

$$\text{for } x = N+1 \text{ is } f(x) = r \text{ so that } \phi(N+1) = \frac{1}{r}.$$

Then

$$(3.20) \quad p(x) = \frac{\frac{\rho^x}{x!}}{\sum_{k=0}^N \frac{\rho^k}{k!} + \frac{1}{r} \frac{\rho^{N+1}}{(N+1)!}}, \quad x = 0, \dots, N,$$

$$= \frac{\frac{1}{r} \frac{\rho^{N+1}}{(N+1)!}}{\sum_{k=0}^N \frac{\rho^k}{k!} + \frac{1}{r} \frac{\rho^{N+1}}{(N+1)!}}, \quad x = N+1.$$

Obviously the service rate per customer is equal to one if $x_t \leq N$ and r if $x_t = N+1$; hence the larger r becomes the sooner a state with $N+1$ customers in the system will disappear. Hence if a transition from state N to $N+1$ is caused by an arriving customer and if r is very large then almost immediately the customer, who has the shortest service time still to be obtained directly

after the transition, will leave the system and the system returns to state N. Obviously (3.19) becomes for $r \rightarrow \infty$

$$(3.21) \quad p(x) = \frac{\frac{\rho^x}{x!}}{\sum_{k=0}^N \frac{\rho^k}{k!}}, \quad x = 0, \dots, N,$$

$$= 0 \quad x = N + 1.$$

Consider the following model with Poissonian arrival stream. An arriving customer who meets less than N customers in the system is taken into service and the service rate is one for $x_t \leq N$. If an arriving customer meets N customers in the system, of the N+1 customers then present the customer with the shortest service time still to be obtained is discarded from the system and of each of the remaining N customers the service time still to be obtained is reduced by the amount of the residual service time of the customer discarded.

From the results above it follows that for this model the stationary distribution of the number of customers present is given by (3.21). A remarkable result, showing a type of insensitivity with respect to the "service discipline" of the classical Erlang model.

To calculate for the present model the average amount of traffic lost it is first noted that for this model the stationary distribution of the number x_t of customers in the system at time t and of the service times $\omega_{\lambda_i}(t)$, $i = 1, \dots, x_t$ still to be obtained is given by

$$(3.22) \quad \Pr\{x_t = x, \omega_{\lambda_i}(t) < \omega_i, i = 1, \dots, x\} =$$

$$p(x) \prod_{i=1}^x \left\{ \int_0^{\omega_i} \frac{1-B(\tau)}{\beta} d\tau \right\}, \quad x = 0, \dots, N,$$

with p(x) given by (3.21). A result which is easily derived from (3.17), ..., (3.19) for $r \rightarrow \infty$, note herefore that

$$(3.23) \quad \Pr\{\omega_{\lambda_i}(t) < \omega_i \mid \tau_{\lambda_i}(t) = \tau_i\} = \frac{B(\omega_i + \tau_i) - B(\tau_i)}{1 - B(\tau_i)}.$$

Because the service time τ_{N+1} of the customer who meets N customers in the system has distribution B(.) and because all service times are independent it follows from (3.22) that

$$(3.24) \Pr\left\{\min_{i=1, \dots, N} (\tau_{N+1}, \omega_{\lambda_i}(t)) \geq \tau \mid \underline{x}(t) = N\right\} = (1-B(\tau)) \left\{ \int_{\sigma=\tau}^{\infty} \frac{1-B(\sigma)}{\beta} d\sigma \right\}^N,$$

hence

$$(3.25) E\left\{\min_{i=1, \dots, N} (\tau_{N+1}, \omega_{\lambda_i}(t)) \mid \underline{x}_t = N\right\} = \int_0^{\infty} (1-B(\tau)) \left\{ \int_{\sigma=\tau}^{\infty} \frac{1-B(\sigma)}{\beta} d\sigma \right\}^N d\tau$$

$$= \frac{\beta}{N+1}.$$

Hence $\beta/(N+1)$ is the average residual service time of the discarded customer. Because the residual service times of the customers who stay are shortened by that of the discarded customer the average total lost traffic is $(N+1)$ times as large, hence equal to β . This occurs each time an arriving customer meets N in the system, hence the average traffic lost is equal to

$$\beta \frac{\rho^N}{N!} / \sum_{x=0}^N \frac{\rho^x}{x!},$$

it is obviously equal to that for the classical Erlang model.

The same argumentation as used above leads to the conclusion that the formulas for the Engset model are also valid if in this model the congestion discipline is of the type just described, i.e. "shortest out with reduction".

Above we have discussed a number of generalizations of the classical Engset model; generalizations which all have the insensitivity property with respect to the service time distributions. All these types of generalizations can be incorporated in a very general model (cf. [4], see also [10]). Here we shall not discuss such a general model. An interesting question in this respect is: what are the necessary and sufficient conditions for the insensitivity property to hold, see e.g. [10], [11].

4. Sensitivity

From the discussions in the preceding section it is seen that many important practical models possess the insensitivity property with respect to the service time distributions. On the other hand models like e.g. the basic queueing model $M/G/1$ show that the inherent stochastic processes are highly sensitive to the type of service time distribution. For real queueing models this sensitivity can be understood intuitively. Is this also possible for models with congestion (i.e. with lost call situations)?

A clear insight in this problem is not yet available, although there have been several attempts to formulate necessary and sufficient conditions for insensitivity to be present, cf. e.g. [10], [11].

Apart from real queueing problems rather little is known about the class of congestion models, which are sensitive. The best available results concern so-called "gradings", see figure 1.

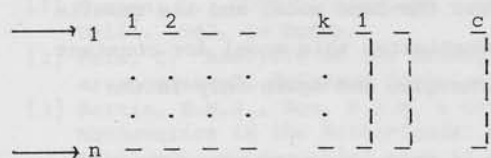


fig. 1.

The model consists of n independent, Poissonian arrival streams. Arrivals from one stream have access to one group of k servers; if an arrival meets all k servers of his group busy then he has access to a for all arrival streams accessible group of c servers; if these are also busy the arrival is lost. This is actually a very simple grading; essential is that not every of the $nk+c$ servers is accessible for every arrival, even if the system is empty.

We discuss some examples to show that the congestion probabilities of gradings are indeed sensitive to the service time distribution.

Kosten [13] p. 104 considers the grading above with $n=2$, $k=1$, $c=1$ for two cases, viz. the service time distribution is negative exponential and it is the Erlang 2 type. For a large range of the traffic parameter numerical calculations showed that the state probabilities for both cases agree in three significant decimals.

Van Marion [14] considers the asymmetrical grading (see fig. 2) for the negative

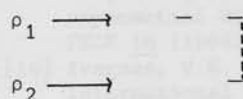


fig. 2.

exponential service time distribution and for the service time distribution

$$B(t) = 1 - \frac{h_1 e^{-t/h_1} - h_2 e^{-t/h_2}}{h_1 - h_2}, \quad t \geq 0,$$

$0 \leq h_1 \leq 1, h_1 + h_2 = 1$ (Erlang 2 if $h_1 = h_2$).

He calculates the congestion probabilities for $h_1 = 0.5$ and 0.9 for a large range of the traffic parameter. His results are expressed in six decimals, and it turns out that for $\rho_1 = \rho_2 = 0.50 \div 2.50$ the difference with the negative exponential case is manifest only in the fourth decimal. Van Marion's results are in complete agreement with the results of Tånge and Wikell [15] obtained by simulation. Iversen [16] analyses the same model and his results agree with those of van Marion; he also investigates this model for constant service time distribution by simulation techniques and again only in the fourth decimal a difference is noted.

In the table below some of Van Marion's results are listed, here c_i is the congestion probability for arrival stream i , $i = 1, 2$.

$\rho_1 = \rho_2$	h_1	c_1	c_2
0.05	1	0.003371	0.049726
	0.9	0.003371	0.049726
	0.5	0.003372	0.049726
0.50	1	0.151515	0.393939
	0.9	0.151545	0.393930
	0.5	0.151699	0.393878
1.00	1	0.318182	0.590909
	0.9	0.318234	0.590883
	0.5	0.318457	0.590772
2.50	1	0.587703	0.804702
	0.9	0.587749	0.804669
	0.5	0.587874	0.804580
7.50	1	0.825642	0.932392
	0.9	0.825655	0.932381
	0.5	0.825670	0.932368

The examples discussed above show that gradings are sensitive to the service time distribution, but how strong the sensitivity can be is an unsolved problem.

The insensitivity of the classical Erlang model depends strongly on the arrival stream being Poissonian, as it is shown in [17] and [18], where the G/M/n loss model is investigated. How sensitive the numerical results for this case are to changes in the interarrival time distribution seems not to be known.

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The Early History of Computing at PTT

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In this article I shall try to recall a number of facts from the early days of building computers at the Central Laboratory of the Netherlands Postal and Telecommunications Services at it was called at that time (1950). Later it was renamed Dr. Neher Laboratory and we shall further abbreviate this here to DNL.

Kosten was head of a rather new department, called Mathematical Department (Mathematische Afdeling, further abbreviated by MA). This was founded in 1948 as a central service for the other departments of the Laboratory mainly to do complicated calculations on desk calculators and giving advice on solution methods for difficult mathematical problems as arise in topics of research, that range from communication theory, transmission networks, dimensioning of telephone exchanges; to ionosphere calculations for radiotransmission and many more. The personnel consisted of Kosten as head, Steiner as principal mathematician, two people of operating the desk calculators and a few technicians.

Kosten had previous experience in building another kind of computer, i.e. he had built a traffic machine for simulating traffic in telephone exchanges. This machine was entirely built out of telephone relays and stepping switches and formed the main part of his doctoral thesis (1942).

Around 1948 the news about the American computers such as ENIAC and the English developments in Cambridge and elsewhere came through. This aroused Kosten's interests in building a modest computer for general purpose calculations at DNL. Perhaps at that time he was still more interested in building a perfect traffic machine. In any case, the technical components for storage and computation were the same. So some research was started on the so called Williams tube stores. These are ordinary cathode ray tubes on the screen of which some minute charges

could be deposited in a prearranged raster. These charges can be maintained by secondary emission of the screen. They can be erased by pulling them away from the spots by beam deflection and they can be read off by an induction plate or fine wire mesh in front of the screen.

At the same time (48-50) there was a young student at the Delft University of Technology, building a relay computer at the optical department of the Physics Laboratory for ray tracing purposes. That was me, I cannot remember how Kosten and I found each other but I certainly remember that he once visited the Delft Laboratory and I also know that I asked Kosten whether he could secure a party of discarded telephone relays (about 600 of them) at the general workshops of PTT. Kosten had many relations at PTT and soon he lent these 600 relays to the University in a rather unofficial, unauthorized fashion. This kind of material was very scarce in those days and when his director later heard of this transactions he had to take the rap for it.

In any case, this resulted in me being asked to join PTT in the group of Kosten to pull forces together for building a real computer, which at that time I gratefully accepted immediately. This could be the chance of my life.

When I entered DNL the Williams tube just began to work properly. Everybody was enchanted that at one day a raster of $32 * 32$ points (bits) could be maintained on the screen for one whole hour without a single error. However, the whole thing was so sensitive to slight changes in the supply voltages, that very costly stabilizers had to be used. The whole rig had to be placed in a Faraday cage to prevent interference. To make a long story short: the thing never worked again after this one hour! The whole project of using this kind of store was dropped as being too costly and too unreliable. Nevertheless, several machines in the USA and even one of the very first commercial machines of that time (the Ferranti machine as e.g. sold to the Shell labs in Amsterdam) used the Williams tube. Even as late as 1962 I saw the STRELA computer in Moscow still working with these tubes.

A new and promising kind of storage was presenting itself almost everywhere, i.e. the magnetic drum. Magnetic recording techniques on wire and even on tape were just coming out of the experimental phase and it certainly should be possible to record on a fast rotating drum. An additional difficulty was that the heads could not be run in contact, and floating heads were not invented yet.

In other laboratories different solutions were tried. E.g. should the drum be placed vertically or horizontally? A vertical drum needs a more costly axial bearing and when not placed in the true vertical position, it could exhibit precession as a fast spinning top. Hence we decided for horizontal drums. A further design decision was the coating. Should a plain nickel plating be good enough, or should a ferrite powder coating be applied, giving more output, but being more difficult to apply in the correct thickness and more easily damaged. We chose for the nickel plating. The Mathematical Centre, which in the early days was our friendly competitor in building pioneer computers, chose ferrite.

On one day the test drum was ready with one hand-made recording and reading head. We wiped the surface clean with a demagnetizing magnet and started to write pulses on the surface to see how much signal would come off on reading. But lo and behold. On reading there were far more pulses on the drum than were ever written. Continuously more and more pulses appeared without any writing at all. All interfering machinery was switched off, the oscilloscope was floated and nevertheless the spurious pulses kept appearing! Kosten always was a very broadly thinking engineer with a wide field of experience and he saw what was wrong. The belt drive from the motor acted as a kind of Van de Graaff generator and carried static charge to the body of the drum. From there a spark occasionally discharged the drum to the head, thereby inducing a small current and a surrounding magnetic field, and a new pulse was written on the drum. An earthing strip near the bearing solved the problem forever.

Speaking about oscilloscopes; that was not an easy problem in the early 50's. All oscilloscopes were of the audio type. Nobody had pulse oscilloscopes except the radar people, so we obtained one of the first pulse oscilloscopes from Dumont. Only much later the ubiquitous Tektronix scopes with delayed sweep and vernier (the 545) came on the scene. We even designed a special pulse scope ourselves, but this was no success.

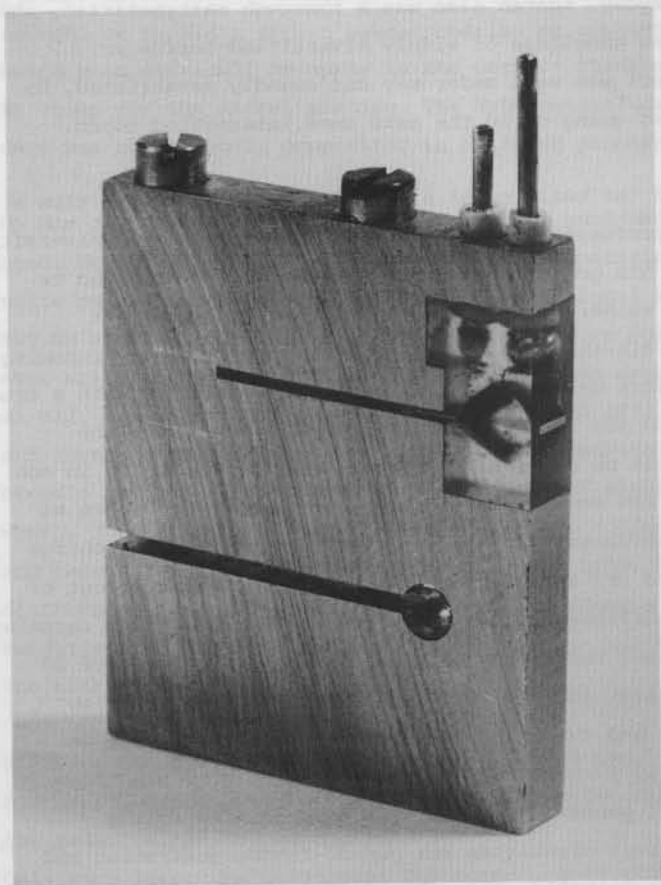
Another very funny story about drums was the following. The early drums were nickel plated in a small factory outside of the DNL. Later we mastered the techniques ourselves with the help of the Chemical Department of DNL. We once sent out a drum to be plated and got it back a week later. On measurement absolutely no signal came out even with the strongest current pulse we could apply! We asked the plating shop what they had done with the thing. Oh, they said, we have chromium plated the thing. That looks much nicer than nickel!

Let us highlight another quality of Kosten. As a technician he was always on the inventive side and bristled with new ideas. In fact it even was sometimes difficult for the rest of the staff to moderate and resist all new ideas. Fortunately, a relatively long-term project such as the design and building of a computer cannot be changed fundamentally everyday. Kosten also was a thorough mathematician, who often amazed us with his sound knowledge of widely diversified topics in mathematics. But once a project was well under way and soundly established, he lost interest, as his mind was going on to the next more interesting topic.

One of those topics was still the building of a traffic machine. At that time a student E.J. Gröneveld (now professor of electrical engineering in the University of Technology in Twente) did his practical work in the lab, and Kosten and he together made a design for a rather pretentious traffic machine. The most difficult part to make was a die-throwing machine for the simulation of incoming traffic. The main building block was a flip-flop, that flips or flops with a true chance of 50% for the flip and 50% chance for the flop. To begin with: the flip-flop itself should exhibit no marginal amount of bias towards being in one or the other state. But also the moment of switching over should be chosen at random. The source of true randomness we found at that time was a gasdischarge tube, that was switched on and off on alternating current. The exact moment of onset of the discharge is conditioned by the ionization of the gas by an incoming particle of cosmic radiation and the spread in time can be in the order of 20 microseconds. This was sufficient for the purpose. A whole battery of these die-throwing units were built and then the whole effort seemed futile as we realized that for all practical purposes a pseudo-random generator algorithm could be executed on a general purpose computer. The work shifted to the experimental testing of different algorithms for pseudo-random generation and the die-throwing machines died silently. However, some of the basic ideas were used again in other machines in the Switching Department where machines for generating truly random keys for cryptographic purposes were made.

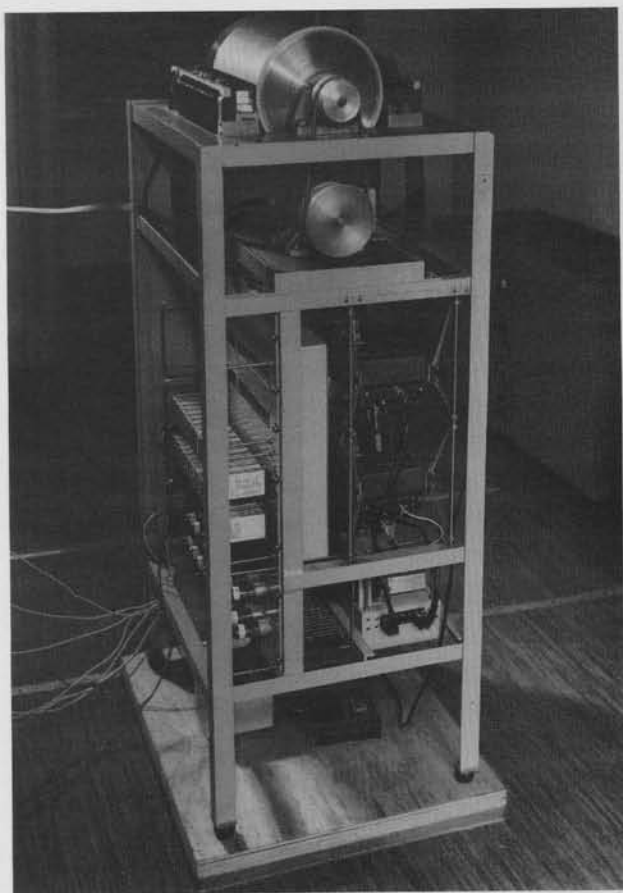
Let me recall the story of the manufacturing of the magnetic heads. One of the technicians made a head by hand out of a small strip of permalloy in the form of a lozenge. Four turns of winding was all we could get rid of in the space. The track width still was 2mm, considered presently very large. The problem was how an appreciable amount (some few hundred) of these heads could be manufactured. Fortunately Mr. Rab came along as a visitor to the lab, he saw the design and offered us to make them for a prearranged price. Had he known his difficulties in advance, he would never have done it. Nevertheless, his

product was a success and even the Mathematical Centre in Amsterdam became one of his customers. The design for adjusting was clever enough. A deep slit in the fixture with a screw for squeezing the upper part toward the lower part was used for adjusting the distance to the drum. (See photograph).



The old experience of Kosten as a telephone engineer came to good help for solving another minor problem with the drum. For the selection of one track, use was made of fast polar relays. Recall that in those days we had no transistors yet and the easiest way to select one reading/writing head was by relay. An amplifier per head was completely out of the question with radio valves. Of course the switching rate of these relays was quite high and after a while they appeared not to make a reliable contact any more. The currents through the contacts were extremely small but Kosten knew the remedy. A small potential was put across the contact by a simple few volts battery. This caused a so-called fritter current across the contact, biting through any eventual build up of a film of dirt. The DC component could not hurt the signal, as this was a complete balanced AC waveform, resulting

from the Manchester recording system that we employed. One can see that battery lying on the bottom of fig. 2.

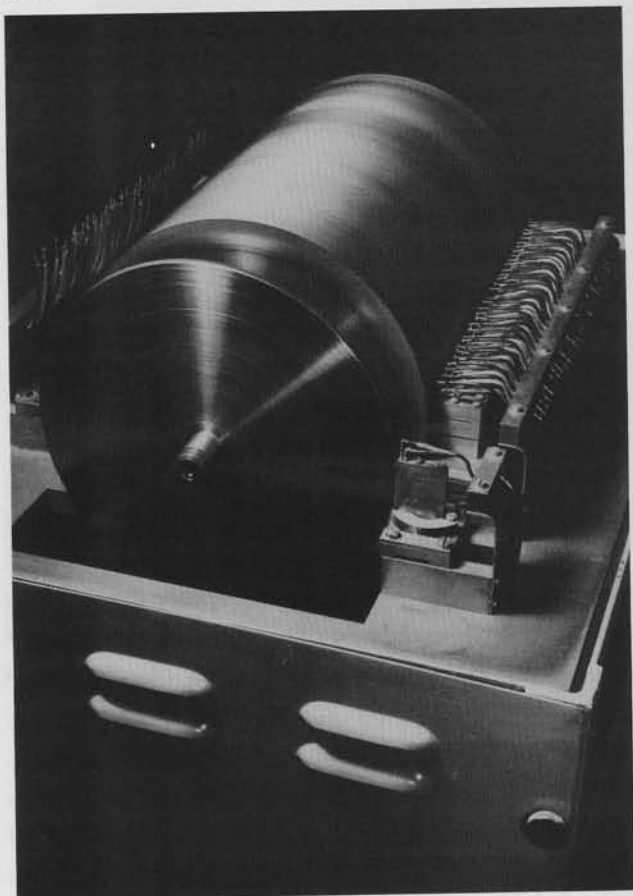


The relays for the head selection are visible in the photograph in the middle left. The amplifiers were carefully hung in rubber bands to prevent microphonic effect. The belt that worked as the Van de Graaff generator is clearly visible but the little spring contact is not.

The design of this amplifier brings me to another small story. When I entered into the laboratory as a completely green engineer with a little experience in relays but no experience in electronics, I had to design that amplifier. It should be able to amplify a signal of 1 mV coming from the drum into about 100 V output signal to drive the logic circuits (Valves you remember!). Rather much for an amplifier. The design was quickly done but my conceitedness dwindled quickly when my radio technician, who had to build the thing, very laconically pointed out, that this could never work. He said: you better put screens between

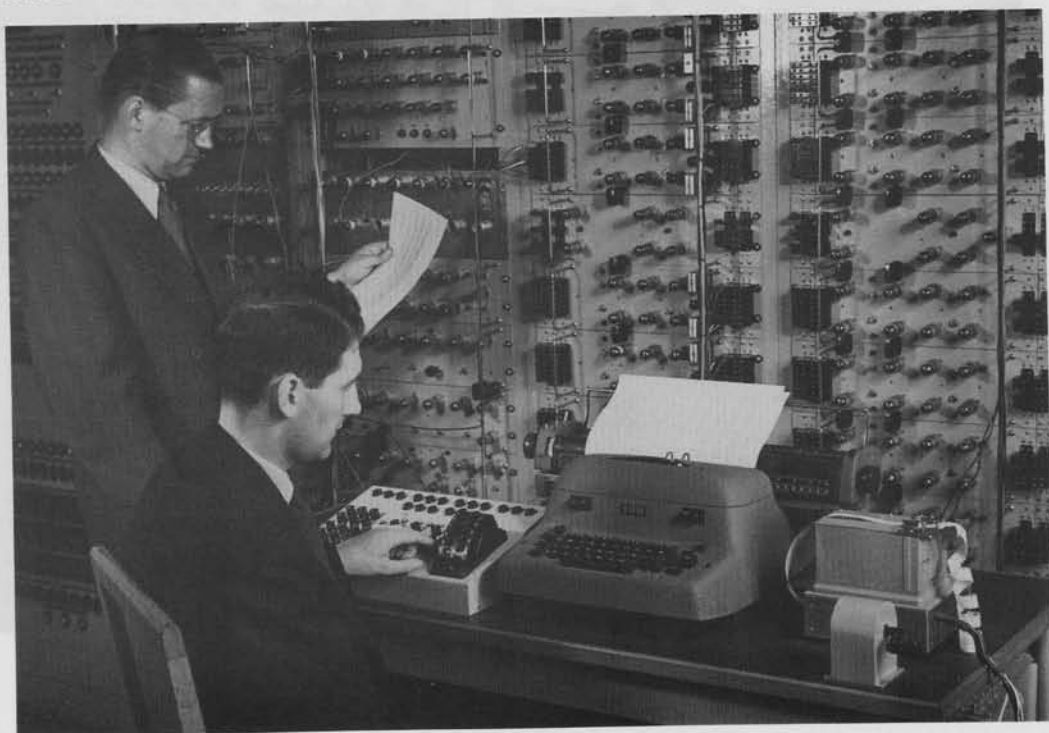
all the stages, otherwise the whole thing will be a very nice oscillator. I then learned the lesson that the people from practice know many things much better than a learned engineer from Delft, who has never met these problems in reality. From then on the division between logical design and actual construction was much better determined.

The following picture shows a close-up of the drum while spinning. The separate disk in front was the phonic wheel for the generation of the clock pulse for the whole machine. The little semicircular segment at the bottom of the head was a permanent magnet to induce a magnetic field in the otherwise neutral iron desk.

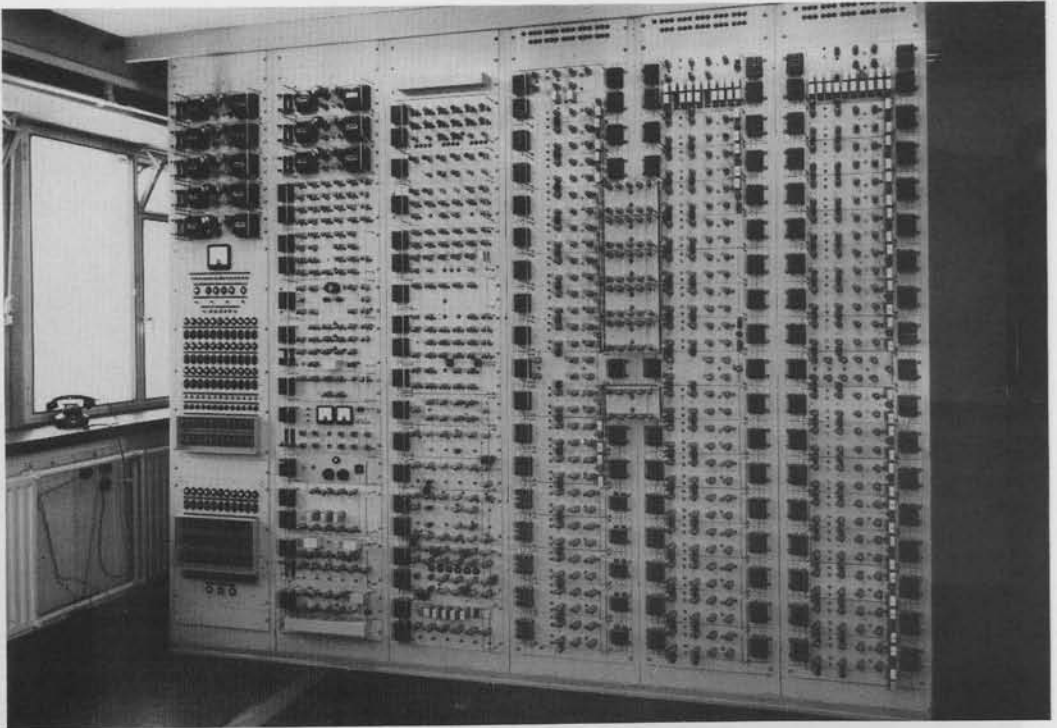


The next picture shows Kosten en Van der Poel in front of the PTERA on one of the first occasions of it doing useful work. It was still located on the second floor of an old house behind the building on the Kortenaerkade in The Hague. All good computers in those days were on the second floor of some old buildings. There

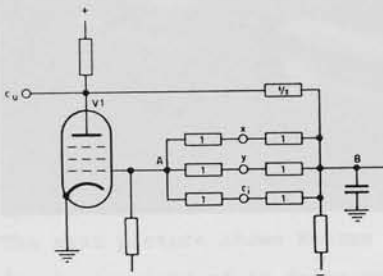
were not many, and the Mathematical Centre machine and the Cambridge University machine were also on the second floor, from which the conclusion (almost) follows!



The following photograph is PTERA in its later days when it had been transferred to the new DNL in Leidschendam.



Until so far I have not told anything about the arithmetic unit of the machine. One of the early ideas of Kosten that were fixed before I came into the scene was the adder. It was a so-called Kirchhoff adder consisting of only one single penthode and a few resistors per stage. (See figure)



Two or more incoming ones make a carry. The three resistors on the left of x , y and c form the analogue sum of the incoming signals, the penthode amplifies and forms the inverted carry to the next stage. The sum is formed by observing that

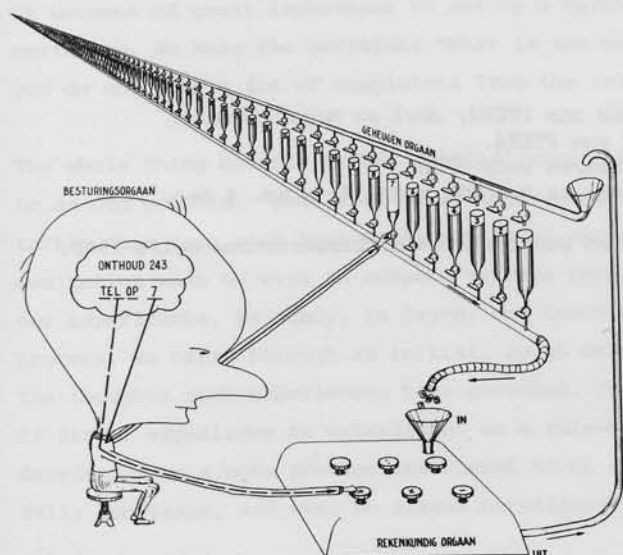
$$x + y + ci = 2cu + s$$

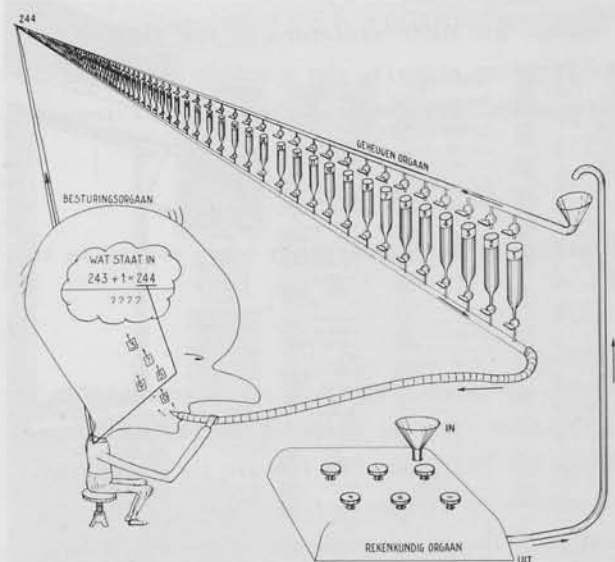
where x and y are the digits to be added, ci is the incoming carry and cu is the outgoing carry. By rewriting we set

$$s = x + y + ci - 2cu.$$

Hence, the sum can be formed by a similar network of three resistors, adding in the just inverted carry with a resistor of half the value of the others. There is only one "but". For the next stage the carry and the sum are both inverted. That would spoil the simplicity of the whole arrangement. Solution: represent 0 and 1 alternately by low/high and high/low in the successive stages. This characterizes the kind of inventiveness of Kosten very well.

As a last contribution to this anecdotic approach to the old history of computers I may present a few original pictures I still kept, drawn by Kosten himself, to illustrate the main actions of a computer in a pictorial way.





1. L. Kosten, *Wordingsgeschiedenis van PTERA; doel en mogelijkheden.*
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Yesterday's Trouble Today's Response Tomorrow's Theory

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"If you can hail a taxi on New Year's Eve, then too many taxis are available." Such a statement is not of much use when customers complain about lack of capacity within the service function, or when they do not complain due to surplus capacity.

When steady conditions prevail, it may well be that, what is acceptable, and what is not acceptable, becomes tradition. When we have to expand, however, we have to decide on the magnitude of the expansion. If we live in a period of dynamic development and increasing demands, we become uncertain about our plans. It becomes of great importance to set up a basis on which we can act with more certainty. We hear the question: "What is the minimum you can get by with, when you do not want a lot of complaints from the telephone subscribers?"

The whole thing becomes rather critical when there is a new technical solution to an old problem. "How is it going to operate?" "Is it really true that we can tackle this task with that small amount of material?" We lack the basis of evaluation when we wish to compare various technical solutions. We systematize our experiences. We study, in depth, the function and character of the service process. We carry through an initial, rough description of our experiences, and the thoughts such experiences have provoked. Then the theory begins to shape. At first, experience is established as a rule-of-thumb. As time goes by, it develops into a more precise instrument to be applied when we carry out our daily functions, and when we assess heretofore unknown conditions.

With these introductory remarks I believe I have touched on important elements in Leendert Kosten's works. In carrying out his daily tasks, Kosten has utilized his talent marvellously when he faced traffic problems. By reformulating the

problems, he also contributed to the theory when it did not live up to expectations. He observed, he showed, and substantiated WHY the already existing theory in a number of cases did actually meet the challenges of the problem. He was not only involved in the technological solution. He stood ready to carry out what you would call satisfactory service to meet the customer's needs, all the time paying due consideration to the optimal plans. He paid attention to the repercussions of the administrations' action on the customer's demands. Kosten covered a wide field - from traffic observation via traffic theory to the operational research of the traffic:

- From Yesterday's Trouble to Today's Response and Tomorrow's Theory - respecting the technological development and its optimal operational use.

Kosten has the ability to see and formulate problems the solution of which causes that wider fields than the immediately obvious ones are covered. Applying his deep technological background and vast mathematical knowledge, he tackles the solutions of such problems. He does not stop until he has reached results which satisfy his demands for quality and which are dictated by his scientific integrity. He understands the customer's problems. He does not only solve the problems that arise when the systems do not meet the customer's service demands. He is able to anticipate and remedy the difficulties before they become pronounced. Applied sciences have become a vital part of his life and attitudes.

Our Background

Application of the theory to everyday's life is a yardstick for the success of our science. How long time elapses before a theory is applied? How is it applied? We should get the inspiration from everyday life. Everyday life should also lead us when we set up our list of priorities for future research.

We do not very often talk about this. The reason is that the majority of our research workers very distinctly know, from experience, what is important and what is interesting. This applied both to the construction of systems, the comparison of tenders, and the supervision of daily operation. Many research workers also know distinctly in which cases sub-optimization is acceptable, to what extent it is advisable to carry out decentralized plans, and when it is necessary to use the more centralized plans. The latter requires, as we all know, more labour and more sophisticated methodology, and tends to create

conflicts - but this might be necessary within today's complex teletraffic network.

It is characteristic that already generations ago it was accepted that no single individual was able to deal with everything. It was not allowable to act without the assistance of specialists - with the consequent difficulties integration of experts always causes. This also applies to the adaptation of the teletraffic theorist to the tele-organization.

We have all been exposed to mathematical difficulties due to a narrow technical formulation. The result has been an operational solution which did not very well reflect real life, sometimes not even the structure of real life. We have often seen international compromises within the service area which do not at all meet the demands of everyday life. The deviation between recommendation and daily life can be considerable.

It may very well be true - as my old Professor jokingly said - that practice is incorrectly applied theory. However, when it comes to larger deviations between theory and practice, it is justifiable to ask: "WHY are the theoretical results exploited in this incompetent way?"

Do the rules of action sufficiently well meet the demands of our users, the subscribers, when it comes to various degrees of service? Is it possible for our staff - with the technical equipment available - to arrange their working day in a reasonable way? Do the responsible persons have the ability to deviate from established rules?

The theorists are not always capable of covering the many-faceted reality - at times not even the most important ones. Most of them have to compromise on one or more of the facets: Description of the traffic picture, problem formulation, choice of mathematical tool, expected control equipment, technical alternatives and alternatives of action.

Anticipation

The subscribers experience a different service. How do we respond to the subscriber's reaction which - although changes were anticipated - will come when they start using the new, different system?

So far, we have not talked about the working conditions of the persons who have to carry out the application. I am thinking of our colleagues at the exchange and planning office. It is even important how work-schedules - meeting the requirements of the operators - are made up. In a complex reality, the ability to anticipate is essential.

When we look ahead, and try to anticipate the development of teletraffic and tele-planning, it is only natural to try to do so on the background of past development.

Up to now teletraffic has mainly been centered around the service criteria. Applying probability theory, what are our possibilities to present a reliable estimate of the degree of service? On this basis we had to develop rules for an optimal or sub-optimal application to everyday life, and we had to make allowance for the restrictions prevailing in a given situation. In other words, we had to find methods of measurement for the daily control of the telephone system. We had to find methods suitable for the overall planning of larger regional extensions, and to consider the problems which are bound to turn up when we use the more or less well-formulated forecasts necessary to carry out the expansion.

The Dynamic Development in Service of Applied Sciences

It is characteristic of many research workers within teletraffic theory and tele-planning that their development goes from probability (establishment of the degree of service) via measurement technique to the establishment of rules for optimal planning. This is also true for Leendert Kosten. Very early in his professional life he took up important problems within operational research - as we would call it today. Let me mention his work on the statistical foundation for simulation. He clearly saw that data processing of the measurement material was not feasible at the time, i.e., if he applied the mathematical ethics he demanded. However, it was essential to set a fixed point before tackling this much larger problem. Such point was established in his works from 1949*).

*) "On the Accuracy of Measurements of Probabilities of Loss" by L. Kosten, J.R. Manning and F. Garwood, 1949.

It is also expressed in later works. On the basis of Bellman's innovation, dynamic programming, he tried to solve some characteristic service system problems. He studied possible rapid adaptations of price policy and resources to changed conditions within the system - problems which today are of great interest *). This is also exemplified in his beautiful work on overbooking within air traffic. **)

At this point it is only natural to draw a parallel with Conny Palm. Around 1940, Conny Palm took up measurement problems on the basis of probability theory. He characterized his observations by the so-called rapid and slow traffic variation. Later on, Conny Palm studied an interesting operational research problem: a series of machines serviced by a limited number of operators.

Kosten took up problems such as overflow, measurements, and simulation, and this proved later on to be of great value. You do not meet many people like Kosten who to such an extent become a part of their job. He has contributed so much to the literature and, I believe, Kosten feels that he has also benefited from the literature. Let me give you - although somewhat distorted - an example. That example expresses in a very simple way what I am trying to get across.

When the Erlang tools were introduced, they very soon became well known, became famous, and were applied - but how? Does the degree of service in a given situation always have to be the same? How can we establish the degree of service so that everybody can live with it in a reasonable way? Using the Erlang tool, we were now able to compute the degree of service. It suddenly became a problem, however, how to use the ensuing result.

Did we change all the rules because we now had more precise expressions for the degree of service in a number of characteristic situations? What would happen if we began to think rationally? Direct application - careful adaptation - zero change, all the time realizing that economic and institutional conditions require other and more answers than those probability theory can give you? At first sight the tools provided us with an enormous strength. We were able to

*) "On Operational Research Problems in Theory of Congestion"
International Teletraffic Congress, 1961.

**) "Traffic Theory and Dynamic Programming", 3rd International Conference
on O.R., Oslo, 1963

compare very precisely alternate systems. However, application often required that we had to wait a generation or so before the responsible persons accepted the innovation and introduced it (often in a modified form). I make this statement on the background of the generally known fact that all companies have a considerable inertia when it comes to innovations.

Molina, for instance, had, so far, used the Poisson-distribution. He was pleased with its results and he did not feel like making any changes within the Bell system. He had, like other teletraffic people, read Erlang's work with pleasure and despair (due to Erlang's unfinished way of explaining things), and he had studied his thoughts and results. Within Erlang's own company, the Copenhagen Telephone Company where, by tradition, the P.V. Christensen expression for deciding the number of lines

$$n = A + 3,3 \sqrt{A} \quad (1)$$

was used, the change to the Erlang tool did not take place overnight. When it finally was introduced, a number of additional conditions were established at the same time, e.g., the rule about overloading ability. As we know from Lubberger's works, the Germans for a long time based their rules on observed results obtained from already existing installations. They applied this procedure for not yet known cases as well.

With Moe's work from 1923-24, we were given the marginal utility principle. We learned that it was not that easy to transform the degree of service into appropriate and suitable rules. Cost, price policy, and subscribers' reactions resulted in rather complicated parameters for the establishment of rules for everyday life. Such rules were even dependent on place and surroundings - and, then, they only expressed a sub-optimization.

They covered quite a number of essential issues of the time. But we had to take a lot of things into consideration when applying them to large complex networks. We had to study hard and to listen to many viewpoints before it was possible to introduce them into practice. In other words, the final rules did often contain much more knowledge than to be seen at first sight. This is something, by the way, we also face today when service systems are automated; these systems start behaving in an unexpected way since they contain all this hidden knowledge. I

recall when Brockmeyer *) finally gave the green light for Moe's principle. This was shortly after calculations had shown that the Moe principle also contained rules about overloading. However, Brockmeyer was very attracted by the fact that we obtained a suitable result in a simple way. By the pronounced reactions of the busy hour, reflected in the integrated annual results, the subsequent plans indirectly contained overloading phenomena within the 24 hours, and within the year. The question of how to cope with the uncertainty of forecasting, however, is still of current interest.

Administration of the Results

A rule is not done with its appearance on paper. We must learn how to apply it. In the process of application, we have come across various procedures which hide unsolved problems.

In addition to the quantity of traffic (also a tool when considering the financial revenue), we have traditionally measured the number of calls rejected due to busy lines. Some people - among others Brockmeyer - put more emphasis on the "final circuit". Brockmeyer, when organizing the gradings, included therefore a "final circuit" on which he measured. In that way he obtained a relatively direct estimate of the load on the "final circuit". The Moe principle tells us what the load should be on a "fictive circuit" after the "final circuit". So, Brockmeyer's attitude was not all that different.

How we can best measure the service is still a rather disputed question. Admittedly, the basic distribution - the Poisson - distribution - is a well-established tool within telephony. Nevertheless, parameters suitable for the description of the central parts of the distribution cannot be used thoughtlessly on their tails - the basis for the service level. Within telephony we have similar difficulties, although of another kind. We wish to plan on the basis of an integrated traffic picture, to include variations in the traffic values. Due to this, the extreme value has in our discussions on measurements and service been brought into the limelight during the last decennium. This is due to the stability issue which extreme values offer.

*) former head of the Technical Department's Traffic Group on Gradings at The Copenhagen Telephone Company.

During the last 20 years - during which period we have been facing an increased number of complications due to Repeated Attempts, we have learned how very difficult it is to unite our own desire of stringency of thought and mathematics with practical easy-to-handle results. At the beginning this was due to an overloaded, international network. Today it is because traffic tends to aim at a few, but very busy numbers. Therefore, we will be discussing for a long time the issue of increased concentration of traffic.

The Stony Way of Applied Mathematics

I hope I have been able to give you some impression of the very difficult situation the researcher within applied mathematics is facing. He has to live up to the ethics of the mathematician, of the engineer, and of the economist in such a way that the administrator feels he can act in a reasonable way. This might be conveyed directly, but often indirectly, yes, at times only expressed through the mathematician's personality.

Throughout the years Kosten has so eminently demonstrated his talent for writing a problem formulation in such a way that it was acceptable both to the mathematician and the engineer - resulting in a mathematically elegant solution operable for the administrator. All during his life he has been the pioneer. He has always anticipated events.

I only need to mention the work by Kosten, Manning and Garwood. This paper tells us so well how Kosten is thinking. He asks: "What is simulation worth? What can the results tell us about measurement?" This is also expressed in his 1961 work about the OR-minded innkeeper. Here he also anticipated problems - flexible price policy when time was running out - today of interest when we discuss price discrimination. He has exploited Bellman's dynamic programming exactly according to its "recipe". Again he demonstrated his mathematical abilities. To be quite honest, such demonstration was not at all what Bellman had in mind. In the sixties, when I discussed it with him, Bellman told me that he never intended his expressions to be solved in a purely mathematical way. He had wanted to give some hints aimed at a numerical solution. However, Bellman forgot to tell his readers this. You cannot blame those who took what he wrote literally - and certainly not those who reached a mathematical solution, as Kosten did.

Teletraffic Congresses for the openness and spontaneity with which you have left a mark on our meetings - aspects that are so very important for our professional and human growth, and our adaptation to the still changing surroundings.

For the benefit of the next generations, I very much hope that in the future we can also account on you in discussions at our meetings and gatherings all over the world. You still have what the youth has - enthusiasm!

Simulation: from OR Technique to a Field of Science

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The title of this paper suggests that the development of simulation techniques and methodologies started in the field of operational research, which is certainly not true. This paper just points out how this development is performed in the operational research section of the department at Delft's University of Technology during the time L. Kosten was responsible for this section. It follows the ups and downs of one of the many ways the development of simulation has taken place.

0. Introduction

Simulation can be defined as a way to study the dynamic behaviour of a system by means of experimentation with a model of that system.

In this sense simulation is a rather old technique. The first simulations were used to study war situations where the models were constructions of wood and sand or consisted of special maps. Well-known is the "Neues Kriegsspiel" used at Schleswig in 1798.

In this paper only digital simulation will be considered which means that the model consists of a program for a digital computer, but the word 'digital' will be dropped for reasons of simplicity.

As soon as people learnt to program digital computers, simulation was used to study systems belonging to almost all fields of science. Those first simulation users discovered and rediscovered several simulation techniques and principles, sometimes not even realizing that they were simulation users at all.

During the past twenty years simulation has grown out towards a field of science itself.

In 1977 Oren (10) counted:

- over 200 application areas
- 23 associations or groups specializing in simulation
- over 1300 doctoral dissertations
- over 1000 terms of special terminology
- about 12 conferences or symposia each year
- 18 special periodicals
- more than 300 books.

Simulation is and has always been a very important tool in the practice of operational research (12). Therefore, operational researchers contributed to the development of simulation.

As to all techniques that looked promising for solving problems Kosten paid special attention to simulation. Already in 1955 (5) he predicted the importance of the use of digital computers for simulation investigations. Due to him we shared those developments as will be discussed below.

1. The Early Sixties

In 1962 Kosten spent two hours of his student course on waiting-line and blocking models to explain the use of discrete simulation and Monte-Carlo techniques. This does not look very much, but we must realise now that those lectures were the first ones about discrete simulation in the Netherlands. In these lectures he explained how the problem to simulate parallel processes can be solved by replacing those processes by just one process: the consecutive calculations of the changes in the state variables caused by events. This so called 'event description modelling method' can be applied in all cases where the occurrence of events takes no system time, which causes the state variables to be discrete time functions. This method covered almost all models we used in the practice of operational research, certainly those describing tele-traffic systems. Therefore we did not pay any attention to techniques belonging to continuous simulation. We did not even distinguish between the use of numerical analysis and continuous simulation. But not only we were guilty: during the whole sixties those two fields were completely separated.

In those days we first of all were problem solvers without any sense of methodology or model building theory: straightforward, no highbrow, and we enjoyed it.

Kosten paid attention to the construction and testing of random number generators, especially those based on the additive congruential - fibonacci - principle were his favorites. Among investigations to improve O-R techniques he tried to combine heuristic methods with Monte-Carlo techniques. I clearly remember one of those efforts: Kosten tried to tackle the travelling salesman problem with such a combination. Each time the salesman must be moved to a next place, all remaining places were ranked according to some heuristic rule and then the selection was made from the top down using a Monte-Carlo method with a decreasing series of probabilities with sum one. For every choice of these probabilities the algorithm had to be repeated several times to obtain statistical information about the influence of randomness. I calculated that the whole investigation would take 24 hours cpu time of our very new and 'fast' TR-4 computer. Rather upset I asked Kosten whether I should go through with it. 'Of course', he replied calmly: 'research will never be stopped'. And so it happened: six runs of four hours each. This special investigation was not very successful but the same idea proved its value when solving the line balancing problem several years later (9).

2. The Late Sixties

In this period we really started with research about simulation techniques, -languages and modelling methods.

It was about time to do so because the world was not waiting for us. Remember that:

- in 1962 Forrester wrote his "Industrial Dynamics" while Pugh constructed a simulation language called "Dynamo" for it.
- Important simulation languages for discrete simulation already existed. Widely distributed in 1965 were: (in order of appearance) GPSS, SIMSCRIPT, CSL and SIMULA I.
- in 1965 a one week conference about the use of digital simulation in Operational Research was held in Hamburg.

Kosten got things started by posing the question: "Why, are there so many simulation languages?" (It turned out to be a good question; some time later we

counted 52 languages or packages.)

The 'Stichting het Nederlands Studiecentrum voor Administratieve Automatisering' was very helpful by starting a working group with almost all Dutch 'specialists' in simulation gathered to answer Kosten's question and to study several simulation features.

Kosten was chairman of this group and caused us to make up our arrears. I can not remember how many languages we had to study in a few months but it must be at least ten. Most languages were badly described but for the most important ones members of this working group were available to supply information.

We discovered that:

- continuous simulation languages contain more simulation facilities than numerical methods to solve differential equations do. However, the programming facilities particularly those for parallel processing were rather poor at that time.
- there were three modelling methods for discrete simulation:
 - * the event description method used in SIMSCRIPT ('SIMSCRIPT's world view') and GASP as it was already known to us.
 - * the activity description method used in CSL. In this case the dynamic behaviour of a system is described by summing up all the actions that change the state of the system. For each action a set of conditions must be specified to enable the performance of that action.
 - * the process description method used in GPSS and SIMULA 1 where the system is described by descriptions of the behaviour of the 'living' components of the system. This method models a system in the most natural way.
- there was an ambiguous use of simulation terms and only a few efforts to define a methodology apart from the rules needed to use special languages.
- the main reason for the existence of all those discrete simulation languages was that discrete simulation needs dynamic core allocation and list processing. Those features are not available in ALGOL60 and FORTRAN.

Kosten reintroduced his roulette model principle (6,7). This principle which he already described in 1942 (8), reduces simulation to a Monte-Carlo technique in

those cases where every change in the state of a system is independent of what 'happened before'. This so called 'memoryless property' holds in many tele-traffic models for instance models to solve grading problems.

If this memoryless property holds it does not matter how long a system remains in a state.

Just the number of times a state occurs gives enough information to calculate the answer to almost all questions.

Because the changes of the state are ruled by known probabilities every next state can be found by means of the Monte-Carlo principle. Therefore this method causes a substantial reduction of cpu time.

Before getting familiar with discrete simulation languages we used ALGOL60 for our simulations. I extended ALGOL60 with a set of procedures called 'the entity room procedures' to cover the lack of dynamic core allocation and list processing. During the meetings of the working group it turned out that Kerbosch (Eindhoven University of Technology) constructed a similar set of procedures called 'hook on and hook off procedures'. Therefore we combined efforts. Our general ideas were:

1. to make list processing features available for simulation users.
2. to define a modelling method based on the event and activity description methods.

We had some good reasons to proceed in this direction:

- The process description method could not be implemented in ALGOL60 and FORTRAN without the use of assembly language.
- We both had some bad experiences with what we called 'underwater programming features' as they occur in most simulation languages (especially GPSS).
- Most programmers were rather stuck to the use of ALGOL or FORTRAN not willing to learn and to use special languages for simulation purposes.
- The event - as well as - the activity modelling method can be easily applied in ALGOL60 and FORTRAN.

Therefore Kerbosch and I wrote a book (4) in which we explained the use of discrete simulation. Furthermore this book contains the complete texts of the so called ASP procedures in ALGOL60, FORTRAN and PL/1 providing dynamic core allocation and list processing for almost every programmer. It took us a long time to overcome many difficulties (as for instance to specify and define simulation

terms). Luckily we were supported by a number of enthusiastic colleagues solving many problems for us.

3. The Early Seventies

During the seventies simulation grew to a field of science. Studies about simulation methodology and model building theory (17) appeared. Simulation users learnt to understand each other. The walls between continuous simulation and discrete simulation crumbled away. Even people using analogue/hybrid computers and people using digital computers find each other at the same simulation conferences with more or less understanding. It may be expected that in the next decenniads the chips will break down the last obstacles between simulation users.

Already in the early seventies I spent most of my time with simulation activities neglecting operational research studies. I am still grateful to Kosten that he let me have my way but it caused a separation through which I miss the enthusiastic talks and the many lessons he taught me when we discussed so many problems.

Those days were rather chaotic because lots of investigators belonging to several fields of science started to use simulation and asked for assistance. Several specialists among Kosten and I tried to stop the chaos by organizing symposia and writing chapters about simulation in text-books (1,2,3).

In the same time it occurred that the event description modelling method was not as good as we supposed it to be some years before. The method fails when very complex systems must be modelled because this method depends on a set of well defined state variables. If a system is complex, such a set cannot be defined in advance. (It is one of the main reasons that cause a system to be called 'complex'.) The process description modelling method which enables to model a system according to the 'top down' approach must be more promising. Following the principle that simulation must be possible using general purpose languages, I investigated the possibility to implement the process description method in PL/1 and found out that this could be done but that it would be a tedious job. Fortunately I found my colleague Onno de Gans willing to be my partner.

We started in 1973 with the construction of a software system in PL/1 for discrete simulation called PROSIM (13,14) (PROcess SIMulation) based on the process

description method. The first PROSIM programs run in 1974. From that moment on this software system is used successfully in several Dutch industries and institutes.

4. The Late Seventies

Although some specialists in the late sixties doubted that combined discrete-continuous simulation would be possible, languages for combined simulation were constructed.

GASP IV (11) was the first (1973) well-documented combined simulation language. It is based on the event description method using FORTRAN as reference language. For reasons mentioned above it will be clear that we wanted to combine continuous simulation with the process description method.

The main problem was to create a modelling concept for such a combination. From the methodology of System Theory the next deduction can be obtained:

The state of a system is the union of the states of its components while the state of a component is given by the values of its time dependent attributes. Therefore, in principle, every time dependent variable in a model whether it is a discrete or a continuous variable must be an attribute of some component.

Because the changes of attribute values are caused by activities of components, integration of continuous attributes ought to be carried out as activities of components too.

According to this concept the implementation of continuous attributes in PROSIM was developed rather quickly (15). As a consequence of the concept, the problem of parallel integration of sets of differential equations - which causes the newest developments in continuous simulation - was solved too because every component can have its own continuous attributes, specified as a set of differential equations, while the components integrate their differential equations apart from each other. It is remarkable to note how quickly people get accustomed to the use of combined simulation. We were never asked for the construction of a combined language while some years later some users maintain that they could not solve the problems without it!

During four years of experience with PROSIM we discovered that:

- the world is full of modellers but only a few of them are programmers too. People not being familiar with programming have many problems with the use of PL/1 based structures and pointer variables.
- readability of programs is of greater importance than we ever could imagine. In the early days a simulation investigation in most cases was a one man's job. Nowadays many systems to be simulated are so complex that teams or working groups are involved. Therefore simulation programs must be very good readable for reasons of communication.

From these statements it follows that a simulation language must be a modelling language in the first place. The construction of modelling languages is the newest development in the research of digital simulation. The ideal is to deliver the user a language containing modelling concepts in which he can describe a system without any need of programming knowledge. With PROSIM78 (16), Onno and I tried to make the first steps. This language enables the user to describe a system directly in terms of components, classes of components, attributes, queues etc. The relations between components follow from the process or activity descriptions of the living ones. The PROSIM78 user does not need knowledge of PL/1, however he must have any idea about programming, we are not yet able to avoid that. The first experiences are hopeful; the mean time needed for a simulation investigation is decreased again and more people are able to use simulation than before.

5. Prospects

The field of simulation is increasing so rapidly that it is hard to predict its future course. Some developments are rather clear:

- minicomputers will be constructed for special simulation purposes.
- computer assisted model building will become available.
- special features for data handling will be implemented in simulation software.
- simulation methodology together with modelling languages will enable people to tackle large-scale systems.
- modelling languages will become more hardware independent offering a lot of techniques in a user-friendly way.
- modelling theory will become of greater importance in education.

For the two of us it is impossible to share all those activities. For the present v will be busy to extend PROSIM78 with the following developments in mind:

- features for decomposition of models which, for instance, enables interchanging of submodels.
- the implementation of optimizing methods in a user-friendly way.
- automatic control of numerical methods.
- features to define sets of differential equations in matrix notation.
- features to enable the use of the so called 'method of finite elements' in a convenient way.
- features to perform statistical analyses for input and output variables.

However, we realise that this list will grow quicker than we are able to get through it.

6. Epilogue

Speaking about the complexity of systems Kosten stated in 1955:

"It is certain, that only general purpose computers show enough flexibility to deal with problems possessing characteristics that vary so widely".

Ever since that time he successfully used digital computers for simulation purposes. Especially during the sixties, he investigated many simulation features and opened the ways for further explorations. Due to him the developments described above could be achieved.

Dear professor Kosten, I am very grateful to you for all your wise lessons and the way you guided me!

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List of Students who took their Master's Degree under Professor Kosten's Supervision

- | | | | |
|------|---|------|---|
| 1962 | F.W. Hoff
W.A. Masselink
P.A. Tas
Mw. E. Terpstra-Meijers | 1971 | J.C. Derriks
H. Dijkers
H. Geerling
T.C.A. Mensch
W.R.P.C. Stiphout
H.H.M. Vinkenburg |
| 1963 | H. Kamphorst
A.G. Noordam
C. de Ridder
N.F. Wiersema | 1972 | J.R. de Cuba
L.C.J.M. Obels
J.A.M. Schreuder |
| 1964 | D.J. de Boer
M.L.L. Nuyts
J. Wildschut | 1973 | A.K. Blaauw
J.C. Kooij
J.F. Storm |
| 1965 | J.C. Abbink
A.P. van Baardwijk
W.L.C.H.M. van den Berg
A. Kreuzen
R. de Regt
H. Schipper | 1974 | Th. Geerinck
H.G.M. de Koning
M.A. Mulder
R.F. de Voogd
O.J. Vrieze |
| 1966 | A.M. ten Broeke
L.A. Eijgenraam
L.B.D. Harkema
W. Jensema
J. Molenaar | 1975 | R.T. van der Ham
B.J. Wering |
| 1967 | J.F.L. Hazelzet
L. Sombroek
R. Tanis
H. Terpstra
N. Wit | 1976 | P.B. Berger
W.J. van der Bilt
S.C. Enzler
L.C. Fierloos
L. Hoedemaker
J. Koene
Mw. M. Kruit
W.P.A. Schuyffel |
| 1968 | W.L. van Dinten
J. de Lang
L.B.J.M. Sturm
Th. Viergever
D. te Winkel | 1977 | R.J. Steenge |
| 1969 | R.V.H. Vinke | 1978 | G.F. Boulogne
C. Noordegraaf |
| 1970 | A.J. te Boveldt
P.M. Bruys
W.P.A. van der Heyden
T.J. Stahlie | 1980 | B. Kievits
R.W.J. Plazier |

List of Students who took their Doctor's Degree under Professor Kosten's Supervision.

The doctor's degree under the supervision of Prof. Kosten was obtained by:

H.J. Heijn, May 1960, on the thesis entitled: *Representation of Switching Functions and their Applications to Computers.*

List of Scientific Publications by L. Kosten

1934

1. Over damping, afkomstig van verliezen in spoelen en condensatoren van reciproke filters, *De Ingenieur*, 49 no. 15 (1934) pp. E169 - E173.
2. *De bedrijfsdamping van niet-ideale filters*, Mededeeling van het Zwakstroom-laboratorium der Technische Hoogeschool te Delft, Delft, 1934.

1935

3. Zur Theorie der Ausgleichvorgänge auf homogenen Leitungen, *Elektrische Nachrichten Technik*, 12 no. 2 (1935) pp. 60 - 68.
4. Anwendung eines operatorischen Entwicklungssatzes in der Theorie der Ausgleichvorgänge auf homogenen Leitungen, *Elektrische Nachrichten Technik*, 12 no. 8 (1935) pp. 231 - 236.
5. Ueber einen neuen Entwicklungssatz der Operatorenrechnung, *Christiaan Huygens*, 13 no. 6 (1935) pp. 312 - 320.
6. (with C.W. Kosten) Experimenteel onderzoek over den trillingsvorm van snaren, *Nederlandsch Tijdschrift voor Natuurkunde*, 2 (1935) pp. 3 - 50.

1937

7. Sur la probabilité d'encroûtement dans les multiplages gradués, *Annales des PTT* 26 no. 11 (1937) pp. 1002 - 1019.
8. Ueber Sperrungswahrscheinlichkeiten bei Staffelschaltungen, *Elektrische Nachrichten Technik*, 14 no. 1 (1937) pp. 5 - 12.

1942

9. *Over blokkeerings- en wachtproblemen*, Doctoral Thesis, Delft University of Technology, 1942.

1943

10. On the frequency distributions of the number of discharges counted by a Geiger-Müller-counter in a constant interval, *Physica*, 10 (1943) pp. 749 - 756.

1947

11. Over het bepalen van een verdeelingsfunctie uit haar momenten, *Handelingen XXXe Nederlands Natuur- en Geneeskundig Congres*, Delft, 1947, pp. 106 - 107.
12. Over de invloed van herhaalde oproepen in de theorie der blokkeringskansen, *De Ingenieur*, 59 no. 47 (1947) pp. E123 - E131.

1948/1949

13. On the measurement of congestion quantities by means of fictitious traffic, *Het PTT-bedrijf*, 2 no. 1 (1948/1949) pp. 15 - 25.
14. On the validity of the Erlang- and Engset loss-formulae, *Het PTT-bedrijf*, 2 no. 2 (1948/1949) pp. 42 - 45.
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17. Electronische rekenmachines; Algemene opbouw en uitvoeringsvormen, *Tijdschrift Nederlands Radiogenootschap*, 15 no. 6 (1950) pp. 313 - 338.
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19. Electronische kansorganen, *Het PTT-bedrijf*, 3 no. 4 (1951) pp. 135 - 144.
20. Over de nauwkeurigheid van metingen van stagnatiekansen en van de verwachtingswaarden van wachttijden, I. Schatting van stagnatiekansen, *Het PTT-bedrijf*, 3 no. 3 (1951) pp. 98 - 109; II. Schatting van verwachtingswaarden van wachttijden, *Het PTT-bedrijf*, 4 no. 1 (1951) pp. 26 - 33.
21. Beschrijving van een machine voor kunstmatig verkeer op electronische basis, *De Ingenieur*, 63 (1951) pp. E17 - E21.
22. Waarschijnlijkheidsrekening in de telecommunicatietechniek, *Proceedings Symposium over toepassing van statistiek en waarschijnlijkheidsrekening in de techniek*, Koninklijk Instituut van Ingenieurs, The Hague, 1951, pp. 81 - 91.
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25. PTERA I. Wordingsgeschiedenis van PTERA; doel en mogelijkheden, *Het PTT-bedrijf*, 5 no. 4 (1953) pp. 116 - 123.

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26. *Mens en automaat*, Rede uitgesproken bij de aanvaarding van het ambt van gewoon hoogleraar aan de Technische Hogeschool te Delft, Delft, 1956.

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27. Application of artificial traffic methods to telephone problems, Paper presented at The First International Congress on the Application of the Theory of Probability in Telephone Engineering and Administration (Copenhagen, 1955), *Teleteknik*, 1 no. 1 (1957) pp. 107 - 110.

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28. Een mathematisch model voor een reserveringsprobleem, *Statistica Neerlandica*, 14 no. 1 (1960) pp. 85 - 94.
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30. *On operational research problems in congestion theory*, Report Delft University of Technology, Department of Mathematics, 1961.

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31. De betekenis van de simulatiemethode voor de natuurwetenschappen, *Maandblad voor Accountancy en Bedrijfshuishoudkunde*, 39 no. 2/3 (1962) pp. 79 - 82.

1963

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1965

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38. Simulatie in het algemeen, *Informatie*, 10 no. 3 (1968) pp. 55 - 60.
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40. Simulation in traffic theory, *Proceedings 6th International Teletraffic Congress*, München, 1970, pp. 411/1 - 411/8.

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