"PLANNING KLM'S AIRCRAFT MAINTENANCE PERSONNEL"

by

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Abstract

A Decision Support System (DSS) has been developed for the aircraft maintenance department of KLM Royal Dutch Airlines at Schiphol Airport. The aircraft maintenance department is responsible for carrying out inspections on aircraft during their ground time at the airport. The main resource of the department is its workforce. Since January 1990 the DSS has supported the management in analysing several capacity planning problems related to the size and organization of the workforce. In particular, the DSS is used to determine the appropriate number of maintenance engineers and their training requirements. Furthermore, the DSS is used to analyse the efficiency and effectiveness of the maintenance department.

Case description

KLM Royal Dutch Airlines has been the major Dutch carrier since 1919. KLM's home base is Schiphol Airport near Amsterdam. Currently (1992), KLM owns about 90 aircraft of 8 different types. With this fleet, KLM carries out flights to 150 cities in 79 countries. Of course, safety of passengers and crew has top priority. In order to guarantee this safety, high quality aircraft maintenance needs to be carried out. About 3000 employees of KLM's maintenance department take care of this. They also carry out maintenance operations on aircraft of about 30 other carriers, as far as these have maintenance contracts with KLM.

Aircraft maintenance consists partly of *large* inspections and partly of *small* inspections. Large inspections take place in KLM's hangars after a prespecified number of flight hours depending on the aircraft type. The time required for carrying out such a large inspection ranges from several hours up to several months. Small inspections take place during the ground time between the arrival to and the next departure from Schiphol Airport. Such an inspection, also called a *project*, consists of the following services:

- arrival services (fixing ground power supply, compiling a list of technical complaints based on the crew's flight records, and collecting resources such as mobile cranes and scaffoldings),
- platform services (checking the technical state of the aircraft, and, if necessary, performing small repairs),

- departure services (performing a final technical pre-flight check of the aircraft).

These projects are carried out by maintenance engineers of KLM-VOC (*Vliegtuig Onderhoud Centrum* in Dutch). KLM-VOC is a sub-department of KLM's maintenance department, consisting of about 400 employees. The DSS has been developed to support the management of this sub-department in analysing capacity planning problems related to the size and organization of its workforce. In particular the system provides information on the *workload* and the *workforce* of KLM-VOC, and on the quality of the *matching* of these two.

The workload of KLM-VOC's technical staff is mainly based on:

- the timetables of KLM and other carriers,
- the contracts with other carriers,
- the maintenance norms.

The maintenance norms specify *(i)* in which time interval each service must be scheduled, *(ii)* how much time must be spent on each service, and *(iii)* the skill required for each service (i.e. Mechanical, Electrical, or Radio skill). The maintenance norms depend on the aircraft type and on the carrier owning the aircraft. Usually, maintenance norms are specified by aircraft manufacturers, governments, and the carriers themselves.

KLM's timetable and those of other carriers have a *cyclic pattern* with a cycle length of one week. As a result, the workload of KLM-VOC also shows a cyclic pattern. Furthermore, the workload on an average day shows some clearly distinguishable *peaks*, caused by KLM's desire to have short waiting times for transit passengers. For example, early in the morning a stream of intercontinental flights arrives at Schiphol Airport. Shortly thereafter a stream of continental flights departs from Schiphol Airport to several destinations in Europe.
In the future KLM intends to increase the utilization rate of its fleet, and to smoothen the workload pattern of its ground service departments. The latter will be achieved by increasing the number of peaks and by reducing the size of the peaks. For this type of studies, KLM-VOC's management is interested both in aggregated and in more detailed information on the pattern of the workload, since this provides valuable insights into the required size and organization of the workforce. Information on the workload pattern is visualized by the DSS. A typical example of a workload graph is shown in Figure 1.

Insert Figure 1 about here

Figure 1. Workload between Saturday 0.00h and Sunday 0.00h as represented by the DSS for Airbus A310, Boeing 737, and Boeing 747. The figure shows that the number of maintenance engineers required must be at least 11 (A310), 15 (B737), and 27 (B747) respectively.

The workforce of KLM-VOC consists of about 250 *ground engineers*, and 150 *non-technical employees*. The ground engineers are highly skilled and well trained employees, since their job is a very responsible one. A governmental rule specifies that an engineer is only allowed to carry out inspections on a specific ***aircraft type*** if he has a *license* for that aircraft type. Besides a license for an aircraft type, an engineer also has a specific *skill*, either for Mechanical, Electrical, or Radio operations. A license for an aircraft type and a skill is obtained by attending a training program consisting of theoretical and practical courses, a field training, and exams. The time to complete a training program depends on the engineer's experience, and ranges from several months to several years.
From a managerial point of view, it would be preferable if all engineers would have licenses for all aircraft types and all skills. In that case the flexibility of each engineer would be maximal. However, KLM's internal safety rules state that each engineer is allowed to have licenses for at most *two* aircraft types and *one* skill.
The engineers operate in *teams*, which constitute the smallest organizational sub-units of KLM-VOC. Currently there are 12 teams of about 20 engineers each. The assignment of engineers to teams is such that teams are almost identical with respect to the available licenses and skills.

Insert Figure 2 about here

Figure 2. Composition of one team of engineers. Each block represents one engineer. Here, two engineers have a license for mechanical work on the Airbus A310 and the Boeing B737.

The teams operate in a four shift system (early day shift, late day shift, evening shift, and night shift) with shifts of about eight consecutive hours. An example is given in Figure 3. The assignment of teams to shifts is constrained by several governmental, union, and internal KLM rules. For instance, for each team the average number of shifts per week should be equal to 5, and there should be at least one day off between a night shift and the next day shift.

Insert Figure 3 about here

Figure 3. Shift scheme on a typical Saturday as represented by the DSS. Each team of engineers is represented by one block. For example, in the early day shift four teams of engineers are available.

Managerial problems

The main managerial problem is to find a good *matching* of workload and workforce. The elements that play a role in this matching are shown in Figure 4.

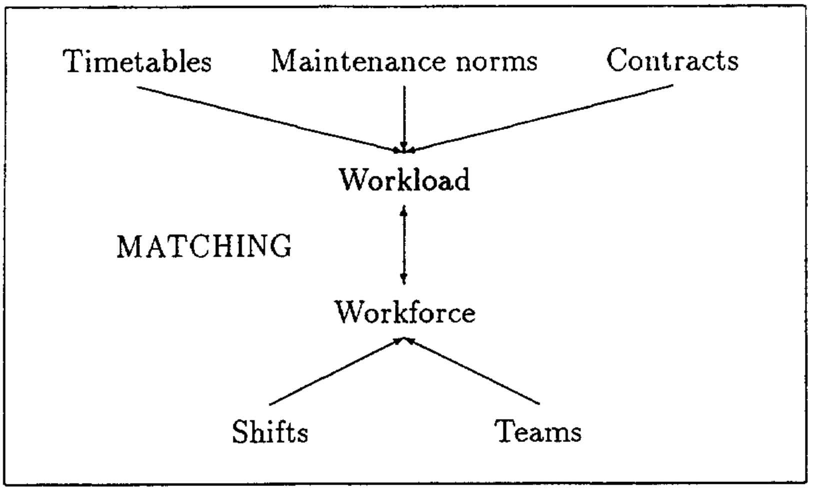

Figure 4. Scheme of relevant problem components.

The quality of the matching in a certain planning period (day, week, or month) is expressed in terms of a *service level* and a *utilization rate.* These performance indicators are defined as:

$$\text{service level} = 1 - \frac{\#\text{ delayed aircraft}}{\text{total }\#\text{ of aircraft}},$$

$$\text{utilization rate} = \frac{\text{total }\#\text{ of productive man hours}}{\text{total }\#\text{ of available man hours}}.$$

Main consequences of a *bad matching* are:

- a *low* service level, caused by a too *high* utilization rate of the workforce. In the airline industry delayed aircraft should be avoided as much as possible, because of customer dissatisfaction and high costs,

- a *low* utilization rate of the workforce, caused either by the presence of too many engineers, or by the presence of engineers with inappropriate licenses or skills. Of course, both causes lead to an inefficient and hence costly maintenance organization.

Planning for a good matching of workload and workforce is therefore important, and involves both the *strategic* and the *tactical* planning level. Relevant *strategic* problems to be solved by KLM-VOC's management are:

- to set an appropriate target for the service level,

- to obtain insights into the relationship between the size and organization of the workforce and the resulting service level,

- to determine the impact of timetable adjustments on the size and organization of the workforce,

- to analyse the consequences of the introduction of new aircraft types on the size and organization of the workforce, and
- to perform cost/benefit calculations for potential new contracts with other carriers, in order to evaluate their financial implications.

KLM-VOC's management is also faced with a number of problems at the *tactical* decision level. Examples are:

- to establish a shift schedule, i.e. to determine the number of shifts per day, and the begin and end times of each shift,
- to design an appropriate composition of the teams with respect to license combinations and skills,
- to develop a training program, i.e. to determine the required capacity and desired contents of the educational program for maintenance engineers, and
- to provide estimates of next year's personnel budgets for the maintenance department.

The DSS is used to support the management of the maintenance department in dealing with these problems. It focuses in particular on problems induced by the existence of different aircraft types, license combinations, and skills. Before the DSS was developed, strategic and tactical capacity planning was based on rough aggregate workload calculations for the various aircraft types. The problems caused by the different aircraft types, license combinations, and skills could not be evaluated to a sufficient level of detail. Furthermore, carrying out these calculations was very time consuming. As a consequence, due to time pressure in the planning process, typically only a limited number of scenarios could be evaluated.

Decision Support System

One of the system constraints set by KLM-VOC's management was that the DSS should be *stand-alone*, and able to run on a personal computer. The DSS consists of a *database module* and an *analysis module*. The following data is stored in the database: generic data, data with respect to the workload, and data with respect to the workforce. The database contains the following tables:

Generic data	**Workload**	**Workforce**
Carriers	Projects	Composition of teams
Aircraft types	Contracts	License combinations
Services	Maintenance norms	Shifts

The table *Composition of teams* does not contain data on individual engineers, but describes for each license combination and skill how many engineers should be available in each team. A representation of the composition of one team of engineers is given in Figure 2. Furthermore, the table *Projects* does not contain data on individual projects, but contains a list of generic projects that are carried out weekly. The structure of the table *Projects* is as follows:

Attribute	**Domain**
Carrier group	Set of carrier groups
Aircraft type	Set of aircraft types
Day of arrival	1,..,7
Time of arrival	Time
Day of departure	1,..,7
Time of departure	Time

For example, the record (KLM, B747, 6, 9.00, 6, 11.25) specifies that a Boeing 747 of KLM is scheduled to arrive each Saturday at 9.00 AM and is scheduled to depart on the same day at 11.25 AM. The contents of the table *Projects* is derived from the timetables of KLM and contract carriers. The structure of the table *Maintenance norms* is as follows:

Attribute	**Domain**
Carrier	Set of carriers
Aircraft type	Set of aircraft types
Service	Set of services
Skill	Set of skills
Amount of work	$0, ..., \infty$
Reference begin	{A,D}
Difference begin	$-\infty, ..., \infty$
Reference end	{A,D}
Difference end	$-\infty, ..., \infty$

For example, the record (KLM, B747, Platform, Mechanical, 160, A, +15, D, -30) specifies that the Mechanical part of the Platform inspection of a Boeing 747 of KLM requires 160 minutes of work. This amount of work must be carried out in the time interval starting 15 minutes after Arrival and ending 30 minutes before Departure.
A complete set of tables is called a *scenario*. The database module provides functions for operations on complete scenarios and functions for operations on individual tables of a selected scenario. By analysing different scenarios the DSS user obtains valuable insights into the effects of changes in the data.

The analysis module provides extensive possibilities for analysing a scenario through functions for:

- *Estimating* the aggregate workload. Based on the set of projects to be carried out, the maintenance norms, and the contracts stored in the database, the total workload is determined. These calculations are illustrated by the following example concerning the Mechanical part of the Platform inspection of the project (KLM, B747, 6, 9.00, 6, 11.25) that was described before. The maintenance norm (KLM, B747, Platform, Mechanical, 160, A, +15, D, -30) specifies that 160 minutes of work must be carried out in the time interval between A+15 and D-30. In this example the actual time between A+15 and D-30 is 100 minutes. This implies that at least 2 engineers are required to carry out this inspection. Therefore 2 jobs are created, each one corresponding to an amount of work to be carried out by one engineer. It is assumed that the total amount of work is divided equally among these 2 jobs. In order to have a minimum expected time of completion of the Platform inspection, both jobs start at A+15 and end at A+95 = D-50. The latter is in accordance with the maintenance norms which specify that all jobs must be carried out as early as possible. Analogous calculations are carried out for the other services corresponding to this project and for the other projects. An example of a workload graph resulting from such computations was given in Figure 1.

- *Generating* specifications for the size and organization of the workforce. Given the workload, the begin and end times of the shifts, and the user-specified service level, the system uses a heuristic procedure to determine the size and organization of the teams, such that all required work can be carried out. A simplified version of the integer programming formulation that is used to solve this problem is described in the Appendix (Model 1).

- *Simulating* the maintenance processes within KLM-VOC, in order to evaluate the quality of the matching between workload and workforce in terms of service level and utilization rate. These performance indicators are determined by a heuristic procedure, which assigns the workload to the available workforce. The solution to this procedure contains an assignment of services to engineers, and a list of services that cannot be carried out. (In practice these services either cause a delay, or they are postponed until the next stop of the aircraft at an airport.) The model of the problem that is solved by the heuristic is described in the Appendix (Model 2). By running this heuristic for various compositions of the teams, the user becomes aware of the behaviour of service level and utilization rate as a function of the composition of the teams.

Insert Figure 5 about here

Figure 5. Service level on a typical Saturday. The dark areas show that part of the workload that can be carried out by the available engineers. The small grey areas show that part of the workload that cannot be carried out in time.

Insert Figure 6 about here

Figure 6. Utilization rate on a typical Saturday. The figure shows the activities of the engineers per license combination and per aircraft type.

System use

The DSS is mainly used by staff employees to answer questions from KLM-VOC's management. Much effort was devoted to user-friendliness of the system, which resulted in quick user acceptance. The DSS is used to analyse the managerial problems mentioned before. Until now the system provided valuable support in the following studies:

- A study to determine the required number of engineers and their licenses for 1992 and 1993,
- A study on the impact of new timetable structures (for example, timetables with an increased number of arrival and departure peaks per day) on the logistics of the maintenance department,
- A study on the financial and workload effects of contracts with other carriers,
- A study on the effects of allowing engineers to have licenses for *three* aircraft types instead of *two*,
- A study on the required workforce per group of gates, in case that maintenance processes would become decentralized (per gate group) instead of centralized, as in the current situation.

Summarizing, the DSS provides KLM-VOC's management with additional information that was either not available before, or too time-consuming to be obtained within a short planning cycle. The DSS contributes to increased insights into the various problems that have to be solved within the maintenance department. It is therefore considered to be a valuable tool for analysing strategic and tactical problems. The users of the system even advocated its use to other departments of KLM, such as the helicopter department.
However, evaluation of a DSS is generally more difficult than evaluation of more traditional information systems, since simple criteria like costs and benefits are hardly useful (Keen [2]). First, a DSS is never completely finished and therefore costs are difficult to specify. Second, the benefits of a DSS are often found in qualitative aspects, such as the impact on the organization, the quality of decision making processes, and the resulting decisions. Evaluation of these aspects in quantitative terms is difficult and has not obtained much attention in the literature yet (Elam et al. [1]).
When considering the results of a DSS it is important to keep in mind that these results are based on mathematical models which are abstractions of reality. Optimality in *mathematical* terms need not necessarily match optimality in *practical* terms. Furthermore, most of the calculations within a DSS are based on approximation algorithms. Therefore the results of a DSS must be *handled with care*. It is always the user of the DSS who is in charge of judging the practical value of a solution by confronting it with qualitative or quantitative aspects that were not taken into account by the models within the DSS. Hence, a DSS must be used in an interactive way, where the intelligence of the user is combined with the capability of the DSS to organize and process enormous amounts of

data, and to solve complex mathematical decision problems using sophisticated Operational Research techniques.

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Appendix

In this appendix we present a mathematical description of the optimization problems solved within the analysis module. In order to keep the presentation clear, we make the simplifying assumption that there is only one shift and one skill. However, it is easy to modify the model in such a way that multiple shifts and skills are properly taken into account. We suppose that the set J of jobs (services) has to be carried out. Job $j \in J$ requires continuous processing in the interval (s_j, f_j) and is related to an aircraft of type a_j. Hence, each job j can be represented by a triple (s_j, f_j, a_j). The jobs must be carried out in a *non-preemptive* way by a number of engineers. Each engineer is assumed to have a license combination which specifies the aircraft types he is allowed to work on. The set of different license combinations is denoted by C. For $c \in C$ we associate costs k_c with each engineer with license combination c. Furthermore, the set J_c denotes the set of jobs that can be carried out by engineers with license combination c. Conversely, we use the notation C_j for the set of license combinations that can be used for carrying out job $j \in J$. Furthermore, $\{t_p | p \in P\}$ is the set of start times of the jobs. That is $\{t_p | p \in P\} = \{s_j | j \in J\}$.

Model 1 (Generation function)

Here the problem is to determine a minimum cost organization of the workforce, such that all jobs can be carried out. The decision variables of this Integer Program are defined as follows:

X_{jc}: a binary variable indicating whether job j has to be carried out by an engineer with license combination $c \in C_j$.

Y_c: an integer variable indicating the required number of engineers with license combination c.

In terms of these decision variables, the objective and the constraints can be stated as follows:

$$\min Q = \textstyle\sum_{c \in C} k_c Y_c \tag{1}$$

subject to

$$\textstyle\sum_{c \in C_j} X_{jc} = 1 \qquad \text{for } j \in J \tag{2}$$

$$\textstyle\sum_{\{j \in J_c | s_j \le t_p < f_j\}} X_{jc} \le Y_c \qquad \text{for } c \in C \text{ and } p \in P \tag{3}$$

all variables are integer (4)

The objective function (1) expresses that we are interested in minimizing the total costs associated with the engineers. The constraints (2) guarantee that each job is carried out exactly once. The constraints (3) specify that the maximum job overlap of the jobs that are assigned to the engineers with license combination c should not exceed the number of available engineers with license combination c. This implies that a feasible solution to the integer program can be transformed into a feasible nono-preemptive assignment of jobs to engineers and vice versa. Finally, the integrality constraints (4) specify the integer character of the decision variables.
Kroon [4] shows that in general this optimization problem belongs to the class of NP-hard problems and presents algorithms that can be used to find optimal or approximate solutions.

Model 2 (Simulation function)

Here the problem is to determine an optimal (maximum revenue) assignment of the jobs given the size and the composition of the workforce. Now each job j has a value v_j. The number of engineers with license combination c is known and denoted by M_c.

X_{jc}: a binary variable indicating whether job j has to be carried out by an engineer with license combination $c \in C_j$.

In terms of these decision variables, the objective and the constraints can be stated as follows:

$$\max Q = \sum_{j \in J} \sum_{c \in C_j} v_j X_{jc} \qquad (5)$$

subject to

$$\sum_{c \in C_j} X_{jc} \leq 1 \qquad \text{for } j \in J \qquad (6)$$

$$\sum_{\{j \in J_c | s_j \leq t_p < f_j\}} X_{jc} \leq M_c \qquad \text{for } c \in C \text{ and } p \in P \qquad (7)$$

all variables are integer (8)

The objective function (5) expresses that we are interested in maximizing the total value of the assigned jobs. The constraints (6) guarantee that each job is carried out at most once. The interpretation of the constraints (7) and (8) is similar to that of the constraints (3) and (4) in Model 1. Kolen and Kroon [3] show that generally this optimization problem belongs to the class of NP-hard problems. Algorithms that can be used to find optimal or approximate solutions are described by Kroon et al. [5].

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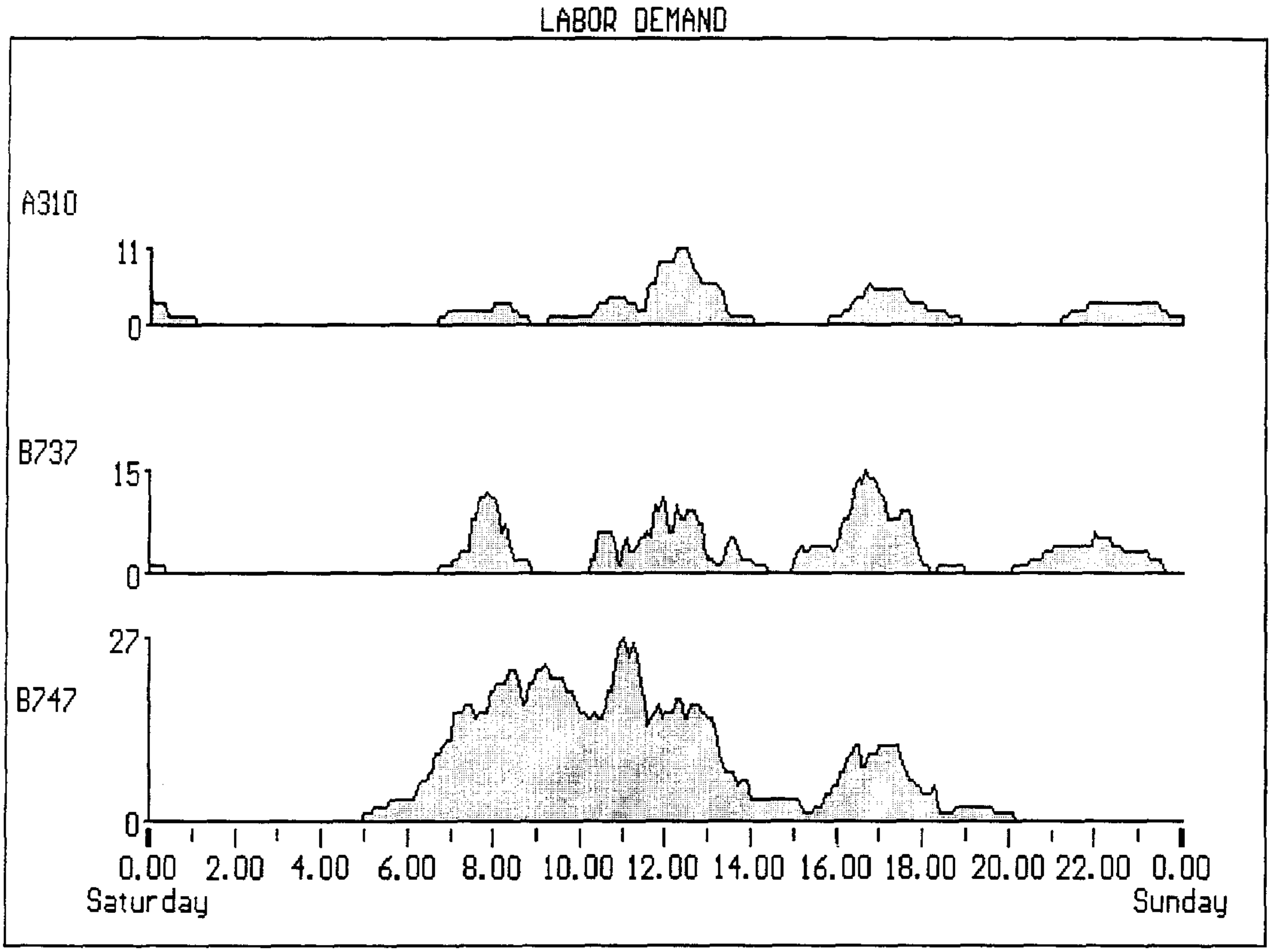
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Figure 1

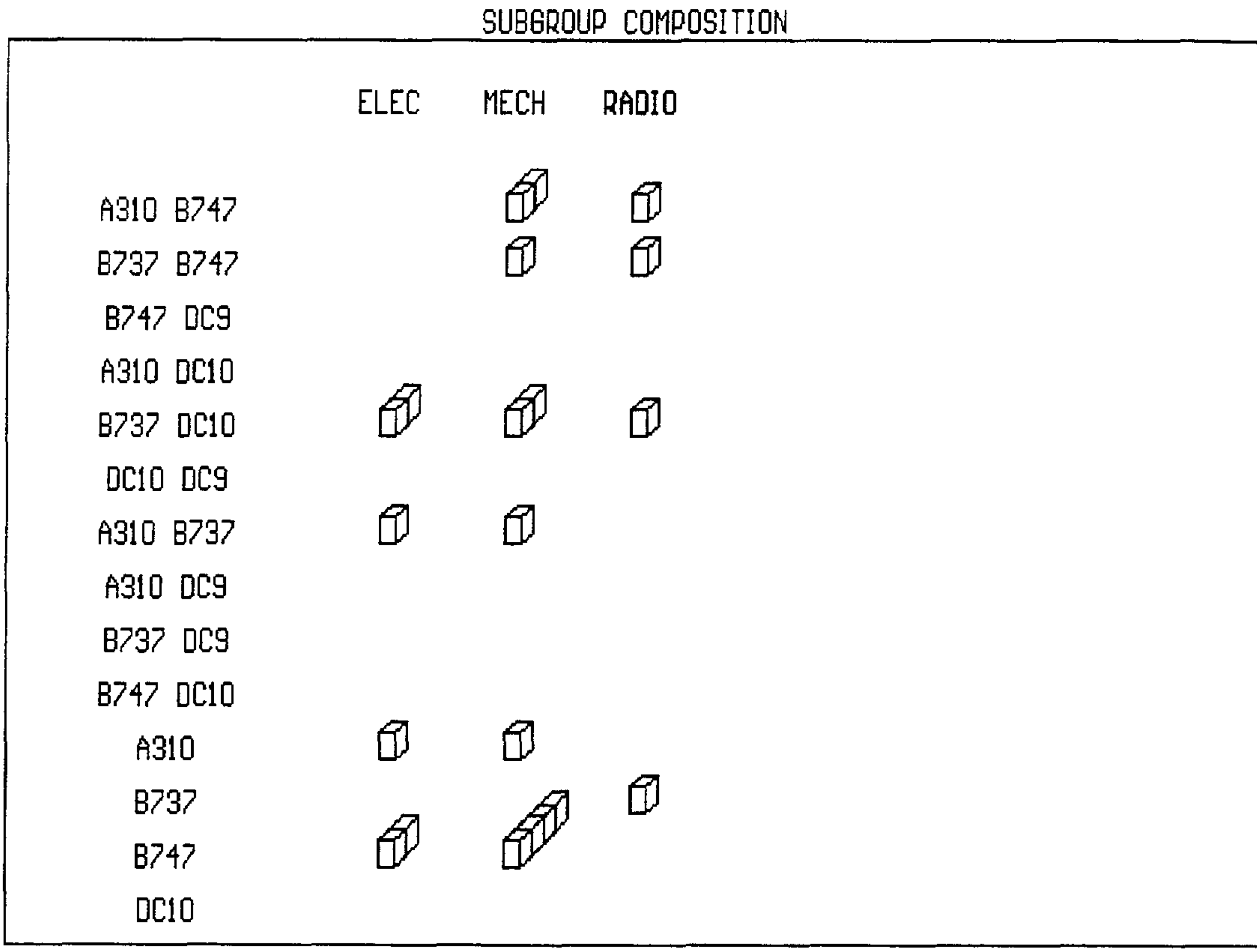
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Figure 2

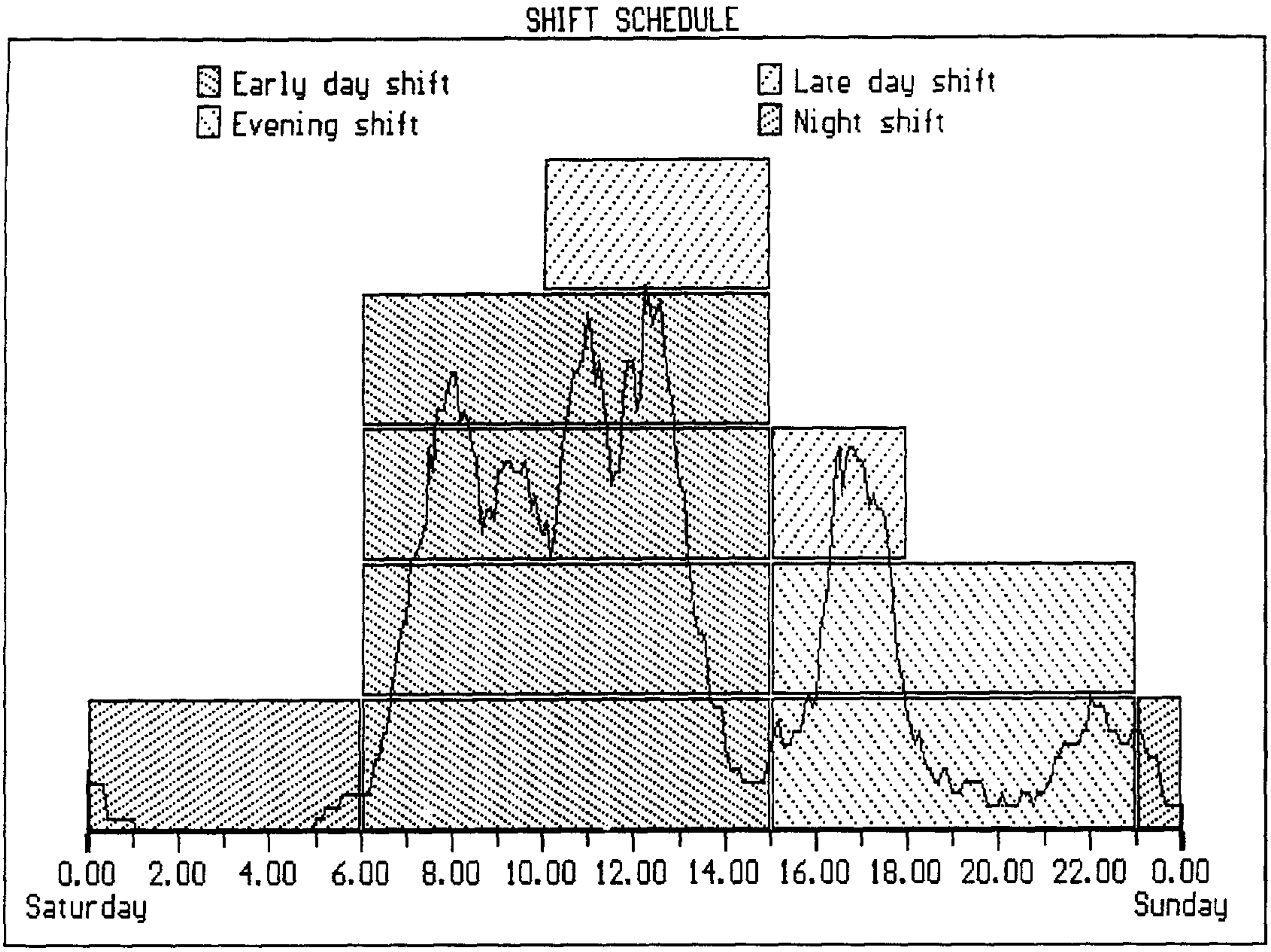
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Figure 3

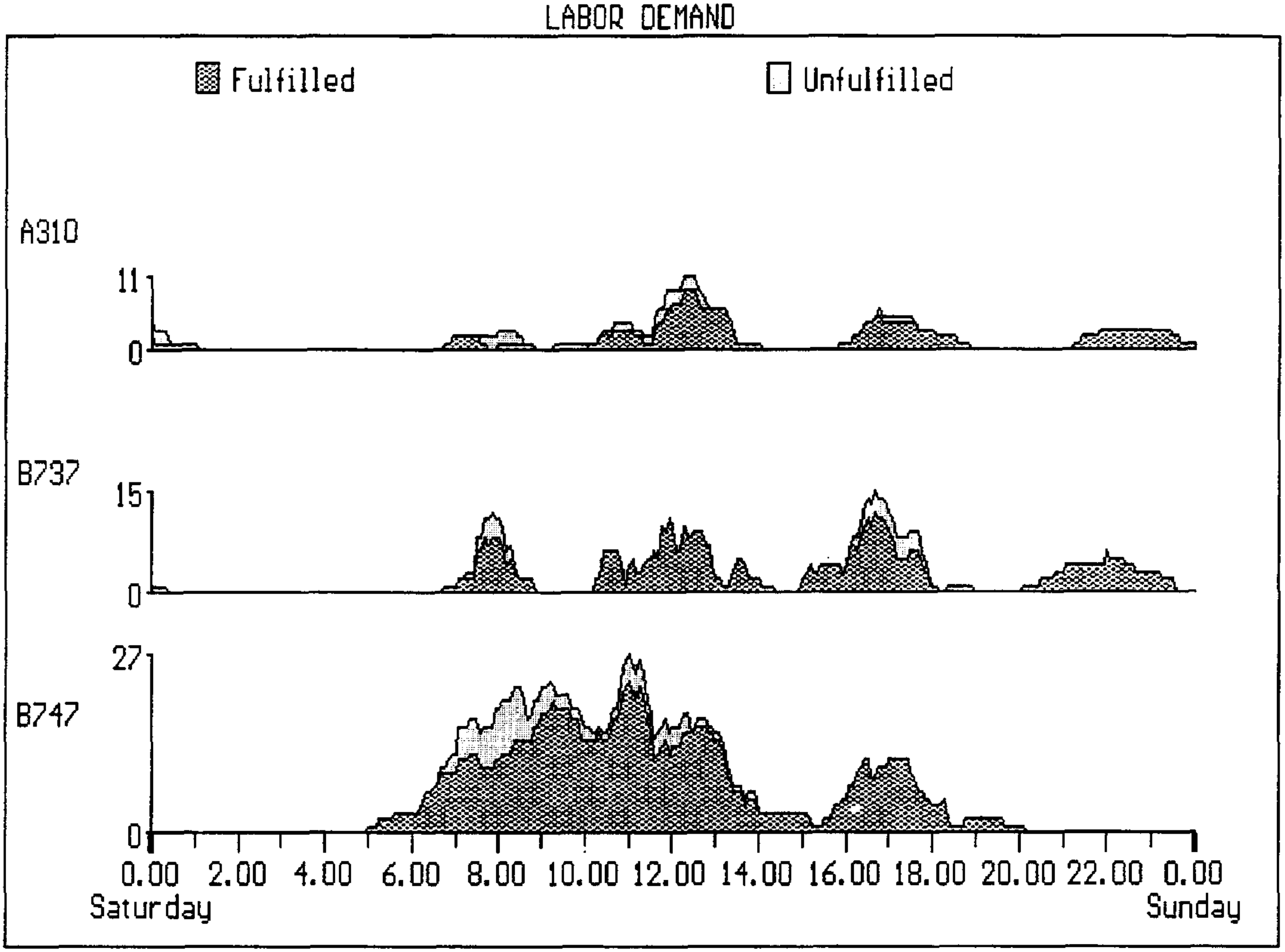
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Figure 5

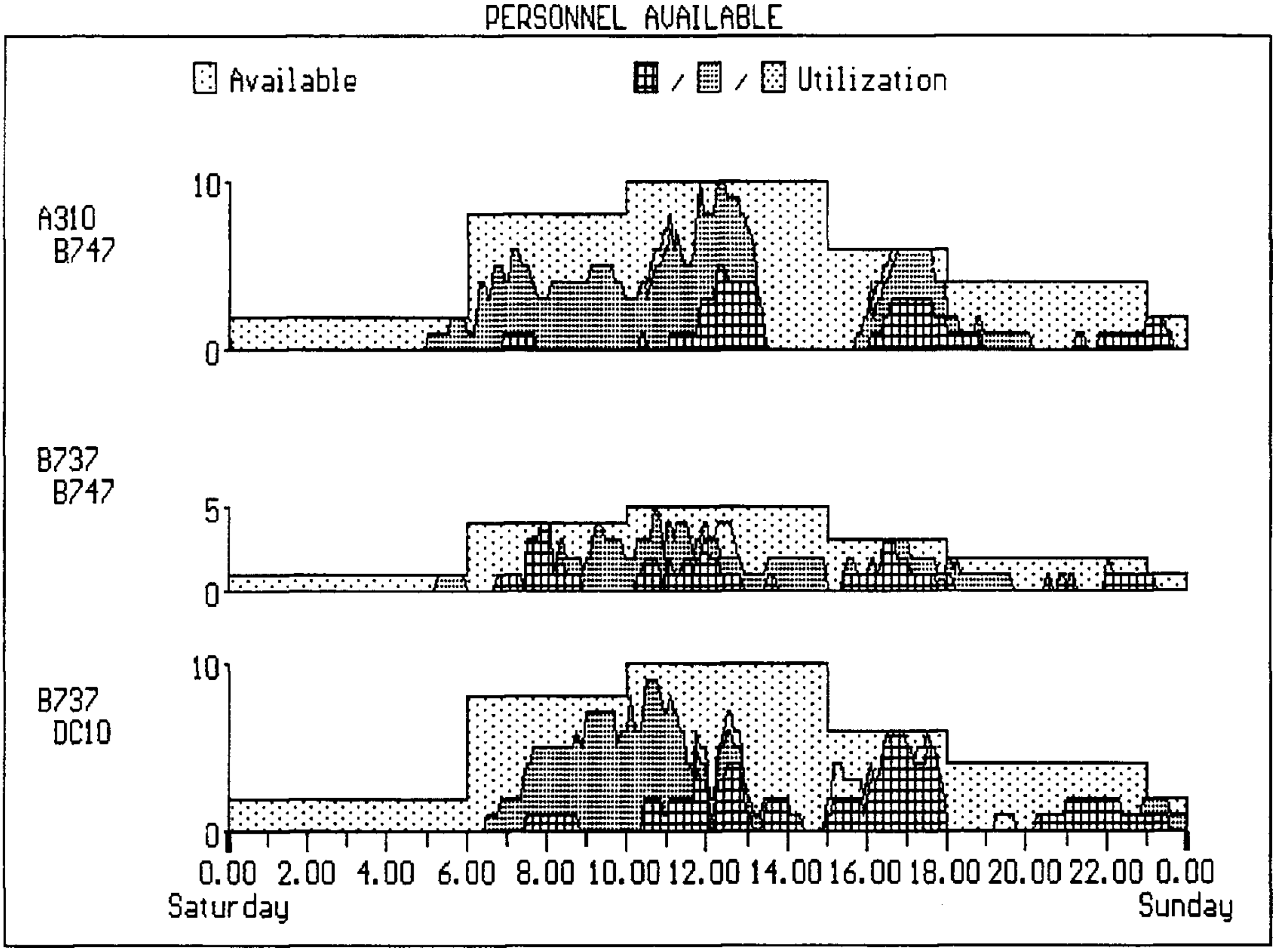
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Figure 6