

Exact solution to a Lindley-type equation on a bounded support

Citation for published version (APA):

Vlasiou, M., & Adan, I. J. B. F. (2005). *Exact solution to a Lindley-type equation on a bounded support*. (Report Eurandom; Vol. 2005032). Eurandom.

Document status and date:

Published: 01/01/2005

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Exact solution to a Lindley-type equation on a bounded support

M. Vlasiou[†]
I.J.B.F. Adan^{†‡}

September 8, 2005

Abstract: We derive the limiting waiting-time distribution F_W of a model described by the Lindley-type equation $W = \max\{0, B - A - W\}$, where B has a polynomial distribution. This exact solution is applied to derive approximations of F_W when B is generally distributed on a finite support. We provide error bounds for these approximations.

[†]EURANDOM, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.

[‡]Department of Mathematics & Computer Science, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.

1 Introduction

Consider a server alternating between two service points. At each service point there is an infinite queue of customers waiting to be served. Only one customer can occupy each service point. Once a customer enters the service point, his total service is divided into two separate phases. First there is a preparation phase, where the server is not involved at all. After the preparation phase is completed the customer is allowed to start with the second phase, which is the actual service. The customer either has to wait for the server to return from the other service point, where he may be still busy with the previous customer, or he may commence with his actual service immediately after completing his preparation phase. This would be the case only if the server had completed serving the previous customer and was waiting for this customer to complete his preparation phase. The server is obliged to alternate; therefore he serves all odd-numbered customers at one service point and all even-numbered customers at the other. Once the service is completed, a new customer immediately enters the empty service point and starts his preparation phase without any delay. In the above setting, the steady-state waiting time of the server W is given by the Lindley-type equation (cf. Vlasiou *et al.* [10])

$$W = \max\{0, B - A - W\}, \quad (1.1)$$

where B and A are the steady-state preparation and service time respectively.

It is interesting to note that this equation is very similar to Lindley's equation. The only difference between the two equations is the sign of W at the right hand side. Lindley's equation describes the relation between the waiting time of a customer W and the interarrival time A and service time B in a single server queue. It is one of the fundamental and most well-studied equations in queuing theory. For a detailed study of Lindley's equation we refer to Asmussen [1], Cohen [4], and the references therein.

The model described by (1.1) applies in many real-life situations that involve a single server alternating between two stations. It was first introduced by Park *et al.* [7], who study a two-carousel bi-directional system that is operated by a single picker. In this setting, the preparation time B represents the rotation time of the carousels and A is the time needed to pick an item. It is assumed that B is uniformly distributed, while the pick time A is either exponential or deterministic. The authors are mainly interested in the steady-state waiting time of the picker. This problem is further investigated in Vlasiou *et al.* [11], where the authors expand the results in [7] by allowing the pick times to follow a phase-type distribution.

In general, it is not possible to derive a closed-form expression for the distribution of W for every given distribution F_B of B (or F_A of A). In [10] the authors derive an exact solution under the assumption that A is generally distributed and B follows a phase-type distribution. For the classic Lindley-equation, the M/G/1 single server queue is perhaps the most easy case to analyse. The analogous scenario for our model would be to allow the service time A to be exponentially distributed and the preparation time B to follow a general distribution. For this model though, the analysis is not straightforward, as is the case for Lindley's equation. The structure of F_B (or the lack thereof) is essential for this model. If F_B belongs to a specific class of distributions, exact computations are possible. This class of distributions includes at least all distribution functions that have a rational Laplace transform and a density on an unbounded support. Both this class and the closed-form expression for the distribution of W are described in detail in Vlasiou [9].

Despite the fact that this class is fairly big, it does not include all distribution functions. For example, if F_B is a Pareto distribution, the method described in [9] is inapplicable. Polynomial distributions are another example of distributions that do not belong to this class. However, they are extremely useful, since they can be used to approximate any distribution function that has a

bounded support. Our main goal in this paper is to complement the above mentioned results by deriving a closed-form expression of the steady-state distribution of the waiting time, F_W , under the assumption that A is exponentially distributed and B follows a polynomial distribution. In Section 2 we derive F_W under these assumptions. As an application, in Section 3 we discuss how one can use this result in order to derive good approximate solutions for F_W when B is generally distributed on a bounded support, and we provide error bounds of these approximations.

2 Exact solution of the waiting time distribution

In this section we derive a closed-form expression of F_W , under the assumption that A is exponentially distributed and B follows a polynomial distribution. Without loss of generality we can assume that F_B has all its mass on $[0, 1]$. Therefore, let

$$F_A(x) = 1 - e^{-\mu x} \quad \text{and} \quad F_B(x) = \begin{cases} \sum_{i=0}^n c_i x^i, & \text{for } 0 \leq x \leq 1; \\ 1, & \text{for } x \geq 1, \end{cases} \quad (2.1)$$

where $\sum_{i=0}^n c_i = 1$. Let $X = B - A$. As we have shown in [9, Section 4], the mapping

$$(\mathcal{T}F)(x) = 1 - \int_x^\infty F(y-x) dF_X(y) \quad (2.2)$$

is a contraction mapping –with the contraction constant equal to $\mathbb{P}[B > A]$ – in the space $\mathcal{L}^\infty([0, \infty))$, i.e., the space of measurable and bounded functions on the real line with the norm

$$\|F\| = \sup_{x \geq 0} |F(x)|.$$

Furthermore, we have shown that F_W , provided that it is continuous, is the unique solution to the fixed-point equation $F = \mathcal{T}F$. Then from (2.2), for $F = F_W$, we have that

$$\begin{aligned} F_W(x) &= 1 - \int_x^\infty F_W(y-x) dF_X(y) \\ &= 1 - \mathbb{P}[X - W \geq x] = \mathbb{P}[B - W - A \leq x] \\ &= \int_0^\infty \int_0^\infty \mathbb{P}[B \leq x + z + y] dF_A(z) dF_W(y) \\ &= \pi_0 \int_0^\infty F_B(x+z) \mu e^{-\mu z} dz + \int_{0+}^\infty \int_0^\infty F_B(x+y+z) \mu e^{-\mu z} dz dF_W(y), \end{aligned} \quad (2.3)$$

where π_0 is the mass of the distribution at the origin, i.e., $\pi_0 = \mathbb{P}[W = 0]$. Now, by differentiating with respect to x , we have after some rewriting (cf. [9, Section 6]) that

$$f_W(x) = \mu F_W(x) - \mu \pi_0 F_B(x) - \mu \int_0^\infty F_B(x+y) f_W(y) dy. \quad (2.4)$$

Since B is defined on $[0, 1]$, then from Equation (1.1) it emerges that W is also defined on the same interval. Therefore, the integrand at the right-hand side of (2.4) is nonzero only on $[0, 1]$. So, substituting (2.1) in (2.4), we obtain for $0 \leq x \leq 1$,

$$\begin{aligned} f_W(x) &= \mu F_W(x) - \mu \pi_0 \sum_{i=0}^n c_i x^i - \mu \int_0^{1-x} \sum_{i=0}^n c_i (x+y)^i f_W(y) dy - \mu \int_{1-x}^1 f_W(y) dy \\ &= \mu F_W(x) - \mu \pi_0 \sum_{i=0}^n c_i x^i - \mu \sum_{i=0}^n \sum_{k=0}^i c_i \binom{i}{k} x^{i-k} \int_0^{1-x} y^k f_W(y) dy - \mu \int_{1-x}^1 f_W(y) dy. \end{aligned} \quad (2.5)$$

We know from [9, Section 3] that (2.5) has a unique solution f_W and π_0 , provided that they satisfy the normalisation equation

$$\pi_0 = 1 - \int_0^1 f_W(x) dx. \quad (2.6)$$

To determine f_W and π_0 , we shall transform the integral equation (2.5) into a (high order) differential equation for f_W . Let $f^{(i)}$ denote the i -th derivative of a function f . Then differentiating (2.5) with respect to x yields

$$\begin{aligned} f_W^{(1)}(x) &= \mu f_W(x) - \mu \pi_0 \sum_{i=1}^n i c_i x^{i-1} - \mu \sum_{i=0}^{n-1} \sum_{k=0}^i c_{i+1} (i+1) \binom{i}{k} x^{i-k} \int_0^{1-x} y^k f_W(y) dy \\ &\quad + \mu \sum_{i=0}^n \sum_{k=0}^i c_i \binom{i}{k} x^{i-k} (1-x)^k f_W(1-x) - \mu f_W(1-x) \\ &= \mu f_W(x) - \mu \pi_0 \sum_{i=1}^n i c_i x^{i-1} - \mu \sum_{i=0}^{n-1} \sum_{k=0}^i c_{i+1} (i+1) \binom{i}{k} x^{i-k} \int_0^{1-x} y^k f_W(y) dy \end{aligned}$$

and in general, for $\ell = 1, 2, \dots, n$,

$$f_W^{(\ell)}(x) = a_\ell(x) + \sum_{j=0}^{\ell-1} \nu_{n-j} (-1)^{\ell-1-j} f_W^{(\ell-1-j)}(1-x), \quad (2.7)$$

where

$$\begin{aligned} \nu_{n-j} &= \mu \sum_{i=0}^{n-j} \frac{(i+j)!}{i!} c_{i+j} \\ a_\ell(x) &= \mu f_W^{(\ell-1)}(x) - \mu \pi_0 \sum_{i=0}^{n-\ell} \frac{(i+\ell)!}{i!} c_{i+\ell} x^i - \mu (-1)^{\ell-1} f_W^{(\ell-1)}(1-x) \\ &\quad - \mu \sum_{i=0}^{n-\ell} \sum_{k=0}^i c_{i+\ell} \frac{(i+\ell)!}{i!} \binom{i}{k} x^{i-k} \int_0^{1-x} y^k f_W(y) dy. \end{aligned} \quad (2.8)$$

From (2.7) we have that the n -th derivative of f_W is given by

$$\begin{aligned} f_W^{(n)}(x) &= \mu f_W^{(n-1)}(x) - \mu \pi_0 n! c_n - \mu (-1)^{n-1} f_W^{(n-1)}(1-x) \\ &\quad - \mu n! c_n \int_0^{1-x} f_W(y) dy + \sum_{j=0}^{n-1} \nu_{n-j} (-1)^{n-1-j} f_W^{(n-1-j)}(1-x) \\ &= \mu f_W^{(n-1)}(x) - \mu \pi_0 n! c_n - \mu n! c_n \int_0^{1-x} f_W(y) dy + \sum_{j=1}^{n-1} \nu_{n-j} (-1)^{n-1-j} f_W^{(n-1-j)}(1-x), \end{aligned}$$

which implies that for $0 \leq x \leq 1$,

$$\begin{aligned} f_W^{(n+1)}(x) &= \mu f_W^{(n)}(x) + \mu n! c_n f_W(1-x) + \sum_{j=1}^{n-1} \nu_j (-1)^j f_W^{(j)}(1-x) \\ &= \mu f_W^{(n)}(x) + \sum_{j=0}^{n-1} \nu_j (-1)^j f_W^{(j)}(1-x). \end{aligned} \quad (2.9)$$

Up to this point, we have differentiated Equation (2.5) a total of $n + 1$ times. Therefore, we need a total of $n + 1$ additional conditions in order to guarantee that any solution to (2.9) is also a solution to (2.5). Since for every value of x in $[0, 1]$, Equations (2.5), (2.7), and (2.9) are satisfied, then we can evaluate all these equations for a specific x , say $x = 0$, which provides us with the $n + 1$ initial conditions, for $\ell = 1, 2, \dots, n$,

$$f_W^{(\ell)}(0) = a_\ell(0) + \sum_{j=0}^{\ell-1} \nu_{n-j} (-1)^{\ell-1-j} f_W^{(\ell-1-j)}(1) \quad (2.10)$$

and $f_W^{(n+1)}(0) = \mu f_W^{(n)}(0) + \sum_{j=0}^{n-1} \nu_j (-1)^j f_W^{(j)}(1).$

So we now have that Equation (2.9) has a unique solution that satisfies these conditions, along with the normalisation equation (2.6).

Equation (2.9) is a homogeneous linear differential equation, not of a standard form because of the argument $1 - x$ that appears at the right-hand side. Therefore, we need to proceed with caution. Note that the unknown probability π_0 is not involved in (2.9). We shall solve this equation by transforming it into a differential equation we can handle. To this end, substitute x for $1 - x$ in (2.9), to obtain the equation

$$f_W^{(n+1)}(1 - x) = \mu f_W^{(n)}(1 - x) + \sum_{j=0}^{n-1} \nu_j (-1)^j f_W^{(j)}(x). \quad (2.11)$$

Equations (2.9) and (2.11) form a system of equations. Now let

$$\mathbf{f}_W(x) = \begin{bmatrix} f_W(x) \\ f_W(1 - x) \end{bmatrix}, \quad \mathbf{A}_n = \begin{bmatrix} 1 & 0 \\ 0 & (-1)^n \end{bmatrix}, \quad \text{and } \mathbf{J} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

Then the system of equations (2.9) and (2.11) can be rewritten as

$$\mathbf{f}_W^{(n+1)}(x) = \mu \mathbf{A}_{n+1} \mathbf{A}_n \mathbf{f}_W^{(n)}(x) + \mathbf{A}_{n+1} \mathbf{J} \sum_{i=0}^{n-1} \nu_i (-1)^i \mathbf{f}_W^{(i)}(x). \quad (2.12)$$

In order to derive the characteristic equation of (2.12), we work as follows. We look for solutions of the form $\boldsymbol{\xi} e^{rx}$, where $\boldsymbol{\xi} = \begin{bmatrix} \zeta \\ \theta \end{bmatrix}$. Substituting this solution into (2.12) and dividing by e^{rx} , we derive the following linear system that determines $\boldsymbol{\xi}$ and r , which is

$$\begin{aligned} \zeta r^{n+1} &= \mu \zeta r^n + \sum_{i=0}^{n-1} \nu_i \theta r^i \\ \theta r^{n+1} &= -\mu \theta r^n + \sum_{i=0}^{n-1} \nu_i (-1)^{n+1+i} \zeta r^i. \end{aligned} \quad (2.13)$$

In order for a nontrivial solution to exist, the determinant of the coefficients of ζ and θ should be equal to zero. This yields that

$$r^{2n}(r^2 - \mu^2) + (-1)^n \left(\sum_{i=0}^{n-1} \nu_i r^i \right) \left(\sum_{j=0}^{n-1} \nu_j (-r)^j \right) = 0, \quad (2.14)$$

which is the characteristic equation of (2.12).

Let us *assume* for the moment that the characteristic equation has only simple roots, and label them r_1, \dots, r_{2n+2} . It is interesting to note here that since (2.14) is a polynomial in r^2 , then for every root r of this polynomial $-r$ is also a root. Therefore, we shall order the roots so that for every i , $r_i = -r_{2n+3-i}$. By substituting each root into the system (2.13), we obtain the corresponding vectors ξ_i , $i = 1, \dots, 2n+2$. Then (2.12) has the $2n+2$ linearly independent solutions $\xi_i e^{r_i x}$. Thus, the general solution of (2.12) is given by

$$f_W(x) = \sum_{i=1}^{2n+2} d_i \xi_i e^{r_i x}, \quad (2.15)$$

where d_i are arbitrary constants.

From (2.15) we can immediately conclude that the solution to Equation (2.9) that we are interested in, is of the form

$$f_W(x) = \sum_{i=1}^{2n+2} d_i \zeta_i e^{r_i x}. \quad (2.16)$$

However, this is not the general solution to (2.9). It does not follow from the derivation of (2.15) that, for any choice of the coefficients d_i , the linear combination (2.16) will satisfy (2.9), since $\zeta_i e^{r_i x}$ is not a solution to (2.9). Therefore, we substitute (2.16) into (2.9), and by keeping in mind that $r_i = -r_{2n+3-i}$, we have that for every $i = 1, \dots, 2n+2$,

$$d_i \zeta_i r_i^n (r_i - \mu) = e^{r_i} d_{2n+3-i} \zeta_{2n+3-i} \sum_{j=0}^{n-1} \nu_j r_i^j. \quad (2.17)$$

These are in fact only $n+1$ relations between the unknown coefficients, since it can easily be shown by using the characteristic equation (2.14) that the equations for every i and $2n+3-i$ are identical. Using the relations between the coefficients d_i , one can rewrite (2.16) as sum of $n+1$ linearly independent solutions to (2.9) as follows

$$f_W(x) = \sum_{i=1}^{n+1} d_i (\zeta_i e^{r_i x} + q_i \zeta_{2n+3-i} e^{-r_i x}), \quad (2.18)$$

where q_i follows from (2.17) if we solve for d_{2n+3-i} . Thus, the general solution to (2.9) is given by (2.18). The coefficients d_i , for $i = 1, \dots, n+1$, and the probability π_0 that we still need to determine, follow now from the initial conditions (2.10) and the normalisation equation (2.6). Namely, by substituting (2.18) to (2.10) and (2.6) we obtain a linear system of $n+2$ equations.

Note that it is not possible to use the same argument in order to determine the coefficients d_i for *any* differential equation of the form (2.9), because of its nonstandard form. Here we heavily rely on the fact that we know beforehand that a unique solution exists. We summarise the above in the following theorem.

Theorem 1. *Let F_B be a polynomial distribution of the form (2.1). Then the waiting time distribution F_W has a mass π_0 at the origin, which is given by*

$$\pi_0 = \mathbb{P}[W = 0] = 1 - \sum_{i=1}^{2n+2} \frac{d_i \zeta_i}{r_i} (e^{r_i} - 1), \quad (2.19)$$

and has a density f_W on $[0, 1]$, given by

$$f_W(x) = \sum_{i=1}^{2n+2} d_i \zeta_i e^{r_i x}.$$

Although the roots r_i and coefficients d_i may be complex-valued, the density and the probability π_0 that appear in Theorem 1 will be nonnegative. This follows from the fact that for every distribution F_B of the preparation time, (2.4) has a unique solution which is a distribution. It is also clear that, since the differential equation (2.9) has real coefficients, then each root r_i and coefficient d_i have a companion conjugate root and conjugate coefficient, which implies that the imaginary parts cancel.

Remark 1. When (2.14) has roots with multiplicity greater than one, the analysis proceeds essentially in the same way. For example assume that $r_1 = r_2$. Then we first look for two solutions to (2.12) of the form $\xi e^{r_1 x}$. If we find only one (that always exists), then we look for a second solution of the form $(x\xi + \eta)e^{r_1 x}$, where η is again a vector. Substituting this solution into (2.12), we obtain a linear system that determines ξ and η . Thus we can obtain the general solution to the differential equation (2.12). From this point on, by following the same method, we can formulate a linear system that determines the coefficients d_i and π_0 , and obtain the solution to (2.9).

Remark 2. Another method to derive the solution to the integral equation (2.5) is through Laplace transforms over a bounded interval. We have illustrated this method in [11]. The steps of this method are as follows. By taking the Laplace transform of (2.5) over the interval $[0, 1]$ we obtain an expression for the Laplace transform ω of F_W that involves the terms $\omega(s)$ and $\omega(-s)$. By substituting s for $-s$ we form a system of two equations from which we can obtain ω . This step is equivalent to the method we used here, namely forming a system of differential equations for $f_W(x)$ and $f_W(1-x)$. It emerges that

$$\omega(s) = \frac{P(s) + e^{-s}Q(s)}{R(s)},$$

where P , Q , and R are polynomials in s . Using the fact that the transform is an analytic function on the whole complex plane, we can deduce that the previous expression is the Laplace transform over a bounded interval of a mixture of $2n + 2$ exponentials. This method is fairly straightforward; it is, however, cumbersome and it does not illustrate the special relation between the exponentials with opposite exponents that appear in the density f_W .

3 Approximations of the waiting time distribution

The result we have obtained in the previous section comes in handy in some cases where it is necessary to resort to approximations of the waiting time distribution. We have already proven in [9] that for any distribution of A and B there exists a unique limiting distribution F_W for (1.1), provided that $\mathbb{P}[B < A] > 0$, although we may not be able to compute it. Some distributions of the preparation time are not suitable for deriving a closed-form expression of F_W . Furthermore, if F_B has a bounded support, then we cannot readily apply previously obtained results. In [11] only the case where F_B is the uniform distribution is covered, while the method described in [9] is not applicable (since distributions on a bounded support are excluded from the class of distributions that are considered there).

Therefore, one may consider approximating F_B in order to be able to compute the distribution of the waiting time, which is our main concern. A reasonable approach is to approximate F_B by a phase-type distribution. An important reason is that the class of phase-type distributions is dense; any distribution on $[0, \infty)$ can, in principle, be approximated arbitrarily well by a phase-type distribution (see Schassberger [8]). Furthermore, we have shown in [10] that if F_B is a phase-type distribution, then we can compute explicitly the waiting time distribution F_W . Nonetheless, if F_B has a bounded support, it is more natural and possibly computationally more

efficient to fit a polynomial distribution. In the sequel, we shall discuss how to fit a polynomial distribution to F_B .

3.1 Fitting polynomial distributions

If F_B is a continuous distribution on a bounded support, it is reasonable to choose \hat{F}_B to be a polynomial distribution. The famous *Weierstrass approximation theorem* asserts the possibility of uniform approximation of a continuous, real-valued function on a closed and bounded support by some polynomial. The following theorem is a more precise version of Weierstrass' theorem. It is a special case of the theorem by S. Bernstein that is stated in Feller [5, Section VII.2].

Theorem 2. *If F is a continuous distribution on the closed interval $[0, 1]$, then as $n \rightarrow \infty$*

$$\hat{F}_n(x) = \sum_{k=0}^n F(k/n) \binom{n}{k} x^k (1-x)^{n-k} \rightarrow F(x) \quad (3.1)$$

uniformly for $x \in [0, 1]$. Furthermore, \hat{F}_n is also a distribution.

Proof. Bernstein's theorem states that if F is a continuous function, then it can be approximated uniformly in x with the polynomial \hat{F}_n . In other words, for any given $\varepsilon > 0$, there is an N independent from x , such that for all $n > N$, $|\hat{F}_n(x) - F(x)| < \varepsilon$, for all x .

It is simple to show that if the function F is a distribution on $[0, 1]$, then the approximation $\hat{F}_n(x)$ is also a distribution, since it is continuous, $0 \leq \hat{F}_n(x) \leq 1$, and, by checking its derivative, we shall show that it is non-decreasing in x . It suffices to note that

$$\begin{aligned} \hat{F}'_n(x) &= \sum_{k=1}^n F(k/n) \binom{n}{k} k x^{k-1} (1-x)^{n-k} - \sum_{k=0}^{n-1} F(k/n) \binom{n}{k} x^k (n-k) (1-x)^{n-k-1} \\ &= \sum_{k=0}^{n-1} x^k (1-x)^{n-k-1} \left[F((k+1)/n) \binom{n}{k+1} (k+1) - F(k/n) \binom{n}{k} (n-k) \right] \\ &= \sum_{k=0}^{n-1} x^k (1-x)^{n-k-1} \frac{n!}{k!(n-k-1)!} [F((k+1)/n) - F(k/n)]. \end{aligned}$$

The expression in the square brackets at the right hand side is positive since F is a distribution, which implies that $F((k+1)/n) \geq F(k/n)$. Therefore, $\hat{F}'_n(x) \geq 0$, for $x \in [0, 1]$. \square

So, given a continuous distribution F_B that has all its mass concentrated on $[0, 1]$, one can compute a polynomial distribution \hat{F}_B that approximates F_B arbitrarily well by using Theorem 2. In this sense, the class of polynomial distributions is dense. Then \hat{F}_W can be computed by using Theorem 1.

Naturally, after having obtained an approximation of F_W , the first question that follows is to determine how good this approximation actually is. Therefore, we shall obtain an upper bound for the error between the approximated distribution for W and the actual one.

3.2 Bounding the approximation error

Error bounds for queueing models have been studied widely. The main question is to define an upper bound of the distance between the distribution in question and its approximation, that depend on the distance between the governing distributions. These bounds are obtained both in terms of weighted metrics (cf. Kalashnikov [6]) and non-weighted metrics (cf. Borovkov [2, 3])

and references therein). An important assumption which is often made in these studies is that the recursion under discussion should be non-decreasing in its main argument. Clearly, in the model we discuss here this assumption does not hold. Because of Theorem 2, we shall limit ourselves to the uniform norm.

Let \widehat{F}_B be an approximation of F_B and \widehat{F}_W the exact solution that we obtain in that case for the distribution of W . Let \widehat{B} be a random variable that is distributed according to \widehat{F}_B , and let $\widehat{X} = \widehat{B} - A$. Define now the mapping (cf. (2.2))

$$(\widehat{\mathcal{T}}F)(x) = 1 - \int_x^\infty F(y-x)dF_{\widehat{X}}(y),$$

which yields that \widehat{F}_W is the solution to $F = \widehat{\mathcal{T}}F$ that can be rewritten in the form (cf. (2.3))

$$(\widehat{\mathcal{T}}F)(x) = \int_0^\infty \int_0^\infty \widehat{F}_B(x+z+y)\mu e^{-\mu z} dz dF(y).$$

Then we can prove the following theorem.

Theorem 3. *Let $\|F_B - \widehat{F}_B\| = \varepsilon$. Then $\|F_W - \widehat{F}_W\| \leq \varepsilon/(1 - \mathbb{P}[B > A])$.*

Proof. We have that

$$\begin{aligned} \|F_W - \widehat{F}_W\| &= \|\mathcal{T}F_W - \widehat{\mathcal{T}}\widehat{F}_W\| = \|\mathcal{T}F_W - \mathcal{T}\widehat{F}_W + \mathcal{T}\widehat{F}_W - \widehat{\mathcal{T}}\widehat{F}_W\| \\ &\leq \|\mathcal{T}F_W - \mathcal{T}\widehat{F}_W\| + \|\mathcal{T}\widehat{F}_W - \widehat{\mathcal{T}}\widehat{F}_W\| \leq \mathbb{P}[B > A]\|F_W - \widehat{F}_W\| + \|\mathcal{T}\widehat{F}_W - \widehat{\mathcal{T}}\widehat{F}_W\|, \end{aligned}$$

since \mathcal{T} is a contraction mapping with contraction constant $\mathbb{P}[B > A]$. Furthermore,

$$\begin{aligned} &\|\mathcal{T}\widehat{F}_W - \widehat{\mathcal{T}}\widehat{F}_W\| \\ &= \sup_{x \geq 0} \left| \int_0^\infty \int_0^\infty F_B(x+z+y)\mu e^{-\mu z} dz d\widehat{F}_W(y) - \int_0^\infty \int_0^\infty \widehat{F}_B(x+z+y)\mu e^{-\mu z} dz d\widehat{F}_W(y) \right| \\ &\leq \sup_{x \geq 0} \int_0^\infty \int_0^\infty \mu e^{-\mu z} \left| F_B(x+z+y) - \widehat{F}_B(x+z+y) \right| dz d\widehat{F}_W(y) \\ &\leq \sup_{x \geq 0} \int_0^\infty \int_0^\infty \mu e^{-\mu z} \sup_{x+y+z \geq 0} \left| F_B(x+z+y) - \widehat{F}_B(x+z+y) \right| dz d\widehat{F}_W(y) \\ &= \varepsilon \int_0^\infty \int_0^\infty \mu e^{-\mu z} dz d\widehat{F}_W(y) = \varepsilon. \end{aligned}$$

So $\|F_W - \widehat{F}_W\| \leq \mathbb{P}[B > A]\|F_W - \widehat{F}_W\| + \varepsilon$, which is what we wanted to prove. \square

An important feature of Equation (1.1) that made the calculation of an error bound straightforward is that the distribution of the waiting time is the fixed point of a contraction mapping. Note that this is not a property of Lindley's recursion.

Remark 3. In the previous, we were concerned with the case where F_B is a continuous distribution (on a bounded support) that is approximated arbitrarily well by the polynomial distribution \widehat{F}_B . However, if F_B is discontinuous, then one may not be able to choose an appropriate approximation that instigates an acceptable error. Nonetheless, one can explicitly compute the invariant distribution of W in the special case that F_B is discontinuous at a single point, x_0 , of its support as follows. Since F_B is a distribution of a mixed type, it can be decomposed into two parts: a discrete distribution F_D and a continuous one F_C . Now, F_C can be approximated arbitrarily well with either a phase-type or a polynomial distribution, and this approximation error will be

the distance $\|F_B - \widehat{F}_B\|$. Whether one should choose to approximate F_B with a phase-type or a polynomial distribution depends on the computational efficiency of each method, in combination with the approximation error that occurs. Here, we shall concentrate on the case that F_C has a bounded support. Therefore, we can assume that F_C is approximated by a polynomial distribution on $[0, 1]$.

If F_C has a bounded support, then we need to make the extra assumption that the discontinuity occurs exactly in the middle of the support. We need to compute F_W separately in each interval $[0, 0.5)$ and $[0.5, 1]$. Keep in mind, that although F_B is discontinuous, F_W is a continuous distribution. For x in the interval $[0.5, 1]$ one can derive a differential equation that yields the density of the waiting time that is almost identical to (2.9). Another differential equation for the density can be derived for the interval $[0, 0.5)$. The characteristic of these two differential equations is that they form a system, since each of them involves the density on the other interval. This system can be solved explicitly by using a method similar to the one described in Section 2. In case that F_D is on a lattice (with more than one discontinuity) we can again derive a system of differential equations that gives the density of the waiting time in each interval. Hence, it seems possible that we can obtain an explicit solution to this system by following the same method as in Section 2.

References

- [1] S. Asmussen. *Applied Probability and Queues*. Springer-Verlag, New York, 2003.
- [2] A. A. Borovkov. *Stochastic Processes in Queueing Theory*. Number 4 in Applications of Mathematics. Springer-Verlag, New York, 1976.
- [3] A. A. Borovkov. *Ergodicity and Stability of Stochastic Processes*. Wiley Series in Probability and Statistics. John Wiley & Sons Ltd., Chichester, 1998.
- [4] J. W. Cohen. *The Single Server Queue*. North-Holland Publishing Co., Amsterdam, 1982.
- [5] W. Feller. *An Introduction to Probability Theory and its Applications, Vol. II*. John Wiley & Sons Inc., New York, second edition, 1971.
- [6] V. Kalashnikov. Stability bounds for queueing models in terms of weighted metrics. In Y. Suhov, editor, *Analytic Methods in Applied Probability*, volume 207 of *American Mathematical Society Translations Ser. 2*, pages 77–90. American Mathematical Society, Providence, RI, 2002.
- [7] B. C. Park, J. Y. Park, and R. D. Foley. Carousel system performance. *Journal of Applied Probability*, 40(3):602–612, 2003.
- [8] R. Schassberger. *Warteschlangen*. Springer-Verlag, Wien, 1973.
- [9] M. Vlasiou. A non-increasing Lindley-type equation. Technical Report 2005-015, Eurandom, Eindhoven, The Netherlands, 2005. Available at <http://www.eurandom.nl>.
- [10] M. Vlasiou and I. J. B. F. Adan. An alternating service problem. *Probability in the Engineering and Informational Sciences*, 19(4):409–426, October 2005.
- [11] M. Vlasiou, I. J. B. F. Adan, and J. Wessels. A Lindley-type equation arising from a carousel problem. *Journal of Applied Probability*, 41(4):1171–1181, December 2004.