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Innovative Applications of O.R.

Capacity planning of a perinatal network with generalised loss network model with overflow

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ABSTRACT

Recent literature shows that the arrival and discharge processes in hospital intensive care units do not satisfy the Markovian property, that is, interarrival times and length of stay tend to have a long tail. In this paper we develop a generalised loss network framework for capacity planning of a perinatal network in the UK. Decomposing the network by hospitals, each unit is analysed with a GI/G/c/0 overflow loss network model. A two-moment approximation is performed to obtain the steady state solution of the GI/G/c/0 loss systems, and expressions for rejection probability and overflow probability have been derived. Using the model framework, the number of required cots can be estimated based on the rejection probability at each level of care of the neonatal units in a network. The generalisation ensures that the model can be applied to any perinatal network for renewal arrival and discharge processes.
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1. Introduction

In most of the developed world neonatal care has been organised into networks of cooperating hospitals (units) in order to provide better and more efficient care for the local population. A neonatal or perinatal network in the UK offers all ranges of neonatal care referred to as intensive, high dependency and special care through level 1 to level 3 units. Recent studies show that perinatal networks in the UK have been struggling with severe capacity crisis (Bliss, 2007; National Audit Office, 2007). Expanding capacity by number of beds in the unit, in general, is not an option since neonatal care is an unusually expensive therapy. Reducing capacity is not an option either, as this would risk sick neonates being denied admission to the unit or released prematurely. Consequently, determining cot capacity has become a major concern for perinatal network managers in the UK. We have addressed this issue in several papers (Asaduzzaman & Chaussalet, 2008; Asaduzzaman, Chaussalet, Robertson, 2010; Asaduzzaman, Chaussalet, Adeyemi, et al., 2010; Asaduzzaman, 2010; Asaduzzaman & Chaussalet, 2011). However, as noted by Asaduzzaman, Chaussalet, Robertson (2010) and Asaduzzaman (2010) the mean is much lower than standard deviation for interarrival times and length of stay (LOS). Clearly this is a violation of the property of the exponential distribution, and hence of the Markovian assumption. Asaduzzaman (2010) has reported that the graphs and diagrams of the interarrival and LOS show a non-exponential pattern, and that a mixture of distributions would provide a better fit. Moreover, several mathematical (Vasilakis & Marshall, 2005; Griffiths, Price-Lloyds, Smithies, & Williams, 2006; Asaduzzaman, 2010) and medical (Weissman, 1997; Weissman, 2000; Rapoport, Teres, Zhao, & Lemeshow, 2003) studies also show that the length of stay is heavily skewed, i.e. has a long tail, in ICU in particular.

Queueing models having zero buffer also referred to as 'loss models' (·/·/·/0) have been widely applied in hospital systems and intensive care in particular (e.g., Van Dijk & Kortbeek, 2009; Litvak, Van Rijsbergen, Boucherie, & Van Houdenhoven, 2008; Asaduzzaman, Chaussalet, Robertson, 2010; Asaduzzaman, Chaussalet, Adeyemi, et al., 2010; Asaduzzaman & Chaussalet, 2011). Van Dijk and Kortbeek (2009) proposed an M/M/c/0 loss model for capacity management in an Operating Theatre-Intensive Care Unit. Litvak et al. (2008) developed an overflow model with loss framework for capacity planning in intensive care units while Asaduzzaman, Chaussalet, Robertson (2010), Asaduzzaman, Chaussalet, Adeyemi, et al. (2010) developed a loss network model for a neonatal unit, and extended the model framework to a perinatal network in Asaduzzaman and Chaussalet (2011). These models assume that interarrival times and length of stay follow exponential distributions.

Queueing models with exponential inter-arrival and service times are easiest to study, since such processes are Markov chains. However, length of stay distribution in intensive care may be highly skewed (Griffiths et al., 2006). Performance measures of a queueing system with non-zero buffer are insensitive to service

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time distribution provided that the arrival process is Poisson (Kelly, 1979). This insensitivity property is, in general, no longer valid in the case of zero buffer or loss systems (Klimenok, Kim, Orlovsky, & Dudin, 2005).

Many approaches have been found towards generalising such processes since Erlang introduced the M/M/c/0 model for a simple telephone network and derived the well-known loss formula that carries his name in 1917 (Kelly, 1991; Whitt, 2004). Takács (1956), Takács (1962) considered the loss system with general arrival pattern (GI/M/c/0) through Laplace transform. Recently there has been a growing interest in loss systems where both arrival and service patterns are generalised (GI/G/c/0). The theoretical investigation of the GI/G/c/0 loss model through the theory of random point processes has attracted many researchers. Brandt and Lisek (1980) gave a method for approximating the GI/GI/c/0 queue by means of the GI/GI/∞ queue, while Whitt (1984) applied a similar approximation under heavy traffic. Franken, Konig, Arndt, and Schmidt (1982) examined the continuity property of the model, and established an equivalence between arrival and departure probability. Miyazawa and Tijms (1993) gave an approximation method for the batch-arrival $GI^{[x]}$/G/c/N queue which is applicable when the traffic intensity is less than one. The M/G/c/N and the GI/G/c/N queue have also been studied widely; for a comparison of methods, see Kimura (2000). Although many studies have been found in the literature, no simple expression for the steady state distribution is available for a GI/G/c/0 system. Hsin and Van de Liefvoort (1996) provided the exact solution for the GI/GI/c/0 system expressing the inter-arrival and service time by matrix exponential distribution. The method is computationally intensive and often includes imaginary components in the expression (which are unrealistic). Diffusion approximations, which require complicated Laplace transforms have also been used for analysing GI/G/c/N queues (e.g., Kimura, 2003; Whitt, 2004). Kim and Chae (2003) derived a transform-free expression for the analysis of the GI/G/1/N queue through the decomposed Little's formula. A two-moment approximation was proposed to estimate the steady state queue length distribution. Using the same approximation, Choi, Kim, and Chae (2005) extended the system for the multi-server finite buffer queue based on the system equations derived by Franken et al. (1982). Atkinson (2008) developed a heuristic approach for the numerical analysis of GI/G/c/0 queueing systems with examples of the two-phase Coxian distribution. Recently, Izady and Worthington (2011) performed an approximate analysis of time-dependent loss queues and networks of loss queues where general service time distributions are considered.

In this paper we derive a generalised loss network model with overflow for a network of neonatal hospitals extending the results obtained by Franken et al. (1982). Since some model parameters cannot be computed practically, a two-moment based approximation method is applied for the steady state analysis as proposed by Kim and Chae (2003). The model is then applied to the north central London Perinatal network, one of the busiest network in the UK. Data obtained from each hospital (neonatal unit) of the network have been used to check the performance of the model. The rest of the paper is organised as follows: in the next section we first discuss a typical perinatal network and then develop a generalised loss model with overflow for the network. The steady state distribution and expression for rejection and overflow probabilities have been derived for each level of care of the neonatal units. Application of the model and numerical results are presented in Section 4.

2. Structure of a perinatal network

A perinatal network in the UK is organised through level 1, level 2 and level 3 units. Fig. 1 shows a typical perinatal network in the UK. Level 1 units consist of a special care baby unit (SCBU). It provides only special care which is the least intensive and most common type of care. In these units, neonates may be fed through a tube, supplied with extra oxygen or treated with ultraviolet light for jaundice. Fig. 2 shows the typical patient flow in a level 1 unit. A level 1 unit may also have an intensive therapy unit (ITU) which provides short-term intensive care to neonates, and the unit may then be referred to as 'level 1 unit with ITU'. Fig. 3 shows the structure of a level 1 unit with ITU. Level 2 units consist of a SCBU and a HDU where neonates can receive high dependency care such as breathing via continuous positive airway pressure or intravenous feeding. These units may also provide short-term intensive care. A level 3 unit provides all ranges of neonatal care and consists of an SCBU, an HDU and an NICU where neonates will often be on a ventilator and need constant care to be kept alive. Level 2 and level 3 units may also have some transitional care (TC) cots, which may be used to tackle overflow and rejection from SCBU. Although level 2 and level 3 units have similar structures level 2 units might not have sufficient clinician support for the NICU. NICU are HDU are often merged in level 2 and level 3 units for higher utilisation of cots. In level 2 or level 3 units, NICU–HDU neonates are sometimes initially cared at SCBU when all NICU cots are occupied. Similarly SCBU neonates are cared at NICU–HDU or TC, depending upon the availability of cots, staff and circumstances. This temporary care is provided by staffing a cot with appropriate nurse and equipment resources, and will be referred to as 'overflow'. Rejection occurs only when all cots are occupied; in such cases neonates are transferred to another neonatal unit. Patient flows in a typical level 3 or level 2 unit are depicted in Fig. 4. Unlike for level 3/level 2 units, overflow does not occur in level 1 units with ITU.

The underlying admission, discharge and transfer policies of a perinatal network are described below.

1. All mothers expecting birth <27 week of gestational age or all neonates with <27 week of gestational age are transferred to a level 3 unit.
2. All mothers expecting birth $\geqslant$27 but <34 week of gestational age or all neonates of the same gestational age are transferred to a level 2 unit depending upon the booked place of delivery.
3. All neonatal units accept neonates for special care booked at the same unit.
4. Neonates admitted into units other than their booked place of delivery are transferred back to their respective neonatal unit receiving after the required level of care.

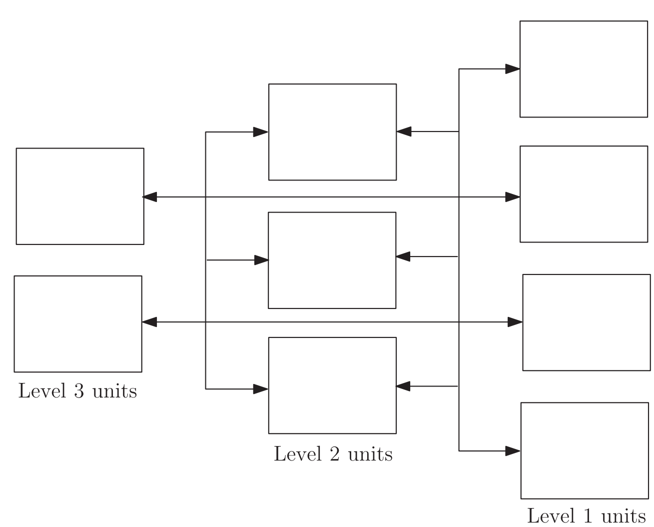

Fig. 1. Topology of a typical perinatal network. The arrows indicate forward and backward transfers between units.

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