A FRAMEWORK FOR THE EVALUATION OF HOSPITAL INFECTION CONTROL TECHNIQUES

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August 1982

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Working Paper Series

CRIS #40

GBA #82-53(CR)

This paper was first presented at the European Conference on Operational Research in Health Services, Patras, Greece, July 19-23, 1982.

Abstract

A cost-effectiveness method for evaluating measures against hospital-aquired infections is based on a network interdiction model. Algorithms for optimal interdiction of the infection network are presented and their applicability is discussed. Implications of the approach for classifying measures, allocating costs and benefits, and analyzing the costs of infections are described. The method is being applied in an interdisciplinary study conducted in several West German hospitals.

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Acknowledgment

This work was supported in part by the Federal Ministry of Labor, Bonn, West Germany. The views and conclusions expressed in this paper are solely those of the author.

1.0 INTRODUCTION

In many ill-structured decision situations with little data availability, operational research models can still serve a useful purpose in structuring thinking about the problem, identifying bottlenecks, and deriving suitable evaluation criteria for actions. This paper deals with the application of an OR model in a cost-effectiveness study of measures against hospital-aquired or nosocomial infections (NI) conducted in several West German hospitals [9].

More than 5% of all hospitalized patients aquire infections during their stay [7,13,14]. While some of these infections are an inescapable consequence of progress in medicine, hygienic procedures have been introduced to reduce the number of avoidable infections that occur. Guidelines for the detection and prevention of NI have been developed by several national and international institutions [1,15,16].

Measures against NI are often associated with high financial costs (e.g., for special air conditioning [18]). In addition, a large number of rules to be followed (e.g., in cleaning and disinfection [10]) causes work and cognitive overload of personnel and thus less than optimal performance. Therefore, it seems useful to set priorities and to stress the most effective and cost-efficient techniques. It is, however, difficult to establish the exact costs and benefits in general.

First, the costs of a measure, especially personnel and investment costs, depend largely on the specific situation.

Second, the costs of NI (= the financial benefit of avoiding them) have so far been largely computed solely from the change in the length of stay resulting from NI. For our purposes, realistic estimates are required of how costs change when a certain number of NI are prevented.

Third, a direct effect of single measures on infection rates cannot often be observed. Because of vast differences among patients and situations very large sample sizes are required to statistically prove even major changes in infection rates [6,8].

In our approach, an operational research model is used to identify classes of measures and to assign practical effectiveness criteria to them. In this way, the lack in sample size dictated by time and financial constraints can be overcome to some extent by a better problem structure.

The paper is organized as follows. In section 2, the general method of cost-effectiveness analysis is specialized to the problem of NI control. In section 3, we present a network interdiction model of measures against NI and analyze the applicability of some algorithms. Section 4 describes the practical implications of the model for classifying measures, allocating costs and benefits, and computing the costs of NI. The paper ends with a summary and conclusions.

2.0 COST-EFFECTIVENESS ANALYSIS OF HOSPITAL INFECTIONS

Similar to cost-benefit analysis, cost-effectiveness analysis is a tool for evaluating solutions to complex multiple objective decision problems. However, cost-effectiveness analysis differs from cost-benefit analysis in that the result is expressed as a vector of financial and non-financial effects rather than as a single monetary value. The final trade-off between efficient solutions is left to the decision-making body. Thus, the role of cost-effectiveness analysis as a decision support tool, not a decision-making instrument, is stressed. The approach also reduces the problem of explicitly determining the relative weights of hardly comparable criteria (e.g., the monetary value of human life).

Figure 1 gives the flowchart of a typical cost-effectiveness study. It can be seen that the feasibility of measures depends on satisfying both the minimal requirements for each evaluation criterion and the external constraints given in a specific clinical situation. Therefore, the same measure can be judged differently in different settings. Consequently, generally applicable recommendations will usually either be negative (the minimal requirements of some criterion are not satisfied) or deal with relatively isolated subsystems (e.g., catheterization techniques). For other measures, at most "what...if"-type results can be expected.

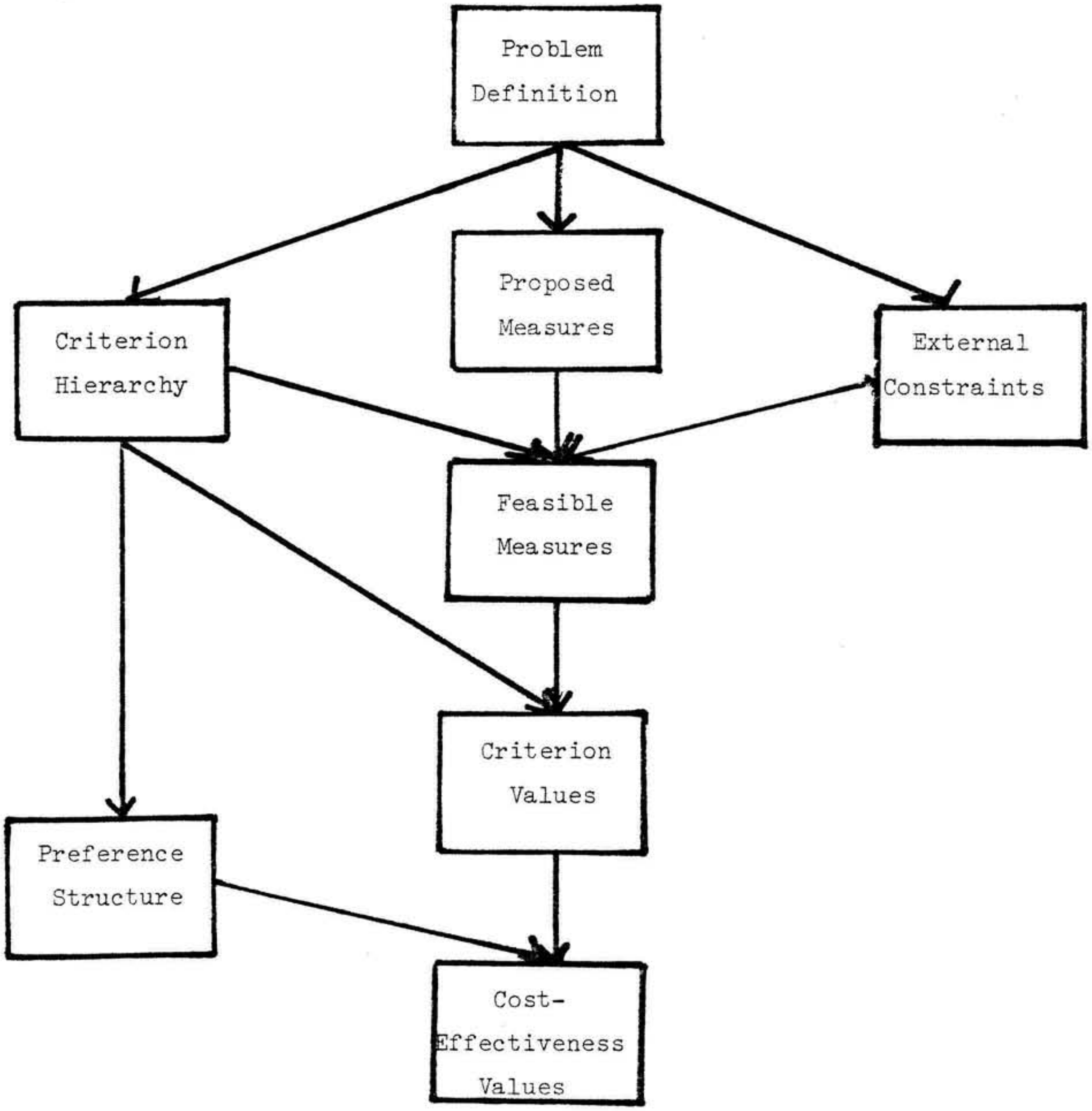

Figure 1: Cost-Effectiveness Schema

As mentioned above, the preference structure of the decision-makers is determined only within groups of comparable criteria in order to reduce the size of the result vector while keeping each element of it meaningful. For our purposes, three criterion groups are considered: medical-hygienic efficacy; financial costs or savings; and effect on the working environment (ergonomical effectiveness). Figure 2 relates these criterion groups to some indicators that can be used to determine the size of the effects. Next, we discuss some problems associated with this relationship.

Our first observation is that the relationship between indicators and criteria is not functional, that is, the criterion hierarchy is not a tree or forest. For example, if a measure requires some personnel time, this may result in changes in ergonomical effectiveness (more stress), changes in costs (overtime, hiring new personnel), or both depending on the size of the change. Our conclusion is to evaluate only sufficiently large combinations of measures to determine the real effect. Which indicators are most important for the evaluation also depends on the class of the measure (see section 4, below).

Another problem is concerned with the measurement of the indicators themselves. Figure 3, a simple model of measure implementation, reveals a duality between the states and the recommended (or implemented) measures in the sense that in principle it should be sufficient to analyze any of the two to determine the cost-effectiveness.

However, a look at the indicators makes clear that practical considerations require exploiting both state and transition (measure) information. Ergonomical and financial indicators are more related to the measure itself while the medical-hygienic indicators require a comparison of two states of the system. The latter is usually more costly and time-consuming and should be simplified as far as possible.

The difference between the old and the planned state gives the theoretical effectiveness of a measure and usually can be determined more easily and more precisely than the observed difference between old and new state.

In order to keep the analysis simple and still realistic, the concept of <u>hygienic management</u> is introduced to explain the difference between planned and actual performance of a measure. The observed effect is considered an overlay of the theoretical effectiveness of the recommended measure and the effectiveness of the related management procedures. To avoid an unrealistically positive evaluation of impractical measures, an additional group of indicators related to issues like learnablity, simplicity, etc. is included in the evaluation scheme.

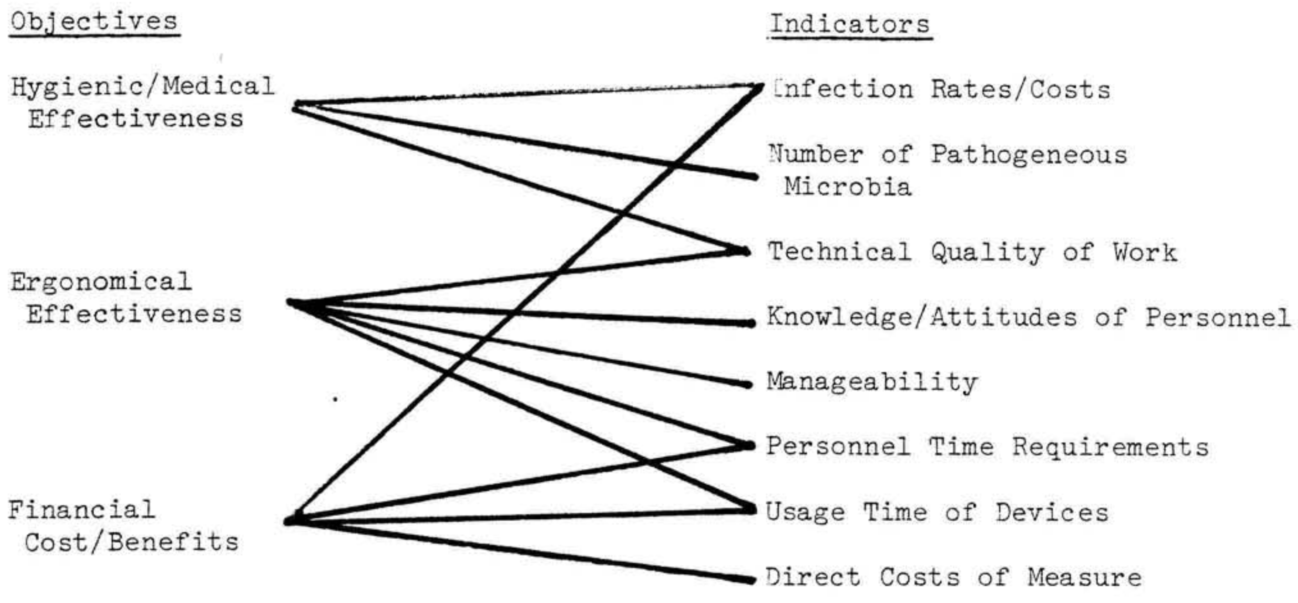

Figure 2: Criterion Hierarchy for Evaluating Measures against NI (Simplified)

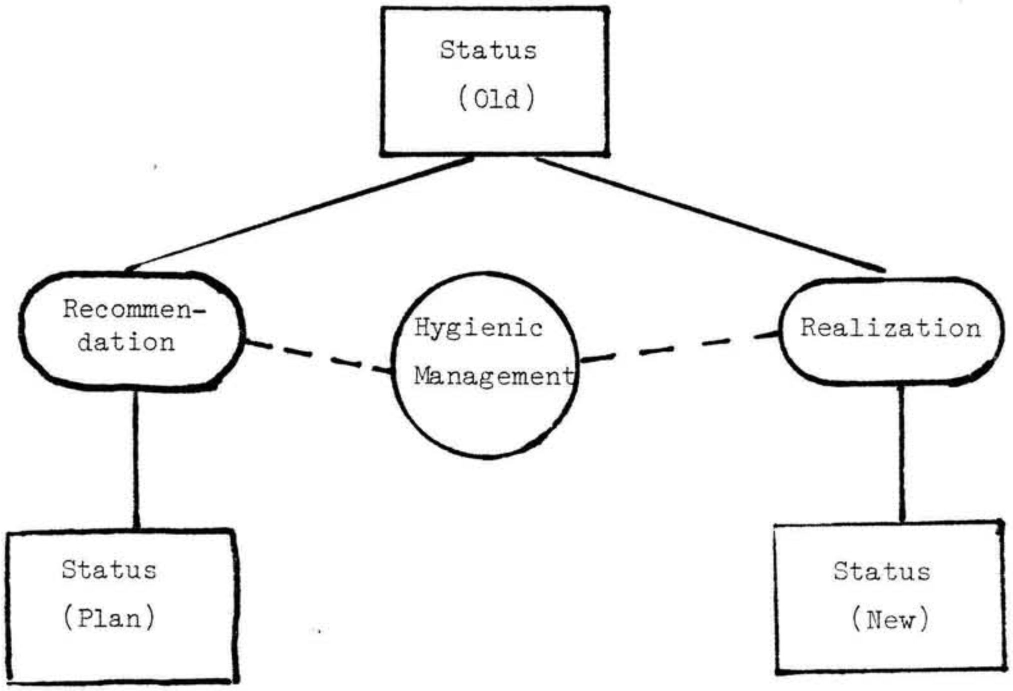

Figure 3: Model of Implementing Measures against NI

3.0 NETWORK INTERDICTION APPROACH TO HOSPITAL INFECTION CONTROL

In order to be able to compare measures in a common framework, this section introduces a general network model of hospital infections. Different refinements of the model lead to several optimization procedures with cost minimization or effectiveness maximization objectives.

3.1 Network Model Of Hospital Infections

The informal idea of infecting organisms (also referred to as germs or bacteria) moving from reservoirs or sources through a network of carriers to entry points into the hospitalized patients is well-known in medicine [12]. Typical sources include infected patients, personnel, and wet areas in the environment ("water bugs"). Carriers can be personnel, patients, technical devices, and surfaces of floors, walls, and furniture. The carriers aquire and transfer germs mostly via physical contact, sometimes through the air.

The entry points are related to the sites of a possible infection; the most frequent are urinary tract infections, infections of surgical and surface wounds, respiratory tract infections, and blood infections (bacteremia) [7]. It should be noted, however, that the presence of bacteria at an entry point does not necessarily result in symptomatic infection; other factors like age, sex, type of service, underlying illnesses and operations play an important role, too [7].

The informal notion described above can be mapped into a network flow model of operational research by defining

* reservoirs and sources as source nodes,
* carriers as transshipment nodes,
* entry points as sink nodes, and
* contacts as arcs of the network.

Figure 4 gives the structure of such a network. Arcs between carriers have been omitted for simplicity. The arcs can be labelled by the type of contact; several contacts between two nodes can exist simultaneously. Thus, the network is a general graph with multiple arcs connecting pairs of nodes.

The actual definition of arc capacities for a faithful mapping of reality can be quite difficult and is beyond the scope of this paper. For example, the potential flow of infecting organisms through an arc is influenced by the frequency and duration as well as by the intensity of contacts and by the predisposition of the destination. Further, the network changes significantly with time, e.g., by growth of bacteria or by the development of infections in patients turning them from sinks into sources.

Fortunately, the problem is greatly simplified by the "safety first" approach prevailing in medicine. All arcs beyond a certain minimal transport capacity are considered as potential health hazards and can therefore be assumed to have the same (unlimited) capacity.

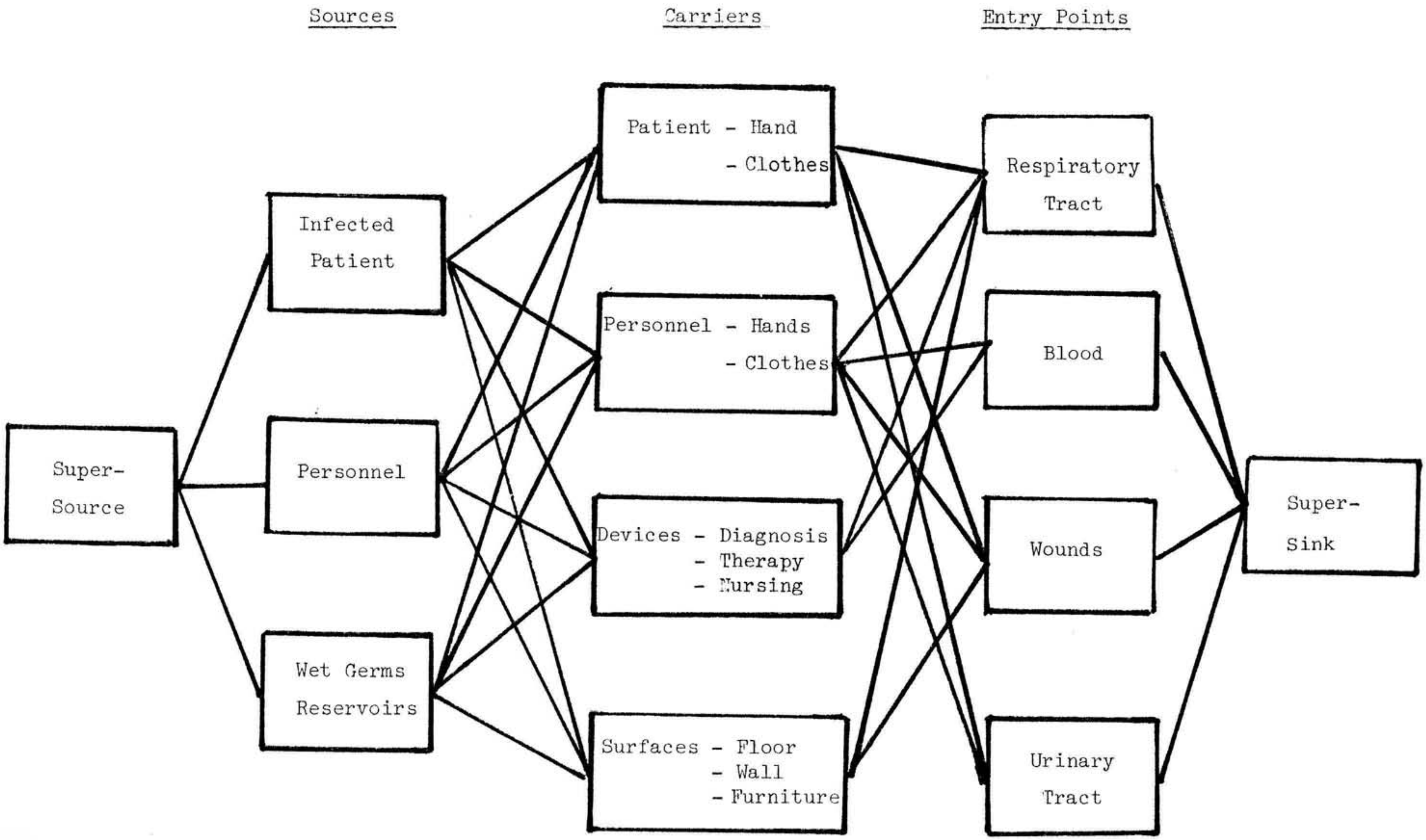

Figure 4: Structure of a Network Model of NI

Measures against NI, then, can be defined as techniques to cut certain arcs in the infection network. One can distinguish between measures that prevent the existence of certain arcs (e.g., isolation in separate rooms), measures that cut existing arcs by introducing hygienic rules to be obeyed during contact, and meta-measures that increase the probability that the rules are actually followed (hygienic management).

As - in the simplified model - all arcs are considered equally dangerous, it makes no sense to analyze measures that cut only one of multiple arcs between two nodes. All evaluations, especially effectiveness evaluations, must be based on packages of measures cutting at least all direct connections between two nodes of the network.

3.2 Cost Minimization Algorithm

In the framework outlined above, the purpose of a cost-effectiveness study of measures against NI can be described as finding the cost-minimal cut in the infection network.

A cut in a network is defined as a minimal set of arcs in a network that must be removed such that no path from any source to any sink exists any longer. The capacity of a cut is defined as the sum of the capacities of its elements.

We now give a procedure that determines a cost-minimal cut in the infection network taking into account the observations made in the previous subsection.

<u>Algorithm 1</u>: Cost Minimal Network Interdiction

<u>Step 1</u>: Construct a simple flow network from the general infection network in the following way:

1. The simple flow network has the same nodes as the general network, i.e., its sources, sinks, and transshipment nodes. In addition, the simple flow network contains a super-source and a super-sink.

2. For each pair of nodes i and j for which one or more arcs (i,j) exist in the infection network, determine the optimal package of measures to cut all such arcs. This partial optimization usually requires a small cost-benefit analysis of its own (see section 4, below).

3. Insert into the simple flow network an arc (i,j) with a <u>capacity</u> equal to the <u>cost</u> of the optimal package found in the previous step. If there is no sufficiently effective package, set the capacity (cost) to infinity.

4. Connect the super-source with all source nodes by infinite capacity arcs. These arcs describe the bacteria potential of the sources.

5. Connect the super-sink with all sink nodes by infinite capacity arcs. These arcs describe the risk of actual infection resulting from bacteria at the entry point mapped by the sink.

<u>Step 2</u>: The maximum flow through a network is determined by the capacity of the minimal cut [2]. As the capacities in the network constructed in step 1 are really the costs of cutting each arc, the <u>application of a maximal flow/ minimal cut algorithm</u> (see, e.g., [20]) gives the minimal total cost of a cut of the infection network as the maximal flow, and the measures to be implemented as the optimal measures for each arc in the minimal cut.

Note, that the procedure is independent of the exact description of the arcs in the infection network and thus fairly general. For example, it can also be applied if the infection network is described as a generalized network with arc multipliers [4], or if minimal utilization of some arcs is required [19], e.g., for necessary contacts.

3.3 Algorithms Using Effectiveness Measurements

There are situations in which a total cut cannot be achieved for medical or economical reasons. In such cases, it becomes necessary to include some measure of effectiveness in the global optimization procedure (step 2 above) making the decision considerably more difficult [11]. In this sub-section, we take a closer look at the applicability of some network interdiction approaches for which algorithms have appeared in the literature.

Network interdiction algorithms have been typically designed for applications in military logistics or communications networks, so some adaptation to infection control is necessary. All algorithms, however, can be described in the context of the general infection network model outlined in sub-section 3.1.

Three kinds of problems can render the simple cost minimization procedure (algorithm 1) infeasible:

1. insufficient medical effectiveness of measure packages resulting in an infinite maximal flow in step 2;
2. insufficient funds to implement the full cost minimal cut;
3. insufficient management capacity to implement more than a limited number of measures.

Consider first the case where the construction procedure in step 1 of algorithm 1 yields one or more paths from (super-) source to (super-) sink with unlimited capacity: there is no safe procedure to cut any of the arcs on these paths completely. In reality, a sequence of measures will be applied to successive arcs on these paths to reduce the probability of infection.

In order to map this situation, the arcs of the flow network constructed in step 1 can be labelled by the probability of transportation of infecting organisms and by the cost to reduce this probability. If one assumes independence of the probabilities, the overall probability along some path is equal to the product of the transportation probabilities.

By defining the arc capacities as the logarithms of the transportation probabilities, one arrives at a model that defines hygienic measures as techniques to lengthen certain arcs in the network (rather than cutting them entirely). One objective of a cost-effectiveness analysis could be to determine the minimal cost combination of measures for which the shortest path in the network has at least a specified length. Under restrictive cost assumptions, Golden [5] has shown this problem to be equivalent to a problem of cost-minimal network flow. A more general approach is under development for our study.

The second type of problem occurs when the minimal cost of the algorithm above is higher than the available funds, that is, not all the arcs that should be cut, can in fact be cut because of financial restrictions.

In this case, each arc of the flow network must be assigned some capacity denoting its dangerousness when open, in addition to the cutting costs as in algorithm 1. A branch-and-bound procedure devised by Ghare et al. [3] can be used to find the optimal interdiction policy for a given spending level.

Another approach was introduced by Wollmer [21] and Ratliff et al. [17]. It limits the number of arcs to be cut rather than the spending level. This can be interpreted as an inability of management to introduce or supervise more than a given number of measures simultaneously. The algorithms find the most vital links in a flow network using a sequence of shortest path problems [17] or network modification procedures [21].

This approach makes no use of cutting cost data from step 1 of algorithm 1 and thus corresponds to the traditional purely medical problem solving approach which ignores cost considerations. It does, however, require information about arc capacities in the infection network and about the feasibility of cutting certain arcs (i.e., medical efficacy of measures).

As mentioned earlier, all three approaches discussed in this section require information about arc capacities in the infection network for the global optimization step rather than only for local pre-optimization.

One problem arising from this fact is the ethical difficulty of trading off different infection hazards for possibly different patients. Another ethical problem is whether it is acceptable to open infection paths in experiments for measuring arc capacities.

In addition, there is a more technical measurement problem. One has to find uniform and measurable effectiveness criteria for comparing competing procedures applying to different areas of the infection network (this, again, is in contrast to the local analysis in step 1.2 of algorithm 1).

Finally, the optimization algorithms tend to become less efficient than the simple procedure in algorithm 1, and a global cost-effectiveness trade-off between medical and economical criteria becomes necessary taking the problem into the political sphere [11].

These problems may endanger the direct applicability of any of these algorithms. Algorithm 1 is much simpler but may yield financially or medically infeasible solutions. This can only be remedied by redefinition of the network or by changing the definition of an "effective" cut. For example, judgement of medical experts can be used for changing hygienic standards in order to obtain feasible solutions.

In the next section, we discuss some practical implications of the network interdiction approach which apply regardless of the algorithm actually used for global optimization.

4.0 IMPLICATIONS FOR COST-EFFECTIVENESS EVALUATION

4.1 Classification And Effectiveness Criteria

The number of arcs in the infection network (figure 4) indicates that carrying out the local cost-effectiveness analyses in step 1.2 of algorithm 1 can be quite a formidable task. The goal of this subsection is to reduce this problem by constructing larger packages of measures and assigning suitable effectiveness indicators (figure 2) to them.

The arcs of the infection network tend to bundle near the source and sink nodes while there is a fuzzy structure of possible paths in the central part covering the animate and - even more - inanimate environment. Several conclusions can be derived from this observation.

As arcs near the sink nodes are bottlenecks in the infection network, they are likely to be in the optimal cut.

One might think that the best way is to cut the links directly at the super-source, that is, to kill or inactivate the organisms after their entry into the patient's body. Unfortunately, the routine prophylactic use of antibiotics for this purpose - though still widespread - has been shown to be: (1) rather costly; (2) connected with some dangerous side-effects for the patient; and (3) a good way to cultivate antibiotic-resistant "hospital germs". Thus, prophylactic use of antibiotics can only be considered a back-up measure in carefully selected special cases.

A more promising approach is to cut the arcs immediately <u>before the entry points</u>. It is desirable to group these measures into larger packages because it simplifies the evaluation of an overall impact, and because it reduces the number of analyses necessary in step 1.2. These advantages offset the possible drawback of a more complicated subsystem to be analyzed. In accordance with the most important entry points, four groups of measures can be distinguished:

- measures against urinary tract infections;
- measures against wound infections;
- measures against respiratory tract infections;
- measures against bacteremia.

For practical analyses, it may be useful to subdivide these groups in manageable clusters of associated procedures. For example, measures against surgical wound infections can be partitioned into measures in the operation theatre and post-operative measures in the ward. However, the importance of the grouping above lies in the commonality of effectiveness criteria within each group. Unless the usage probability of the cut arcs is very low, changes in these measure packages can be directly related to changes in infection frequencies (or costs) of that type. For example, changes in the duration of catheterization have an immediate impact on the number of urinary tract infections [7]. Thus, an effectiveness comparison of measures within each group should be relatively simple.

The situation near sources is similar in the sense that isolating infection sources locally is likely to be cost-effective. One especially important group of such measures centers around the

* isolation of the infected patient.

This package applies to patients with community-aquired infections as well as to patients with NI. However, the latter often constitute a higher risk because of the resistant germs they carry.

The difference to sink-oriented measures lies in the applicability of effectiveness indicators. The effectiveness of isolation measures can be determined only by the number of patient-specific organisms outside the isolated area. The relationship to infections of other patients is very indirect. Even if new infection cases can be traced back to a source the infection path is by no means clear. An effectiveness comparison between measures for entry point isolation and for source isolation can therefore be very difficult although both measure groups involve similar activities.

Measuring the effectiveness of hygienic procedures in the central part of the network is even more difficult. Because of the multiple possible infection paths, many argue that the widespread routine sampling of personnel and inanimate environment for controlling the transport of infecting organisms has at best educational value [16].

Thus, process control seems the only valid indicator of package effectiveness in the area of

* general hygienic measures.

These measures (e.g., surface cleaning and disinfection outside high-risk areas [8,10]) cannot be expected to cut any arcs entirely but they may be a valuable backup in the sense of reducing some arc capacities in the infection network (recall section 3.3. for the use of such measures in network interdiction algorithms).

The final group of measures to be discussed here,

* hygienic management,

cannot be assigned to any specific arcs but only to the network as a whole. Nevertheless, efforts have been made to establish the effectiveness of such measures, especially of infection control programs, in terms of changes in infection rates [6]. As may be expected from our previous discussion, very large sample sizes (several hundred thousand patients) were required to obtain significant results. If such an extensive study is not possible, one has to resort to organizational theory and sometimes process controls to establish some effectiveness evaluation of alternative management structures.

The tasks of hygienic management include teaching, infection surveillance, tracing infection paths, and introducing or enforcing measures. Correspondingly, effectiveness can be measured by knowledge tests of personnel, value and technical quality of the information provided, and process controls of the recommended measures.

We have identified seven classes of measures against NI by their position in the infection network. Our classification is aimed at assigning measurable medical-hygienic effectiveness indicators to measure packages to be evaluated. A similar classification is used in [16]. Other approaches are more concerned with the correct execution of the necessary activities [1,15] or the distribution of responsibilities [15] resulting in different classifiction schemes.

4.2 Infection Cost Analysis

We have seen that a direct influence of changes in hygienic procedures on infection rates can be determined only for sink-related types of measures or if very large sample sizes overcome the randomness of infection paths. But even if this advantageous situation is given, it is still difficult to compare measures against different types of infections because the consequences of infections may vary from type to type. For example, wound infections tend to be more severe than urinary tract infections.

In this sub-section, we give a brief overview of an approach that can be used for analyzing the consequences of infections stressing fincancial consequences. A more thorough treatment of this subject is given in a forthcoming paper.

A cost analysis of NI is not meaningful if it is only based on the prolongation of stay in hospital caused by NI. First, it is hard to achieve agreement among physicians about the exact size of the extension. Second, length of stay is only one of several factors influencing hospital costs. For example, the fact that hospital charges in West Germany are based on length of stay only leads to the paradoxical situation that minor NI are microeconomically attractive for a hospital - certainly not an incentive for promoting measures against NI!

In order to evaluate the overall cost impact of NI, a careful study of possible <u>treatments</u> <u>by</u> <u>infection</u> <u>type</u> is necessary. The network model of infections helps one to determine which activities are actually related to NI. One example is the inclusion of those isolation costs that are attributable to NI but the exclusion of general isolation costs such as investment costs (because patients with community-aquired infections must be isolated anyway). Similarly, prophylactic usage of antibiotics is excluded from NI costs (because it is considered a preventive measure) but therapeutic usage is included.

From the treatment study, a cost model containing all relevant activities can be developed. We found that four major factors influence the costs of treating a patient, p, with a hospital infection of type, i:

1. extension of stay, TS[p];
2. days of isolation, TI[p];
3. antibiotics quantity of type a, TA[p,a];
4. frequency of infection-specific treatment of type t, TT[p,i,t].

This data can be collected by an infection control nurse in a simple extension of a normal infection surveillance program (see, e.g., [14]).

In addition, cost per unit data are required for each of the items above; let the corresponding symbols be KS, KI, KA[a], and KT[i,t]. These values are vectors describing the costs in the multi-dimensional way outlined in figure 2, that is, differentiated by personnel time, equipment usage time, and direct costs for materiel or external services.

Both cost per unit and frequency data are collected in an infection cost control database that is an extension of an infection surveillance database (figure 5).

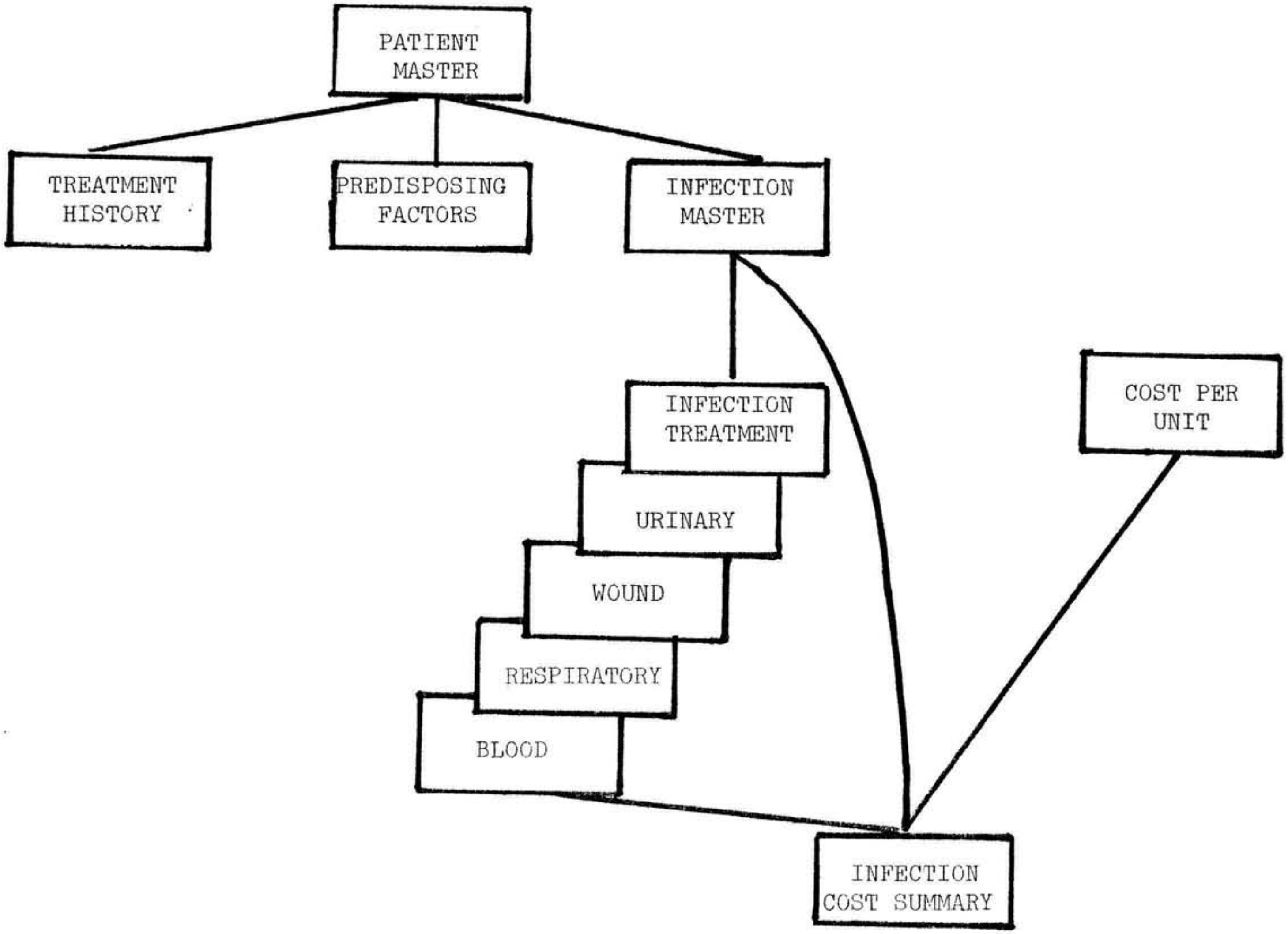

Figure 5: Structure of Infection Cost Control Database

All cost aggregates of interest for decision support can be computed with relative ease from the database. For example, the costs per case can be determined by the following formula:

$$K[p] = KS*TS[p] + KI*TI[p] + \underline{SUM(a)}\ KA[a]*TA[p,a]$$
$$+ \underline{SUM(t)}\ KT[i,t]*TT[p,i,t]$$

Other useful aggregations include

* average cost by infection type;
* average cost by patient group;
* relative importance of cost types and treatment types;
* total costs related to infections to be prevented by a package of measures.

The latter application is the one relevant for the cost-effectiveness evaluation of measures against NI. The multi-dimensional representation of cost types allows for a trade-off within cost types before aggregation thus revealing the overall impact of a measure by cost type. This is important if the assignment of indicators to cost or effectiveness criteria is unclear (compare section 2.0), or if costs are shared by different organizations.

The use of a database system for this kind of analysis greatly simplifies the evaluation of infection costs and thus of measures against NI. An infection cost database based on figure 5 has been set up using the Pascal/R database management system at the University of Hamburg and is being used to evaluate observations of several hundred infection cases.

5.0 SUMMARY AND CONCLUSIONS

The methodology of a cost-effectiveness study of measures against hospital-aquired infections was described. The evaluation is based on a general flow network model of infections derived from an informal notion well-known in medicine. This approach was shown to offer several advantages.

The network interdiction procedures presented in this paper provide structure to the optimization problem under a variety of medical, economical, and behavioural constraints. They also allow for decomposition of the involved overall problem into a sequence of more manageable subtasks.

The network interdiction approach also facilitates the choice of suitable effectiveness criteria for the evaluation of hygienic procedures by supporting a classification scheme. In a similar way, the scope of infection cost analysis is clarified by the model.

Finally, the model alleviates the problem of interdisciplinary communication because its underlying concepts are familiar to hygienic practicioners.

In conclusion, the introduction of an OR model as a paradigm of a health-economic study has proved a useful way to overcome some of the limitations imposed by time and financial constraints.

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