PATIENT SCHEDULING: A REVIEW

by

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Abstract

Patient scheduling can be used to coordinate and control bed and operating room occupancy and to stabilize nursing staff workload. In this publication an overview of literature concerned with the subject is presented. After description of the patient flow system, and its objectives, literature on the subjects of length of stay, census, emergencies and waiting lists is presented since these subjects play an important role with the scheduling of inpatients. Then literature on scheduling models is described. Here a distinction is made between descriptive and control models and between models based on an appointment system and models based on a waiting-list. A list of 131 references to the literature is included, the length is 43 pages.
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1. Introduction

Recent years have shown an increase in the total expenditure for health services in the Netherlands from 7.3 billion Dutch guilders in 1970 to 31.9 billion in 1982, an increase of 337% compared with a rise in the cost of living of 129% in the same period. If you look at these figures you will not find it strange that there has been a growing call for cost control, especially if you take in mind the economic situation, which is not exactly flourishing. This problem is not confined to the Netherlands only. In other countries researches have been carried out in order to control expenditure and to increase the efficiency of health service institutions. One of the methods by which this is attempted is operational research, with the aid of which studies are made into the efficiency of operations and the optimal deployment of resources. A general overview of work in this area can be found in Stimson and Stimson (111), in Milsum, Turban and Vertinsky (80), and more recently in Boldy and O’Kane (12).

The scope of the following review will be confined to the subject of hospitals. I will look at the possibilities of controlling the inflow of patients into the hospital. First a description will be given of the system under consideration, the means of controlling this system and the measures by which the performance of the system may be judged. Then the subjects of length of stay, census, waiting lists and emergency patients, which all have their influence on the system, will be discussed, and an overview will be given of existing models.
2. A description of the patient flow system

As is shown in figure 2.1 a patient can enter the clinical hospital system in two ways. The first possibility is that his general practitioner refers him to the out-patient clinic of a hospital, where a member of the medical staff then decides whether or not he or she should be admitted. Out-patient departments work on principle only on appointment. In case of an emergency the patient can also go to the emergency department. In either case only a member of the medical staff is able to authorize admission of the patient into the hospital.

Once the decision to admit has been made, the physician has to determine how urgent the need for admission is. This can vary from classification as "emergency", when the patient has to be admitted at once, by "urgent", when the patient has to be admitted within a prescribed time-period,

Figure 2.1. patient-flow scheme.
to "elective" which means there is medically speaking, no particular hurry. Patients, who are classified as emergency are immediately admitted to the hospital. If no beds are free, it is often possible to erect emergency beds. If this is not possible, or if these beds are already occupied, the patient is referred to another hospital.

The other patients are either placed on a waiting list, or they receive an appointment. The conceptual difference between the two systems lays in the fact that through the use of a waiting list the decision maker has at his disposal a supply of patients. This is not the case with an appointment system. It is also possible to have a mixture of these two systems in which all patients receive an appointment, but with some patients willing to be admitted earlier at short notice if there is a bed available. The role of the admitting department in this context can vary between hospitals, or even within a hospital between physicians. One extreme is, that all decisions are made by the physician. He decides how many patients will be admitted, when they will be admitted and who they will be. The admitting department then only performs an administrative function. On the other hand it is also possible that the admitting department takes these decisions, while of course taking into account the medical degree of urgency and organizational circumstances. Between these two extremes there are many possible variants.

Once the patient is admitted in the hospital, he is preferably placed in the ward of his attending physician. If, through a shortage of beds, this is not possible, the patient is placed in another ward. As soon as a bed is free in his proper ward, he is transferred. Also when a patient is referred to another attending physician he is transferred to this physician's ward. This mostly happens when a medical patient is found to be in need of surgical treatment.

While in hospital the patient may use some of the available facilities such as radiology or laboratory. The most important of these facilities is the operating room. Patients who are to undergo surgical treatment will, unless in case of emergency, already be in the hospital one or more days before the operation, so that preliminary investigations can be carried out. After the operation they usually spend some time in the recovery room before being transported back to their ward.

The physician decides when the patient is to be discharged. After his discharge the patient does not necessarily go home. It may be that he leaves for another health service institution, such as a nursing home. It is also possible that the patient dies during his stay in hospital.
The moment the decision for admission of a patient has been made, a claim has been laid upon the resources of the hospital. When the patient is admitted he will for some time occupy a bed, which is most of the time a scarce resource in a hospital. His presence will affect the workload of the medical staff and the nursing staff and when he is in need of surgery he will need a part of the available operating time. If we want to control the effect of these claims upon the system we will need two things, namely a means of control and a performance measure, by which the effectiveness of the system can be judged.

If we consider the incoming flow of patients, we see that it is divided into three parts, which have distinct control features. The flow of emergency patients has to be accommodated if humanly possible. It will rarely happen that emergency patients are turned away, although sometimes an ambulance service is directed to take its casualties to another hospital or only emergencies from a certain area are accepted, so it is nearly impossible to exert control on this part of the incoming stream. Patients who are labelled "urgent" are to some limited extent controllable, but since the last date on which they have to be admitted is usually not far off, one cannot expect many results from controlling this inflow. The best control possibilities exist with the third part of the incoming patient flow, the patients who are labelled "elective", since the decision maker is completely free in determining their time of arrival.

Now we have to ascertain the goals by which the performance of the system can be judged. The overall goal of a hospital is normally stated to be the provision of the best possible medical care within the monetary and other restrictions which the society has set. These monetary restrictions are in the Netherlands conveyed by the rules of the COTG, the central organization for tariffs in health care. This goal however is not an operational one, since "the best medical care" is rather a vague notion. The most commonly used operational goal for a hospital is "to maintain a high standard of medical care, while using the available facilities at maximum efficiency". This goal is very often translated as maximizing bed-occupancy, but it can mean more than that. Of course, since the operating cost of a hospital is for a major part independent of the number of in-patients, it is for any hospital very important that no revenue is lost by leaving beds unoccupied unnecessarily, but it is useless to admit a patient scheduled for surgery when there is no operating time available. Also there have to be some beds set aside for future
incoming emergency patients. It is clear that these demands contradict the goal of maximum bed occupancy. Furthermore, care has to be taken that enough nursing staff is available for the treatment of the inpatients. This is mostly solved by having a staff which is large enough to handle all peak workloads. Given this available manpower it would be useful to reduce the variance in the workload, which would enable the hospital either to reduce the nursing staff, or to increase the number of treated patients. One must keep in mind here, that the workload need not be directly proportional to the number of patients to be treated. There are distinct differences in the amount of care which is needed by different kinds of patients. A simular argument can be made for reducing the variance of the workload in the operating room, where we not only have to take into account the number of operations to be performed, but also their length and gravity.

If we sum this up, it is the goal of a hospital organization to maximize the average census under the following constraints:
- not too many emergency patients may be turned away because of the lack of beds
- the same goes for scheduled patients
- patients must not have to wait unnecessarily for admission, nor when admitted stay in hospital longer than necessary.
- there must be coordination between patient scheduling, operating room scheduling and the scheduling of other diagnostic facilities.
- the workload on the wards and in the operating-room has to be as stable as possible.

In order to further the achievement of this goal it would be useful for a hospital to possess information about the length of stay of patients, about the bed occupancy, about the number of emergency patients to be expected and about the behaviour of patients placed on a waiting list. These elements will be discussed in the next chapters.
3. Length of Stay

For the control of a complex input-output system, such as the one described in the previous chapter, it is essential to possess information on the service time, the time the patient spends in the hospital. This average length of stay is one of the most commonly used hospital statistics. This popularity is no doubt caused by the ease by which it can be calculated. However, as discussed by Fineberg (32), de Koning (66) Myers and Slee (83) and Weckwerth (121) it is very often not used in the right way.

The average length of stay of the population of a hospital over a certain period is a meaningless figure. Take for instance a patient who spends one day in hospital for a vasectomy and a patient who spends 39 days after undergoing cardiac surgery. The average figure of 20 days does not tell us if one day is short for the first patient or 39 days is a long period for the other. For the statistic to have some meaning we must take into account different factors, so we must make a distinction between men and women, between different age groups, between different specialisms, as shown by Stewart (110), between different diagnostic groups and even as is shown by Lew (70) and Matteson (78) between patients with a different day of admission.

The above has to be kept in mind while reading the next part which describes several attempts at predicting length of stay. In the past several methods, both subjective and statistical have been used to predict the length of stay of patients.

Bithell and Devlin (5) describe a survey in which the remaining length of stay of 273 patients was repeatedly estimated by members of the medical staff. The estimates were classified into three categories representing the degree of certainty which was felt by the participating physicians. Of the estimates in the first (most certain) category 60.9% proved to be correct. In the other two categories this percentage was much lower (19.6 and 3.5% respectively). For 49 patients no estimate was made due to the irregularity of the physician's visits.

Robinson et al. (94, 95) also experimented with physician supplied length of stay estimates. These were made at two moments: one at admission request and another after a prescribed number of days of hospitalization. Results showed, that estimates for surgical patients are somewhat more accurate than those for medical patients.
Chant and Napier (14) use data provided by surgeons, by nurses and by the two of them combined. Results show that a ward sister and a surgeon together give reasonable predictions for elective surgical patients. This is not so, however, for patients admitted as emergencies. Gustavson (42) compared five models, with which predictions were made at four levels of information for a sample of eight inguinal herniotomy patients. These methods are:
- subjective point estimates by several physicians,
- regression analysis,
- historical mean,
- direct posterior odds estimation,
- Bayesian estimation.
Results showed that all techniques are better than the historical mean, and that the Bayesian methodology appears to perform best. Briggs (13) compares four models, based on:
- physician estimates,
- physician estimates adjusted for bias,
- conditional probabilities based on a historical length of stay distribution and on the number of days the patient has spent in hospital so far,
- conditional probabilities like the previous one, but here different length of stay distributions are used for groups, which are identified through using the Automatic Interaction Detector on basis of sex and unit. The results generated by means of simulation show, that apart from the first method, all methods perform equally well.

Warner (120) compares historical and physician-supplied estimates. He concludes, that at all times the physician is as good or better a source of information. However, like Robinson and Briggs, he encountered considerable difficulty in obtaining the cooperation he needed from physicians. Response tended not to exceed the 50%. For the analysis of the historical data Warner made use of the Automatic Interaction Detector.

Fuhs et al. (37) uses the same method. They then analyse the relationship between variance reduction and discharge prediction. The conclusion is that even a large improvement in the ability to explain length of stay variance will only marginally improve the accuracy of the predictions, with accuracy measured as the number of correct point estimates.

Resh (90), Rubinstein (99) and Trivedi (119) use the conditional probability for a patient's remaining length of stay, given that he has
already spent a certain number of days in hospital. With this method it is possible both to use theoretical and historical length of stay distributions. Although theoretical distributions may have some advantages with respect to data storage and programming efficiency, it is not always possible to find one which fits the available data. Some of the distributions used are the normal (Rubinstein, Trivedi), the lognormal (Rubinstein, Balintfy (1)) and the gamma (Wilkins (122)).

Kao (59) and Smallwood et al. (106) use a semi-markov model for the prediction of the recovery process of patients. The model is described by means of a matrix of transition probabilities between the different states of recovery and a number of distributions to denote the length of stay in a recovery state, if it is known to what state of recovery the patient will go next: the so-called holding-mass functions. Transition probabilities and holding-mass functions may be estimated with the aid of historical data.

Several methods for predicting length of stay data have been described. Subjective estimates made by physicians on the whole seem to be slightly better than estimates obtained by means of statistical methods, provided a correction is applied to take into account the tendency, displayed by physicians, to underestimate the length of stay. However, since great difficulties are encountered in enlisting the necessary cooperation from the side of the medical staff, implementation of this method will be very problematic.

If we take a look at the results which are reported for some of the methods, both subjective and statistical, mentioned above, we can see that none of them succeed in giving accurate point-estimates of discharge days. Since this would be very useful information for control purposes, further research on the subject would be advisable.
4. Census

It is essential for the control of the hospital system that information is available about the present and the future census. This information is the basis upon which the decision about how many elective patients there are to be scheduled, can be founded. The basic issue addressed by census control models is the trade-off between scheduling too many patients, and having to cancel a number of them, and scheduling not enough patients, and having a low occupancy. It is easy to see that an accurate prediction is essential for the correct assessment of this trade-off. In the literature several approaches to the problem can be found.

Several authors try to describe the daily census by means of statistical distribution. Blumberg (10) uses the Poisson distribution to determine the number of beds that has to be left open in order to achieve a certain measure of overloading. Drosness et al. (24) on the basis of data for twelve hospitals find that the normal distribution gives a better description of daily census than the Poisson distribution, and DuFour (25) in his article shows that, although both the normal and the Poisson distribution fit his data extremely well, the results obtained with the normal distribution are slightly better.

Another approach uses historical data in order to provide census predictions. Revelle and Shoultz (91) predict the number of discharges and thus indirectly the census as a product of three factors. These factors represent the effect of the day of the week, a seasonal effect and the effect of holidays, and they are based on historical discharge data. Kwon, Eichenhorst and Adams (68) use regression analysis. Mills (79) divides the patient population into several groups. For each group he determines which day of the week during the last six months had an increased census. This indicator is updated each month. Lippany and Zini (72) use a four-week moving average in order to predict the census. Wood (128) and Kanter and Bailey (58) both use the Box-Jenkins techniques for integrated autoregressive moving average forecasts. The same method is used by Kao and Tung (61). Wood uses data from five hospitals to fit six models, one for each hospital and a general model. The general model, although producing somewhat more error, does not give results which are substantially different from the specific models. Kao and Podladnik (60) describe the census with the aid of a vector whose elements represent a constant component, a linear trend and the
amplitude and phase angle of a seven day cycle, and, if required, shorter cycles. The vector is chosen so as to minimize the discounted squared residuals between the predictions and the realizations. The model can be adapted to special occasions, such as holidays, disasters and a change in trend by changing some of the vector components or the discount factor.

A third approach found in literature is the use of Markov models. Kolesar (65) describes a Markov-chain in which the state of the system is given by the number of beds occupied. Transition probabilities are calculated and formulas are given which denote the steady-state condition of the system. It is now possible to maximize an objective with these formulas as constraints. Offensend (86) describes a similar model with an extra option added. The state of the system is defined by the number of units in service. A unit can mean a bed or a unit of workload.

Another approach within the framework of (semi) Markov-chains is presented by Kao (59), Balintfy (2) and Smallwood et al. (106). As described in the previous chapter, in their terminology the system is described by a matrix of transition probabilities between states of illness and by a number of holding mass functions. From this at any moment a probability distribution of the census can be derived.

It is also possible to use length of stay data to predict the number of discharges. If also the number of emergency admissions, which will be discussed in a following chapter, and the number of scheduled admissions, are known, than the census can easily be calculated. This method is used by Resh (90), Trivedi (119), Swain, Kilpatrick and Marsh (114), Wiorkowski and McLeod (125) and Rubenstein (99) and can be described as follows:

Given a theoretical or empirical distribution of length of stay, the conditional probability of a patient being discharged the next day, given that he has spent a certain number of days in hospital, can easily be calculated. For the $i^{th}$ patient let us call this probability $p_i$. Now the event that this patient will be discharged the next day is the outcome of a Bernoulli trial of a random variable which takes a value 1 with probability $p_i$ and a value 0 with probability $(1-p_i)$. Therefore the number of discharges from a population of $N$ can be seen as a sum of $N$ independent Bernoulli trials. This means that asymptotically the number of discharges will have a normal distribution with a mean of $\sum_{i=1}^{N} p_i$ and a variance $\sum_{i=1}^{N} p_i (1-p_i)$.
of $\sum_{i=1}^{N} p_i (1-p_i)$. Confidence intervals on the number of discharges for the next day can now be computed.

A great number of the models which have been discussed so far rely on historical data to predict the census. These predictions will only be reliable as long as the conditions do not change. However, as soon as control measures take effect, these conditions will change and so invalidate the census predictions. This means that these models are very difficult to use for control purposes. Even with the other models careful attention will have to be paid to the consequences of changing conditions.

To end this chapter I would like to discuss some articles relating to the subject of census. Thompson and Fetter (118) and Rikkers (93) use simulation to determine the effect which an increase of the number of private rooms has on the census level. In both articles the conclusion is that this effect will be positive. Parker (87) uses a statistical model to calculate the gain in occupancy and reduction of overflow effected by pooling the beds of two medical units. The conclusion that this effect is positive is corroborated by researches carried out by Blewitt et al. (9), MacStravic (75) and Hindle (54) by means of a simulation model and by an experiment carried out by Freiwirth (35).
5. Waiting lists
When it is found that a patient has to go to hospital, and low medical urgency is indicated, this patient is labelled "elective". As previously discussed, this patient can either be given an appointment or he can be placed on a waiting list. In this chapter an overview of literature dealing with the subject of waiting lists will be given. There are two reasons for the existence of waiting lists. The first is the most obvious. Since there are not always beds in the hospital to accommodate all incoming patients, some of these patients will have to wait. The second use of a waiting list is as a buffer, by which the incoming flow of inpatients can be regulated, so as not to cause too great a disturbance in the hospital organization. For this second reason a waiting list may also have its uses in an overbedded hospital.

As discussed in an editorial comment in the Hospital and Health Services Review (56) and by Jones and McCarthy (57) a hospital organization can encounter several problems while keeping a waiting list. A major problem is the excessive length of many waiting lists. This may be due to the fact that the demand for health care outstrips the ability of the community to deliver this care as suggested by Jones and McCarthy, but econometric research by Frost (36) suggests that the reverse is true, namely that the demand is regulated by the supply. In this view the present situation would present an equilibrium where an increase in health care supply would have no effect on the average length of waiting lists.

If one wants to compare the performance of hospitals by means of their waiting lists it is misleading merely to look at the number of patients on these lists, without reference to either the population which is creating this demand or the resources that are servicing it. A measure that does take into account these factors is provided by Cottrell (19).

Another problem is the maintenance of waiting lists. In order to have a correct picture of the state of the waiting list and of the occurring changes a regular review has to take place. Patients on the list may not be needing hospitalization any more. They have to be deleted from the list. Also attention has to be paid to the order on which patients are entered on the list. One method is a simple "first come first served" system, but is is also possible to use an admission index, such as the ones
described by Rourke, McFadden and Rogers (97), by Poenix (89) and by Fordyce and Phillips (34) who apart from the length of time already spent on the waiting list, also look at medical and social factors.

A very useful tool for the management of a waiting list is a regular statistical analysis, especially if it is provided on fixed intervals by an automated system, such as the ones described by Kennedy (64) and by Wilson, Rogers and Puddle (123). In particular the method described by Kennedy is very worthwhile. It not only looks at the number of patients in each priority class, but also takes into account other factors, such as changes in the future claims for operating time and nursing manpower which are contained in the waiting list and changes in the number of patients on the list classified by sex, age and priority. An analytical method such as this enables one to achieve a better balance between the supply of and the demand for health care.

A last problem to be discussed in this chapter is the fact that from the patients who are called in for hospitalization from a waiting list, a sizable percentage does not show up. Statistical researches on the subject carried out by Bithell (8), Ferguson and Murray (29), Morris, Hall and Handyside (81) and by Stevens, Webb and Bramson (109) show that in Great Britain this percentage may be as high as 22 percent. A number as great as this will cause considerable disruption in the hospital organization. Other elective patients, who are willing to come into the hospital at a moment's notice will have to be found and contacted at once, or else beds and operating time will be left unused, thus causing considerable loss in revenue to the organization. Finding the causes of this default rate and making amends for it are thus of prime importance to any hospital organization.

Ferguson and Murray, in their researches find that a high default rate is coupled with a long stay on waiting lists. They suggest, that communication between hospital and patient be improved and a proper system of recording priorities be implemented. Bithell suggests that the means of notifying patients (telephone, telegram or letter) and the amount of time given between notification and hospitalization are important factors in causing the problem. He proposes that the situation might be alleviated by using standardized procedures, an admission index and a short notice call list, and by regularly reviewing the waiting list. Morris, Hall and
Handyside finds several influencing factors, of which the most important is the often very short amount of time between the message calling in the patient and the date of hospitalization. A better communication between hospital and patient might help. Stevens, Webb and Bramson find no connection between the amount of notice and the default rate. The only significant factor they found was the priority classification of the patient, which is not subject to control.
6. Emergencies

Every day the hospital organization is faced with the problem of incoming emergency patients for whom immediate access to the system is imperative. So, enough beds have to be kept free in order to accommodate them. However, this number of reserved beds must not be too great so as to lead to an unnecessary waste of resources and the loss of revenue this entails.

In the following a theoretically sound method is presented with which this required number of beds can be computed. However, it has to be kept in mind, that due to the flexibility of most hospitals, they nearly always succeed in accommodating emergency patients without beds being officially set aside for them.

The question arises as to how many beds must be kept free so that emergency patients can be accommodated in x per cent of the time. The exact size of this figure x is a policy decision to be made by the hospital but it will generally lay in the neighbourhood of 95%.

If the distribution of the number of incoming emergency patients is known, it is fairly easy to determine a 95 per cent confidence interval which would answer the question. The problem is now reduced to finding the distribution of the number of incoming emergency patients.

Let us now look at the following four conditions:
- in each limited time interval the number of incoming emergency patients is also limited,
- in each time instance only one emergency patient arrives,
- the number of emergency patients arriving in consecutive time-intervals are mutually independent statistical variables,
- the distribution of the number of emergency patients arriving in a time-interval is only dependent on the length of this interval.

If these conditions are fulfilled it is fairly easy to prove that the distribution of the number of emergency patients is Poisson. This proof may be found in any book on waiting line models, for instance in Grassmann (41a) and indeed it is not unreasonable to assume that the inflow of emergency patients obeys these conditions. These findings are supported by statistical research carried out by Newell (84, 85) and by Pike, Proctor and Wyllie (88) who, after testing empirical data with the aid of the chi-square test find that the hypothesis that the number of incoming emergency patients is Poisson distributed cannot be rejected.

Next we have to find out whether we can use the same Poisson distribution for each day of the week, or whether for each day a separate distribution has to be fitted. Research in this area has been inconclusive. Karas (62) found in his data a clearly defined seven-day cycle, which would indicate a different Poisson parameter for each day of the week. Swartzman (115)
found a difference between the arrival pattern on weekdays and that on weekends. He also found that during weekdays differences were to be detected between the different periods of the day, but not between the same period on different weekdays. Newell also found a difference between the situation on weekdays and the situation in weekends. Both Newell and Swartzman found no differences between the weekdays and Pike, Proctor and Willie did not even find a difference between weekdays and the weekend. These differences in the findings may or may not be caused by local circumstances, but any hospital intending to use this method will have to be aware of the problem.

Once the right Poisson distribution has been found, another problem arises, namely, where to reserve these extra beds. As is shown by Newell, when the average number of incoming emergency patients each day is \( x, (x < 35) \) then when a standard of 95 per cent efficiency is set, \( x + 2 \) beds are to be set aside. If two departments in the same hospital each have an emergency admission rate of \( \frac{1}{2}x \) and each department reserves its own beds, then \( x+4 \) beds are required. However, if they jointly reserve these beds, only \( x+2 \) beds are needed, which means a saving of two beds while reaching the same result. This means that when the hospital uses a special emergency ward, such as the ones described by MacGregor and Ferguson (74), by Pike, Proctor and Wyllie and by Hannan (50) a significant reduction in the number of beds to be reserved can be achieved. This would also reduce the disturbances on the wards, which are caused by the arrival of emergency patients in the middle of the night.

There are, however, many objections to this procedure. The main problem is that quite often a patient needs specialized care which can easily be provided on the ward of his attending physician but not so easy in a general casualty ward, where patients from all specialities are gathered. A solution which would avoid this problem is the use of a special discharge ward, as described by Newell (85), for patients from all specialities who, prior to their discharge home, do not need specialized care any more. Any emergency patient can now be admitted to his appropriate ward. If this ward is full, space is created by transferring a patient, who is approaching his discharge, to the pre-discharge ward. This means that the impact of limited accommodation is transferred from the initial, critical stage of the illness to the final ambulant stay in hospital. An objection to this solution is the disturbance caused by transferring patients in and out of a ward in the middle of the night. Also, as mentioned by Chant and Napier (14), the whole concept of progressive patient care, of which this is an example, has in practice not proved to be very satisfactory.
Not all hospitals are compelled to accept emergency patients every day. In towns or regions with several hospitals an agreement can be reached by which each participant accepts incoming emergency patients on the basis of a rotation schedule. Thus an individual unit may admit emergencies on every alternate day, or every third day, or two days of each week, and so on, depending on the number and the size of the units involved. The influence which the choice of a particular rotation schedule has on the number of emergency beds to be reserved has been examined by means of simulation by Morris and Handyside (82) and by Handyside and Morris (49).
7. System models

7.1. Introduction
Apart from the literature described in the previous chapters, which concentrated on part aspects, a lot of articles have taken the whole system as subject. This part of the literature will be discussed in the following chapter. In order to get some grip on this volume of literature a framework has been set up with which several approaches can be distinguished. First a distinction will be made between those articles which give a descriptive model and those who describe a control model. Within the group of control models a further distinction can be made between models based on an appointment system and those based on a waiting list. Finally, within each group a distinction will be made between analytic and heuristic models.

7.2. Descriptive models
All analytic descriptive models discussed here are solely concerned with bed occupancy and patient waiting times. Several approaches are utilized. Bithell (6) presents a class of discrete-time models based on the use of Markov-chains. It is shown that the restrictions imposed by the Markov-property can be partly evaded by the use of a transition matrix of probabilities that is the product of several other transition matrices. With this method, the way is also opened for describing models based on scheduling patients with several days notice.

Shonick (104) describes a statistical model. He assumes that emergency arrivals and arrivals of elective patients to the waiting list both are Poisson distributed and that the length of stay is negative exponentially distributed. On the basis of this model distributions are calculated for the census, the number of people in the waiting line and the waiting time for admission of elective patient.

Queueing theory is used by Wilkins (122) and by Esogbue (28). Wilkins describes a simple model based on one inflow of patients which is Poisson distributed and a service time which is Erlang distributed. He uses empirical data to verify these assumptions. Esogbue develops recursive equations for the generation of the transition probabilities for three models. The first model only allows emergency arrivals. The second one uses a finite waiting line and no emergency arrivals and the third one
uses a parallel input stream consisting of both emergencies and scheduled cases. The results are independent of the distributions of arrivals and service times.

Descriptive simulation models are given by De Boer (11), Fetter and Thompson (30), Hindle (54), Lim, Uyeno and Vertinski (71), Thompson, Fetter, McIntosh and Pelletier (117) and by Wong and Au (126). All models are concerned with bed occupancy, but the model described by De Boer also takes nursing staff work load into account and the model described by Hindle is also concerned with operating room occupancy. De Boer assumes arrivals that are Poisson distributed, and Wong and Au use several distributions (normal and Poisson), to describe arrivals and services-times. All other distributions used in these models are empirical based on historical data.

7.3. Control models

7.3.1. Introduction

In the introduction to this chapter already mentioned is that a distinction would be made between models based on appointment systems and models based on waiting lists. Both systems have their advantages and disadvantages. Advantages of the waiting list system mentioned are:

- as a result of the often very short period between notification and hospitalization of the elective patient, no great demands are put on the quality of predictions of future capacity occupancy. This means control is fairly easy and as a result the achievement of a high census is possible,
- also due to the short notification period, people who are to be hospitalized have no time to become nervous, and are thus more liable to respond to the call.

Disadvantages mentioned are:

- patients lack the time to arrange their private affairs and are thus sometimes prevented from responding to the call,
- patients remain uncertain as to the date of hospitalization until the last moment,
- physicians lack prior knowledge concerning their case-mix.
Advantages of the appointment system mentioned are:
- patients have time available to arrange their affairs prior to hospitalization,
- physicians know their future case-mix,
- uncertainty on the side of the patients is reduced.

Disadvantages mentioned are:
- higher demands are set upon the quality of predictions concerning future capacity occupancy. Since this demand cannot as yet be met, control is more difficult. This results in a lower census figure because more room has to be left open for emergency patients in order to assure their admission,
- for some patients, looking towards a set date of hospitalization and possible surgery may be such a nerve-wracking process, that they no longer desire treatment when this date arrives,
- it is quite possible, that in case of inadequate planning no beds will be available for scheduled patients.

The arguments quoted above for and against each system are not all quantifiable and sometimes contradictory. No comprehensive comparison of the systems however has been carried out yet. Only Hancock et al. (47, 48, 52) using a simulation model, investigated the effect on the census of changing from one system to the other. The positive effect on the census of using a waiting list system was confirmed. Their recommendation that a hybrid system was to be used, where part of the patients received an appointment and others were put on a waiting list ("on-call"), is based only on this argument. They did not include the other factors in their researches, leaving this as a topic for further research.

While reading the following it has to be kept in mind that models designed for use in connection with an appointment system can quite easily be used together with a waiting list. A slight changing of definitions suffices to achieve this since the quantitative demands on a waiting-list system are less than those on an appointment system. For the same reason the reverse is not possible. In most cases it is not possible to use a model suited for a waiting list system together with an appointment system. In the following, models for which it is not clear to which group they belong will be classified with the group of models based on an appointment system.
7.3.2. Models based on waiting-list systems

For analytical models based on waiting list systems three approaches are used. Dantzig (21) uses a model based on linear programming in order to control the census and to minimize the time between the requested and the realized admission dates. George, Canvin and Fox (40, 41) also use a linear programming model, in which the decision variables are the number of admissions of each aggregate diagnostic category, broken down by level of urgency and patient type. Constraints of the model are the number of available patients in each category, the number of available beds, the available theatre time and the available consultant surgeon's time. The object of the model is to find the optimal throughput of patients, giving preference to the categories with a higher urgency.

Shonick and Jackson (105) and Young (129, 130) both present a statistical model. Emergency arrivals are assumed to be Poisson distributed and the length of stay assumed to be negative exponentially distributed. Control is effected by means of a parameter $B$. If the census exceeds $B$ only emergency arrivals are admitted. The difference between the models lies in the fact that Young assumes a supply of elective patients that is always able to raise occupancy up to the level $B$ whereas Shonick and Jackson assume the existence of a waiting list, which is supplied by a Poisson distributed arrival process of elective patients. With each method it is possible to calculate the average occupancy and the level of overflow which are caused by each value of $B$.

Kolesar (65) presents a Markovian decision model. The state of the system is represented by the bed occupancy. With the formulas for the steady state transition probabilities as conditions it is now possible with the aid of linear programming to reach an optimal census. Collart, Duguay, Haurie, Berger, Pelland (16, 17, 26, 51) in several articles also use Markov models. In early attempts (16, 26) they describe the state of the system by the number of occupied beds. The number of elective admissions needed to optimize the census is calculated by means of an open loop quadratic programming problem. Admissions for several days ahead are calculated, but only the results for the next day are used. In later models (17, 51) the states of the system are represented by states of sickness, as earlier described by Smallwood et al. (106). The same open-loop method is used to optimize the census (17) and, more generally, to control the balance between supply and demand of bed-capacity and
nursing staff workload (51). Rutten and v.d. Gaag (39, 100) in their papers use both Markov and simulation models to evaluate scheduling policies.

Simulation is further used by Spencer (108) and by Chase, Laszlo and Uyeno (15). Spencer uses a simulation model to determine the number of waiting list patients to be sent corresponding with each census level, in order to optimize this census. Chase, Laszlo and Uyeno developed a simulation model describing bed and operating room occupancy.

Markus (77) treats estimates on length of stay and operating time as if they were deterministic. With the aid of this information and a planboard he proposed to schedule waiting list patients taking into account bed and operating room occupancy. Luckman and Murray (73) show how a simple information system assisted with both the day to day control of inpatient admissions and surgical suite scheduling and with longer term planning. Rourke, Rogers, Chow, McPadden and Nikodem (98) describe the working of an automated system. Patients on the waiting list are ordered by means of an algorithm. Patients from the top of the list are then scheduled so as to occupy several resources such as beds and operating time optimally. Resource requirements connected with each procedure are assigned on the basis of historical data. Ultimate controls with the physicians. Kennedy and Facey (63) describe a similar system, only in their model capacity requirements are estimated subjectively. Also the remaining length of stay for each patient is estimated daily by ward nurses. Another automated system is described in the Technische Gids (116). Flynn, Heard and Thomas (33) describe routines and subroutines of an automated system. No description however, is given of the way decisions are made. Procedures for systems which take into account bed and operating room occupancy are also designed by Schuring (103), Hamer (43), Ribbers (92) and Van der Lee (69).

7.3.3. Models based on appointment systems

Again first analytical models will be discussed. Young (129, 130) in the same articles where he described his adaptive control model, also designed a rate control model. The assumptions underlying this model are nearly identical, but instead of a control level B a controllable rate of arrival of elective patients is assumed to exist. Calculations show the effect which changing this rate has on the distribution of the census.
Barber (3) describes a statistical model. Decision variables are the maximum number of patients to be scheduled each day for several days in the future. The model takes into account the number of patients which is in reality available for scheduling. Long term optimization is achieved by scheduling the maximum number of patients for the next day, but progressively less than the maximum for the following days. The object of optimization is the average census.

Several authors opted for an approach which schedules patients for the following days in such numbers that the chance of the census reaching the maximum occupancy is less than a certain figure. Wing (124) describes an automated scheduling system based on subjective estimates of length of stay. Patients are scheduled on a certain day only if admitting them would not cause the expected census to exceed a preset maximum at any time during their expected stay. Offensend (86) uses a Markov model to describe the system. On choice this model optimizes census or nursing workload. Resh (90), Rubenstein (99), Finarelli (31), Connors (18) and Briggs (13) use the conditional probability of a patient's remaining length of stay, as described in chapter 3 to schedule patients. Rubenstein uses only the probability of overflow as a scheduling factor, but Resh uses this probability as a constraint in a mathematical programming model aimed at assigning each elective patient an admission date as close as possible to his desired date of admission. Finarelli adapts the model described by Resh. As a result of this adaptation an analytic solution to the model is not possible, so a heuristic scheduling algorithm is developed with, according to Finarelli, results which are nearly optimal. Connors also describes a model based on probabilistic and deterministic constraints. A scheduling algorithm chooses among feasible data so that the value of a composite function of patient inconvenience and hospital inefficiency is minimized. Briggs describes a decision algorithm aimed at reducing the variance of the census. Parameters controlling this algorithm are found by means of simulation.

Kushner and Chen (67) discuss the possibilities and difficulties associated with using simulation models for the problem of scheduling elective patients. Smith and Solomon (107) designed a simulation model of an admission system with which they tested several scheduling policies. The number of patients to be scheduled was a) fixed, b) a percentage of daily discharges or c) the number of daily discharges each day plus
or minus a fixed number. The goal of the study was to minimize the variance in the number of admissions and to maintain the census at a certain level. Policy a) was found to be the best. Robinson, Wing and Davis (96) also compared three scheduling policies by means of simulation. The first method used was the scheduling of a fixed number of patients each day. The next system schedules the patient on the earliest requested date on which his presence in the hospital will not cause the expected census to exceed some previously defined limit. This method assumes the subjectively estimated length of stay to be correct and uses it without any direct consideration to its possible error. The third method is similar to the second one, but based on conditional probabilities for patients' remaining length of stay. The objective set in the simulation was to attain a high average census level with a small variance. Results show that the first method is clearly worse than the other two, and that between these two no great differences are noticeable.

Hancock, et al. developed and implemented an admission scheduling and control system applicable both in overbedded and in underbedded hospitals. The objective of the overbedded hospital is to minimize the variance in the census while:
- minimum acceptable nursing hours per patient day are maintained,
- admission delays are within policy levels,
- weekend census policies are maintained.
The objective of an underbedded hospital is to maximize the census while:
- cancellations do not exceed an acceptable number,
- turnaways do not exceed an acceptable number,
- weekend census does not exceed policy.
In order to achieve these results the following decision rules for each day of the week are established by means of a simulation model:
- the maximum number of surgical patients to be scheduled,
- the maximum number of medical patients to be scheduled,
- the maximum number of gynaecological patients to be scheduled,
- the number of beds that normally has to be left free for emergencies,
- the number of beds that has to be left open for emergency patients even if scheduled patients have to be cancelled,
- the number of medical call-in's which may not be exceeded in order not to disturb the balance of available beds.
- the number of beds that has to be left open in order to maintain weekend occupancy policies.

A description of development of the model may be found in Heda (53), in Hancock (45) and in Fuhs, Hancock and Martin (38); a complete description of the model is recorded in Hamilton, Hancock, and Hawley (44) and several case studies may be found in Hancock, Warner, Heda, Fuhs (46), in Magdaleno (76), in Strande and Hancock (113) and in Strande and Segal (112).

On the basis of the ideas developed by Hancock et al. a heuristic elective scheduling procedure was designed by Sahney (101, 102). The procedure uses moving average estimates for the number of emergencies and the number of discharges. Debackere, Delesie, De Ridder and Spinnewijn (22, 23) by means of a simulation model investigate the result which delaying some categories elective scheduled patients has on the variance of bed and operating room occupancy. A similar idea is used by Berrevoets (4).

Two computerized admission systems are described by Wood and Lamontagne (127) and by Dunn (27). The model designed by Wood and Montagne is based on length of stay distributions derived from historical data. Each day the computer prepares a projection of the number of beds to be available on a given day two months in the future. Emergency bed room is allotted on the basis of statistics on past needs. With the assistance of the computer both bed space and surgical facilities are scheduled. Dunn describes a computerized scheduling program based on an heuristic algorithm. The idea behind the algorithm is that a certain minimum number of beds will each day be available and that patients for these beds may be scheduled. The algorithm takes into account bed and operating room availability.

Holdich (55) and Cox (20) both describe the operation of a system where for all elective patients appointments for admission and surgery are made by the physician; who on the basis of his experience estimates when beds and operating time will be available.

7.4. Conclusion

Of all the models described in this chapter, only some of the models using heuristic methods were actually implemented in practice. Not one analytical model was ever used in a real working situation. It is not
clear what the reason for this is. It may be that through a lack of communication between operational researchers and the hospital staff by the latter group the enthusiasm needed to implement such methods is lacking. Another possibility however is that maybe the hospital system is too complicated to be represented by an analytically solvable model. The assumptions needed to keep the model solvable might make it too unrealistic. Whichever is the case, only heuristic models are ever applied. The common goal of these models is the control of bed occupancy. For some of these models operating room occupancy is also included in the objective, but none of the heuristic models pay any attention to the control of the variability of the nursing workload, apart from the partial control which results automatically from a reduction of census variability.
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