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Bachelor Thesis in Econometrics and Operations Research

Optimization of the utilization of reusable medical devices

Author:
Francesca Anna-Sophia Beer
373284

Supervisor:
Dr. T.A.B. Dollevoet

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Abstract

This paper deals with the optimization of net compositions within hospitals. A net is a group of standard reusable medical devices (RMDs) needed for either a single surgery or several surgeries. The optimization of net compositions leads to a reduction in the hospital's operation cost. Furthermore, it leads to an improvement in the quality of care. For example, less instruments have to be cleaned by the central sterilization service departments. Solving this problem to optimality is considered an NP-hard problem. To tackle this problem, the paper uses a hybrid solution that identifies RMDs with potential shared level. In addition, it proposes a methodology for another hybrid solution; one enabling surgeries with potential shared RMDs. Furthermore, the paper uses two adjusted metaheuristics simulated annealing and tabu search. None of the two, however, have led to a significant cost reduction, which can be explained by the good performance of the hybrid solutions.

Contents

1 Introduction

Health care costs have steadily been increasing in the past decade. The OECD member states have spent a large percentage of their gross domestic product on health care expenditure, which increased from 7.7% in 2000 to 9.3% in 2013 (World Bank, 2015). In particular, care personnel, equipment, and medicine costs have started to put government budgets under strain. This in combination with fast technological developments has made hospital modernization of paramount importance with the two main objectives: the quality of care and the reduction in health care expenditure. This paper proposes a resource sharing method that optimizes the utilization of reusable medical devices (RMDs).

1.1 General sterilization issues

According to van de Klundert, Muls, and Schadd (2008) a large part of cost reduction in health expenditure can be achieved by standardizing materials. To ensure quality, the capital intensive central sterilization service departments (CSSDs) are of major importance. In case the CSSDs fail to sterilize their RMDs sufficiently, they have to be closed. A hospital that uses insufficiently cleaned RMDs will damage its image, which has major financial consequences (Niklas, 2015). But even more importantly, not sterilizing the RMDs sufficiently sets the patients' life at risk. Over thousands of people die because of nosocomial infections; specialists for hospital hygiene estimate 400-600 thousand of people per year (Niklas, 2015). In most cases, however, it cannot be determined whether the death was caused during a surgical procedure or after the surgery. As recently as February 19$^{\text{th}}$, 2015, Fox (2015) reported that the U.S. Food and Drug Administration issued a warning that 135 patients are possibly infected by infectious agents, including multidrug-resistant bacterial infections due to the use of contaminated duodenoscopes. This had a global impact, as those duodenscopes could have also been used in Europe, which further supports the argument of Frimmel (2015) that CSSDs are one of the most important and most sensitive areas in hospitals. A way to evade infections by contaminated RMDs, is to minimize the amount of RMDs that have to be sterilized. Hence, the CSSD can ensure higher quality in its service.

Even though the sterile supply circle is highly regulated by government, no policy exists stating which instruments have to be present in so-called nets. A net is a group of standard instruments needed for either a single surgery or several surgeries. Essentially, a net is box of instruments (RMDs) which are kept sterile. Optimal net structures can lead to cost reductions in hospitals, more structure in surgical procedures, and reduce the employee pressure. In turn this leads to higher satisfaction among employees (Frimmel, 2015). Thus, with the help of the optimization of nets the performance of hospitals or departments can be improved. This will result in less time to compose the nets and also standardize instrument models (Knopp, 2015). Additionally, it can reduce the number of nets used in surgery, decrease changing times within an operating theater (OT) and limit process time at CSSDs.

1.2 Basic logistic design

Patients are supposed to only get in contact with sterilized instruments within health facilities. Instruments that are designed for single use only, naturally only have to be sterilized once, and thus, are less likely to be contaminated. For RMDs this is more complex. Once a hospital has bought and used the RMDs, they have to transport them to the CSSD. At the CSSD the RMDs are cleaned and disinfected. Afterwards they are inspected and packaged in nets. Those nets are then sterilized and put into sterile storage until they are transported back to the hospital, where they are stored in the sterile storage of the OT. The RMDs will stay there until they are used again and then the cycle restarts.

To minimize the amount of RMDs in circulation a closer look at the hospital itself has to be taken. Most of the RMDs are not stocked individually in the OT, as this would be too time intensive, logistically difficult and impractical for hospital employees.

1.3 Contribution of the paper

This paper aims at optimizing the net compositions of hospitals. Optimizing the net compositions directly targets the two objectives of the modernization of hospitals: the quality of care and the reduction in health care expenditure. Against this background, the main purpose of this paper is to propose a methodology that can solve the NP-hard net compositions problem in practice and within an acceptable runtime. As the problem most likely cannot be solved to optimality for large instances, two hybrid solutions followed by the two metaheuristics - simulated annealing and tabu search - are used instead. This, however, has the disadvantage of not being able to guarantee the optimality of the solution.

2 Previous work

Creating optimal net structures for hospitals is both a grouping and a sizing problem, as the content of the nets have to be determined which influences the storage space of the net and then the nets have to be assigned to the surgeries. The partitioning problem impacts the storage cost, the amount of RMD needed, and the costs of processing them. This is an NP-hard problem, which is extremely complex, as acknowledged in the literature by Reymondon, Pellet, and Marcon (2008), van de Klundert et al. (2008) and Garey and Johnson (1979) among others. Thus, real size problems often cannot be solved to optimality within the given time limit, as also Reymondon et al. (2008) mentions. Besides this, it becomes even more complex nowadays, as surgery techniques are becoming more complex (Knopp, 2015) and instruments become more distinguished. Knopp (2015) also mentions that sometimes nets were assembled in a way that fits the surgeon's need perfectly, rather than making economical sense. Also, a lot of hospitals have nets for each department of the hospital instead of taking the hospitals optimum into consideration. A reason can be the complexity of optimizing the net composition and the nature of it being an NP-hard problem.

2.1 Apparent net structures

Three obvious types of grouping choices for nets exist: (i) one net for one surgical case, (ii) one net for all surgical cases and (iii) one net for one RMD. Type (i) has relatively low net storage cost, as nets only contain the instruments needed in the surgery. This also simplifies the logistical procedure in the hospital. However, it does not allow for instrument sharing across different types of surgeries. Type (ii) has the advantage that all instruments are in circulation all of the time, and the disadvantage that whenever a net is opened all sterile RMDs within the net will be considered contaminated no matter whether they have been used or not. Put simply, a surgeon will have to open a whole net, just to get a scalpel, even if they do not need anything else. As a result, all remaining instruments become contaminated; in itself a form of waste (Reymondon et al., 2008). Another form of waste in hospitals are nets, which are stored more than half a year as they are then considered contaminated and thus have to be sent again to a CSSD (Heddergott, 2015). Type (ii) minimizes net storage cost, but increases the amount of useless instruments in circulation. Type (iii) ensures that only instruments that are needed are actually opened. This minimizes the costs of the RMDs usage, but increases the net storage cost. Additionally, in practice, more instruments than necessary are opened by nurses as they accidentally open the wrong net in the OT. This leads again to more instruments having to be cleaned by the CSSD than necessary (Beer, 2015). Thus, in practice, the instruments are stored collectively in nets. This shows, that the optimum most likely lays within those extremes.

2.2 Quantitative approaches in literature

Van de Klundert et al. (2008) were able to cope with the complexity of a net optimization problem by only taking a subset of all surgeries into consideration. In their paper they acknowledge that the optimum is most likely somewhere between the previously mentioned apparent net structures (i) and (ii). To solve the grouping and sizing problem they made use of a mathematical programming formulation. The objective function they used, allows to obtain the RMDs that go into each net. On the condition that the nets are available on the day in question, the formulation further selects the nets needed for each surgery. In other words, the formulation selects the nets for each surgery, but takes into account whether those nets are not occupied, e.g. being used in another surgery at the same time. The paper further uses a computational experiment to solve to optimality. However, even with this, the researchers concluded that solving the issue to opitmality is very complex.

Reymondon et al. (2008) presented an innovative approach to reduce the complexity of the net optimization problem, by reducing the problem size without changing the problem terms. The methodology they propose consists of two parts. First they suggest to build a hybrid solution identifying the RMDs with a sharing interest to then improve their solution. To identify the RMDs with sharing interest the data has to be structured and analyzed. In the first part of their methodology, they start off with the obvious types of grouping choices for nets (i) and (iii), and then create a so called hybrid solution between them. In the first part a new grouping choice is created presenting nets with only one RMD shared by many types of surgeries and nets dedicated to one surgical case. This hybrid solution is beneficiary as on one side it decreases the amount of nets needed, whilst on the other it allows the same instruments to be used for different surgeries. Thus, for each of the individual RMD there are three options: the RMD can stay packaged individually, it can be assigned to a net for a surgical case or it can be grouped with other RMDs shared by multiple surgical cases. The reduction of the amount of nets needed is of particular importance as this decreases the complexity of the problem. Secondly, they propose to optimize the RMD extracted from the grouping choice of the first step, where they consider each RMD individually. The latter step was, however, not implemented in the paper of Reymondon et al. (2008), but they suggested to use metaheuristics.

2.2.1 Metaheuristics

For the optimization of the composition of nets, this paper makes use of simulated annealing (SA) and tabu search (TS), as these metaheuristics are considered "very effective in the case of the clique partitioning problem" (De Amorim, Barthélemy, & Ribeiro, 1992). Nevertheless, as they are heuristics, solving to optimality cannot always be ensured in both cases. In the paper of De Amorim et al. (1992) they also mention that both approaches perform very well for real-life problems, as in almost all cases the optimal solutions are obtained in reasonable computation times. Additionally, in the paper of Antosiewicz, Koloch, and Kamiński (2013) they compared six metaheuristic optimization algorithms applied to solving the traveling salesman problem. They made use of genetic algorithms, SA and TS, quantum annealing, particle swarm optimization and harmony search. SA and TS have outperformed the other metaheuristics in terms of solution quality, standard deviation of results and computational time. They are thus applied in this paper.

SA has been recognized as a good solution to difficult optimization problems in literature, which began with the work of Kirkpatrick, Vecchi, et al. (1983). The roots of this metaheuristics lay in physics but as Kirkpatrick et al. (1983) recognized "There is a deep and useful connection between statistical mechanics [...] and multivariate or combinatorial optimization". This method is especially interesting for the net optimization problem as it can also be applied to NP-hard combinatorial optimization problems as also recognized by Eglese (1990).

TS has been chosen as the "strengths of the method lie in its simplicity, its efficiency and its robustness [...] Another advantage of this heuristic is its speed of execution and memory usage" (Cordeau, Laporte, Mercier, et al., 2001). Thus, as this metaheuristic can "run on any computer with minimal resources and it requires only a few minutes of computation time before identifying good quality solutions even on large size instances" (Cordeau et al., 2001), this is a reliable method to tackle this NP-hard grouping and sizing problem.

TS and SA are both types of local search algorithms, and distinguish themselves from other metaheuristics in so far as they do not exclude the option of more expensive net compositions. This way both SA and TS try to circumvent a local optimum but reach a global optimum instead (Eglese, 1990). SA starts with an initial solution which can be chosen at random and generates a neighbor of this solution. The corresponding costs are then calculated. While SA makes use of randomization for different solutions, TS follows a completely deterministic approach (Ausiello, 1999).

2.2.2 Evaluation of net compositions

Both Reymondon et al. (2008) and van de Klundert et al. (2008) try to reduce the costs of the sterilization activity by finding a compromise between the shared level storage cost and other costs. Thus, they make use of a multi-component cost function. The first cost that both of them make use of is associated to the cost of RMD storage. According to them this has the biggest potential in reducing the overall cost and is also included in the objective function of van de Klundert et al. (2008). Secondly, they take the costs bound to a net storage into consideration. For simplification both Reymondon et al. (2008) and van de Klundert et al. (2008) only consider one type of package. The same assumption will be made in this paper, as the homogenization of box packages is preferred and allows for standardization, which is wanted in the modernization of hospitals. Additionally, Reymondon et al. (2008) uses of the "costs related to process time". This cost has 4 components: conditioning, picking down and up to the storage and opening box package in surgical room, which depends on the number of packages needed for a given type of surgical case. It will be neglected though in this paper, as data collection in hospitals is very hard, and thus the costs cannot be determined appropriately. Lastly, they take the costs bound to non-used sterile medical devices into consideration. In the paper of van de Klundert et al. (2008) they do this by taking the difference of the instruments stored and used. This cost is important as RMDs that have not been used are considered contaminated. These papers, thus establish a basis for the multi-component cost function used in this study.

2.3 Real life implementation

Due to the importance of this problem, the partitioning of the nets has been optimized in several hospitals. In one hospital, the optimization of nets led to 20% less instruments used (Kalix, 2015), allowing them to centralize their CSSD and to implement a uniform sterile equipment and management system. In another hospital, the data analysis of sterile goods led instruments being stored in inventory and the standardization of nets (Frimmel, 2015). More precisely, they were able to decrease their 'small' net of previously 121 instruments by 30 instruments. This not only led to a large reduction in the weight of the net itself, but also to less instruments having to be cleaned by the CSSD (Knopp, 2015) and hence a considerable cost reduction. Knopp (2015) also mentions that not using appropriate nets led to capacity shortages in the CSSDs and missing transparency. Put simply, there is a lot of potential for the utilization of net compositions.

In the previously mentioned case studies, the consultants directly worked together with the hospitals and surgeons. This way they were able to decrease the amount of instruments mainly by excluding instruments that were useless (Warken, 2015). For example, they excluded instruments of the same type in the net. Those have been included in the past only because of the brand preferences of the surgeons and have not been excluded when the surgeons changed. This led to an increase in non-used RMDs, without any economical incentive. Thus, using field investigations allows to exclude unnecessary RMDs, which otherwise would be included in the data, when finding optimal net compositions. Excluding those RMDs also significantly reduces the complexity of this problem. Given that those instruments have already been excluded from the nets, the partitioning of nets as well as ensuring that nets are available at the right time remain of major importance. Otherwise this provides enormous extra cost and has a large impact on the surgery's development (Frimmel, 2015).

3 Methodology

In this section, the grouping and partitioning problem will be defined mathematically - a corrected version of the one used in van de Klundert et al. (2008). Due to the nature of this problem being NP-hard, an alternative approach for optimizing the net compositions will be provided. This approach contains four steps. First of all, the methodology for finding the hybrid solution is provided as done in Reymondon et al. (2008). The hybrid solution consists of nets that belong to one surgery only, or of nets that contain an individually packaged RMD. Secondly, a new hybrid solution is introduced, which is based on the previous hybrid solution. This new hybrid solution allows different types of surgeries to share the same net with multiple RMDs. Then, the solution will be further optimized by making use of the two metaheuristics: simulated annealing (SA) and tabu search (TS). As the before mentioned metaheuristics can lead to an infeasible solution, the third step of the methodology is to check whether the net compositions provide a feasibile solution.

In order to define this problem mathematically, the following notation will be used. The set of nets is defined to go from $n = 1, ..., N$ and index $t = 1, ..., T$ refers to the planning period. $s = 1, ..., S$ stands for the surgery types and index $r = 1, ..., R$ refers to the type of the RMD. Additionally, each sterile instrument is introduced individually by making use of $i = 1, ..., I$. In this case, important assumptions are made: each instrument is considered unique and instruments of the same type are consecutively indexed. Then, the following parameters are defined:

P_r : Instrument storage cost for instrument of type r, $r = 1, ..., R$

H : The net storage cost

S_r : Instrument usage cost for instrument of type r, $r = 1, ..., R$

m_{rl} : The lowest index for instruments of type r, $r = 1, ..., R$

m_{rh} : The highest index for instruments of type r, $r = 1, ..., R$

N_{sr} : The number of instruments of type r, $r = 1, ..., R$ needed for surgery s, $s = 1, ..., S$

C : Costs associated to not using a RMD

3.1 Mathematical programming formulation

To be able to provide a mathematical programming formulation of the net composition problem, the following decision variables have to be defined:

$$M_{ni} = \begin{cases} 1, & \text{if net } n \text{ contains instrument } i \text{ where } n = 1, ..., N, i = 1, ..., I \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{nts} = \begin{cases} 1, & \text{if net } n \text{ is used on day } t \text{ for surgery } s \text{ where } n = 1, ..., N, t = 1, ..., T, s = 1, ...S \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{ntsi} = \begin{cases} 1, & \text{if net } n \text{ is used on day } t \text{ for surgery } s \text{ and instrument } i \text{ is contained in net } n \\ & \text{where } n = 1, ..., N, t = 1, ..., T, s = 1, ...S, i = 1, ..., I \\ 0, & \text{otherwise} \end{cases}$$

$$Z_n = \begin{cases} 1, & \text{if net } n \text{ is used where } n = 1, ..., N \\ 0, & \text{otherwise} \end{cases}$$

Now the multi-component cost function can be defined as seen in equation (1):

$$\sum_n \left(H \times Z_n + \sum_r \sum_{i=m_{rl}}^{m_{rh}} \left(M_{ni} \times P_r + \sum_t \sum_s \left(Z_{ntsi} \times S_r + C\left(Z_{ntsi} - N_{sr} \right) \right) \right) \right) \tag{1}$$

The first part of the multi-component cost function corresponds to the storage cost of the net, the second part to the storage cost of the instruments, the third to the instrument usage cost and the last to the costs of not using a RMD. The last part might not be an actual cost for the hospital, but with the objective, to decrease the amount of RMDs that have to be sterilized by the CSSD and properly use limited resources, this is of major importance.

With the objective (2) to minimize the multi-component cost function an integer linear programming formulation to solve the net optimization problem exists and is defined as follows:

$$\min \sum_{n} \left(H \times Z_n + \sum_{r} \sum_{i=m_{rl}}^{m_{rh}} \left(M_{ni} \times P_r + \sum_{t} \sum_{s} \left(Z_{ntsi} \times S_r + C \left(Z_{ntsi} - N_{sr} \right) \right) \right) \right) \tag{2}$$

$$\text{s.t.} \sum_{n} M_{ni} \leq 1 \qquad i = 1, ..., I \tag{3}$$

$$\sum_{s} Z_{nts} \leq 1 \qquad t = 1, ..., T, \quad n = 1, ..., N \tag{4}$$

$$M_{ni} \leq Z_n \qquad n = 1, ..., N, \quad i = 1, ..., I \tag{5}$$

$$\sum_{n} \sum_{i=m_{rl}}^{m_{rh}} Z_{ntsi} \geq N_{sr} \qquad t = 1, ..., T, \quad s = 1, ..., S, \quad r = 1, ..., R \tag{6}$$

$$Z_{ntsi} \leq M_{ni} \qquad n = 1, ..., N, \quad t = 1, ..., T, \quad s = 1, ..., S, \quad i = 1, ..., I \tag{7}$$

$$Z_{ntsi} \leq Z_{nts} \qquad n = 1, ..., N, \quad t = 1, ..., T, \quad s = 1, ..., S, \quad i = 1, ..., I \tag{8}$$

$$Z_{ntsi} \geq Z_{nts} + M_{ni} - 1 \qquad n = 1, ..., N, \quad t = 1, ..., T, \quad s = 1, ..., S, \quad i = 1, ..., I \tag{9}$$

$$M_{ni}, Z_{nts}, Z_{ntsi} \in \{0, 1\} \qquad n = 1, ..., N, \quad t = 1, ..., T, \quad s = 1, ..., S, \quad i = 1, ..., I \tag{10}$$

The first constraint (3) ensures that an instrument can be in one net at most. Constraint (4) models that a net can be only used once per day and constraint (5) enforces that the net is used whenever the net contains an instrument. To ensure that at least as many instruments as needed for a given surgery are present on the considered day constraint (6) is needed. Next, with constraint (7) it is ensured that instruments can only be used if they are in a net. Furthermore, constraint (8) models that if an instrument of a net is used for a surgery at a given day, then the net is used for the surgery. Lastly, constraint (9) enforces that if a net is used for a surgery and the instrument is present in the net, then the instrument is contaminated, even if it was not used.

3.2 RMDs with potential shared level

As shown in the paper of van de Klundert et al. (2008), it is very hard to solve the net optimization problem to optimality by integer linear programming. Thus, the employees of Aescolup, a medical equipment producer and consultancy, Koch (2015) and Warken (2015) propose to narrow the data down before feeding the data into the program. The same proposition was made by Reymondon et al. (2008). While Koch (2015) made use of his medical understanding and excluded all instruments of the net that were redundant, Reymondon et al. (2008) proposed a method where they make use of two steps: firstly, they find a hybrid solution by identifying the RMDs with sharing interest and secondly, they look for a better solution starting from the hybrid grouping choice. The same approach will be taken in this paper, with the adjusted multi-component cost function (1). For a detailed discussion of the RMDs with potential shared level see the paper of Reymondon et al. (2008).

The first hybrid solution will be obtained by making use of the two extreme types of grouping choices for nets (i) and (iii), which will further be denoted by $N1$ and $N3$ respectively. After both of the nets are build the cost of the RMD storage for each type of instrument are calculated as done in the paper of Reymondon et al. (2008). Additionally, the costs for each RMD type r will be stored which will be denoted by $C1(r)$ for each type of net.

Based on this it is possible to calculate the difference of $N1$ and $N3$ for each individual RMD type r which will further be denoted by $DC1(r)$. The costs of $N3$ are lower or equal to the costs of $N1$ for an instrument type r as in $N3$ it is possible to use the instruments for more than one surgery, given that the surgery is not conducted on the same day. Thus, $DC1(r)$ is a positive real numbered variable.

Then a threshold of benefit (TB) has to be set, which due to the nature of $DC1(r)$ has to be positive or 0. In case $DC1(r)$ is strictly superior to TB, then the instrument of type r will be removed from the net that is assigned to the surgery, and instead packaged individually as in $N3$. In case the instrument does not get extracted, it will stay in the package dedicated to the surgery.

This way a new composition of nets is created denoted as $N4$. This is the wanted hybrid configuration which contains either nets for surgeries or instruments packaged individually. As it can happen that $N4$ has more individually packaged instruments than necessary, the unnecessary instruments will be removed. This way the amount of nets used can be reduced further. The pseudocode, introduced by Reymondon et al. (2008), can be summarized as seen in Algorithm 4 attached in Appendix A.

Note, that the hybrid solution is highly dependent on the TB value. Thus, to obtain the best hybrid solution the TB value is chosen optimally in this paper. This is done by obtaining the cost of the hybrid solution for each unique value of $DC1(r)$ where this unique value is set as the TB. Thus, TB is chosen in a way that leads to overall minimizes the objective function (2).

3.3 Surgeries with potential shared RMDs

The previous hybrid solution only allows for net compositions with instruments that are either packaged individually or assigned to a given surgery. Thus, the hybrid solution does not consider that some surgeries, that are not scheduled on the same day, can make use of the same nets with multiple instruments. For instance, if two surgeries sharing the same RMDs surgeries are scheduled on the same day, then two nets have to be used. In contrast, when the surgeries are scheduled on different days the same net can be used for both of the surgeries. The net simply is not cleaned fast enough by the CSSD, so another net has to be used additionally. This means that the subset of RMDs needed for some surgeries might be equivalent to the subset of instruments needed for another surgery. Hence, in some cases it might be of advantage to merge the individually packaged instruments to nets with multiple RMDs.

Thus, a new hybrid solution is introduced in this paper, that identifies surgeries with potential shared RMDs. The crucial difference now is, that the nets with multiple RMDs are not necessarily assigned to a single surgery, but also allow for satisfying multiple surgeries at the same time. With the best hybrid solution $N4$ obtained before, the individually packaged instruments can be identified. The starting position of the individually packaged instrument is denoted by $StartInd$ and all instruments that are packaged individually are denoted by $PossibleNeighbor$. Afterwards, for each surgery, the possible neighborhoods are identified and represented by $PossibleNeighbourhood$. They are the instruments that are packaged individually in a given surgery. Both the surgeries and the possible neighborhoods are randomized and denoted by SS and $SPossibleNeighbourhood$ respectively. For each of the surgeries $SPossibleNeighbourhood$ allows to identify how many individually packaged instruments belong to the surgery; this is further denoted by II_S. Then, a copy of the $N4$ is made and saved as $N5$.

For the first randomly chosen surgery the $SPossibleNeighbourhood$ are identified, and then the first instrument that is stored in the $SPossibleNeighbourhood$ determines the net, $NetTo$, where the other instruments can be merged to. The nets that correspond to the instruments, that are stored in $SPossibleNeighbourhood$, are further denoted by $NetMergedTo$. For each instrument, stored in $SPossibleNeighbourhood$, the instrument will be removed from $NetMergedTo$ and added to $NetTo$. This change is stored in the $Temp\_Net$ and is then evaluated, by making use of the functions FEASIBLE() and COST(). FEASIBLE() checks whether those net compositions leads to a feasible or infeasible solution. COST() evaluates the total cost of the net compositions by making use of the cost function (1). In case $Temp\_Net$ is feasible and leads to a cost reduction, $N5$ is updated to be $Temp\_Net$ and the $N5Cost$ will also be updated. In case this does not hold $Temp\_Net$ will be reset to $N5$. Then the second surgery in SS will undergo the same procedure. This will be repeated, until the merging of instruments for all surgeries in SS have been evaluated. The best found $N5$ will then be returned. The algorithm for finding surgeries with potential shared RMD is summarized in Algorithm 1:

3.3.1 Evaluation of the cost and feasibility check

Due to the way the hybrid solutions are constructed, the feasibility of the hybrid solution for all surgeries is ensured. However, when making use of metaheuristics, it can happen

Algorithm 1: Pseudocode for the surgeries with potential shared RMDs

```
Data: hybrid solution N4
begin
    StartInd
    PossibleNeighbor
    PossibleNeighbourhood
    N5 = N4
    N5Cost = COST(N5)
    Temp_Net = N5
    SS
    SPossibleNeighbourhood
    for ss = 1 to SS do
        for n = StartInd to N do
            if Temp_Net(n, ss) !=0 then
                NetMergedTo = n
                for ii_s =1 to II_S do
                    for NetTo = StartInd to N do
                        if Temp_Net(NetTo, ii_s) != 0 then
                            Temp_Net(NetTo, ii_s) = Temp_Net(NetTo, ii_s)-1
                            Temp_Net(NetMergedTo, ii_s) =
                            Temp_Net(NetMergedTo, ii_s) + 1
                            if FEASIBLE(Temp_Net) == true AND
                            COST(Temp_Net)< N5Cost then
                                N5 =Temp_Net
                                N5Cost = COST(Temp_Net)
                            else
                                Temp_Net = N5
                            end
                        end
                    end
                end
            end
        end
    end
    return N5
end
```

that an infeasible solution is created. Thus, whenever a different solution is constructed, the feasibility of the net compositions has to be checked. For this purpose the mathematical programming formulation for the optimization of net compositions is adjusted. Here the assumption, that each instrument i is unique, is relaxed. Instead, it represents the amount of instruments of the type i, and thus allows to get rid of the instrument type index r. Also, Z_n is not a decision variable anymore as the net composition is already given. The same holds for M_{ni}, but M_{ni} is not binary anymore and a natural number instead, that represents the amount of instruments of type i in net n, which was previously denoted by $\sum_{i=m_{rl}}^{m_{rh}} M_{ni}$. Additionally, it can be derived that this equality holds: $Z_{ntsi} = Z_{nts} \times M_{ni}$. Thus, only one decision variable exists namely Z_{nts}, which makes the problem less complex. The multi-component cost function is now adjusted as seen in equation (11):

$$\min \sum_n \left(H \times Z_n + \sum_i \left(M_{ni} \times P_i + \sum_t \sum_s \left(Z_{nts} \times M_{ni} \times S_i + C \left(Z_{nts} \times M_{ni} - N_{si} \right) \right) \right) \right) \tag{11}$$

Again, the first part of the objective function corresponds to the storage cost of the net and the second to the storage cost of the instruments, but they are constants now. The third part corresponds to the instrument usage cost and the last to the costs of not using a RMD.

$$\text{s.t.} \sum_s Z_{nts} \leq 1 \qquad t = 1, ..., T, \quad n = 1, ..., N \tag{12}$$

$$\sum_n Z_{nts} \times M_{ni} \geq N_{si} \qquad t = 1, ..., T, \quad s = 1, ..., S, \quad i = 1, ..., I \tag{13}$$

$$Z_{nts} \in \{0, 1\} \qquad n = 1, ..., N, \quad t = 1, ..., T, \quad s = 1, ..., S, \quad i = 1, ..., I \tag{14}$$

Constraint (12) models that a net can be only used once per day and constraint (13) ensures that at least as many instruments as needed for a given surgery are present on the considered day. In case this leads to a feasible solution, it is possible to partition the nets in a way that satisfy all the needs of the surgeries and the minimal cost is computed.

3.3.2 Optimization of hybrid solution

Up until now the last part of the multi-component cost function (1) has been 0 as only instruments needed were taken into consideration. Thus, after having obtained the hybrid solutions, an optimized solution for the net composition can be found, by making use of the two metaheuristics: SA and TS. Those two metaheuristics allow for net compositions that include non-used instruments.

Simulated Annealing

For the net optimization problem a modified version of SA is used due to three reasons (Eglese, 1990). Firstly, the initial starting position is not chosen randomly, instead the hybrid solution obtained before is used. Secondly, the idea of Connolly (1990) is implemented, which provides empirical evidence that searching sequentially for the best neighbor in the neighborhood is better than randomly being assigned to a neighbor. Lastly, the best solution of the net optimization problem is stored. This allows to keep track of the best solution, as it might happen that in the last iteration a worse solution is obtained, that is neither a global nor a local optimum.

Thus, the modified version of SA looks as follows. First the total cost of the hybrid solution $N5$ is evaluated. $N5$ serves as an initialization of the best net, denoted by $NBest$, and its cost. Then a new net partitioning, $N6$, is created. To remove an instrument from $N6$, by making use of the function EXTRACT_RMD(), a net z is chosen randomly by calling RNG_NET_DUM. This new net partitioning is denoted by $Temp\_Net$. RNG_NET_DUM is a random number generator that generates a number between 1 and $N + DI$. N represents the number of nets in $N6$ in this case, and DI the number of dummy instruments. The dummy instruments are namely the type of instruments that were not individually packaged yet. So for each type of dummy instrument that exists, the dummy matrix will contain the maximum number of the corresponding instrument type that is needed during a day of surgery. Introducing the dummy instruments allows for instruments being present in the net, which are actually not used and thus the last part of the objective function "costs of not using a RMD" does not have to stay 0 necessarily. In case $z > N$ the chosen instrument will be removed from the dummy net and instead placed to one of the 'real nets', that is assigned randomly to one of the nets by making use of the random number generator RNG_NET. A 'real net' is a net that can be assigned to a surgery. Notice, that the dummy instruments cannot be assigned to a surgery. This allows for removing an instrument from a 'real net' or adding an instrument to a 'real net' without changing another 'real net'. If $z \leq N$ the chosen instrument will be removed from the 'real net'. In case it is feasible, this will be the new composition of nets and saved under $N6$. Otherwise this instrument is added, by making used of the function ADD_RMD(), to the best alternative neighboring net. In case no neighboring net exists that leads to feasible solution the instrument will not be removed from the net.

The costs of all feasible net compositions that are created by this heuristic are evaluated. In case the new feasible net composition $N6$ is cheaper than COST($Nbest$), then the best net will be updated to be $N6$. However, even if the new feasible net composition is more expensive than the costs associated to the previous net compositions, there still exists a chance that this new net partitioning is accepted. This depends on the acceptance-rejection function. The acceptance-rejection function is given by $\mathrm{A}R(N5, N6) = exp\left(\frac{\mathrm{COST}(N5)-\mathrm{COST}(N6)}{T}\right)$, where T is the control parameter. In each iteration a random number u between 0 and 1 is chosen by making use of the random number generator RNG_U. Whenever u is smaller than $AR(N5, N6)$ the new net composition is accepted. Due to this exponential acceptance rejection function, small differences have a higher chance of being accepted than big differences. The choice of T is of major importance as well since in case it is close to 0 there is a high chance that it will be rejected. This procedure will continue for a set amount of iterations q. With each additional iteration the probability of accepting a worse solution decreases.

This modified SA method is summarized in the Algorithm 2:

Algorithm 2: Pseudocode for SA

```
Data: hybrid solution N5 and the dummy instruments
begin
    NBest = N5
    N6 = N5
    for i = 1 to q do
        z = Call RNG_NET_DUM
        w = Call RNG_RMD
        N5 = N6
        Temp_Net = N5
        Temp_Net = Call EXTRACT_RMD(w,z)
        if z ≤ N then
            if Call FEASIBLE(Temp_Net) == false then
                for n = 1 to N do
                    if n != z then
                        Temp_Net = Call ADD_RMD(w,n)
                        if Call COST(Temp_Net) < Call COST(N6) then
                            N6 = Temp_Net
                        end
                    end
                end
            else
                N6 = Temp_Net
            end
        else
            y = Call RNG_NET
            Temp_Net = Call ADD_RMD(y,z)
            N6 = Temp_Net
        end
        Set T
        u = Call RNG_U
        if COST(N6) ≤ COST(NBest) then
            N5 = N6
            NBest = N6
        else if u < Call AR(N5,N6)
        then
            N5 = N6
        end
    end
    return NBest
end
```

Tabu Search

Similarly to SA, TS tries to avoid getting trapped in a local minimum. Again, the hybrid solution obtained before is used as the starting point. This will again serve as an initialization to set the net composition $NBest$. Then a new net partitioning, $Temp\_Net$ in this case, is created. This is done in the same manner as in SA only that N now represents the number of nets in $N5$. In the standard TS mechanism the next composition of nets is determined by moving to the best neighboring net composition. This could lead to cycling, as one can be the best neighbor of the other one. Thus, a tabu list, denoted by *tabu_list*, is introduced. Without the tabu list this mechanism could get stuck in a local optimum, instead of obtaining the global optimum (Ghiani, Laporte, & Musmanno, 2013). Hence, an empty tabu list of a set length, L, has to be initialized at the beginning of the algorithm. All feasible neighboring net compositions that have been chosen will be stored in this tabu list. For example, take $L = 100$, then, if a RMD is moved to another net, the previous net composition is 'tabu' for the next 100 iterations. When 100 other net compositions have been stored in the meantime, the original solution can be obtained again. TS allows to reduce the risk of cycling as the chances are low that the solution is trapped in the same local optimum. Also, notice that the chance of cycling is lowered the higher L is.

After initializing the tabu list, TS will search for the best neighboring solution that is not in the tabu list. To check whether the partitioning of nets is in the tabu list it is made use of the function tabu_listCONTAINS(). In TS the stopping condition is the number of iterations, q in this case. To find the best neighboring solution an empty list for possible nets has to be created, denoted by *net_list*. Then all neighboring solutions are checked by means of the multi-component cost function (1) and the best net partitioning solution is chosen, given that it is not in the tabu list. The chosen net composition will then be stored in the tabu list. For the net optimization problem, the neighborhood structures are obtained in the same manner as in SA.

If the best neighbor net partitioning that is allowed, is less expensive then the best so far, *NBest* will be updated. This will also be saved in the tabu list. Thus, in each iteration the net compositions change even if the neighboring solution is worse than the current net composition. As soon as the tabu list is full the first net partitioning, that has been recorded, will be deleted in the manner of a First in First Out (FIFO) concept. The Algorithm 3 represents the TS for this net optimization problem.

4 Results

To be able to merge the models of Reymondon et al. (2008) and van de Klundert et al. (2008), and also implement the new hyrbid solution, certain data has to be available. The RMDs needed for each surgery have to be known as well as the number, type and date of surgical procedures. Additionally, the storage and usage costs of each RMD are required alongside the storage costs for each net. Noting the large data size and the nature of the problem (NP-hard), runtime explosion might still appear. In this case the data can be summarized as done in Reymondon et al. (2008). This allows for a good approximation, reduces the amount of data heavily and thus makes the problem less complex.

The data set in this paper although representative, has been randomized due to confi-

Algorithm 3: Pseudocode for TS

```
Data: hybrid solution N5 and the dummy instruments
begin
    NBest = N5
    Empty vector tabu_list
    for i = 1 to q do
        Empty vector net_list
        z = Call RNG_NET_DUM
        w = Call RNG_RMD
        Temp_Net = Call EXTRACT_RMD(w,z)
        if Call FEASIBLE( Temp_Net) == false AND Call tabu_listCONTAINS
        (Temp_Net) == false OR z > N then
            for n = 1 to N do
                if  n != z then
                    Temp_Net = Call ADD_RMD(w,n)
                    if
                    Call FEASIBLE( Temp_Net)==true AND Call COST(Temp_Net)
                    < Call COST(N5)
                    AND Call tabu_listCONTAINS(Temp_Net) == false then
                        N5 = Temp_Net
                    end
                end
            end
        else
            N5 = Temp_Net
        end
        Call tabu_listADD(N5)
        if Call COST(N5) ≤ Call COST(NBest) then
            NBest = N5
        end
    end
    return NBest
end
```

dentiality reasons. It consists of 100 different instrument types, 56 surgeries and 20 different days. The data adequately captures the needs of the study. That is the usage and storage costs for RMDs are known in addition to net storage costs. Also, the RMDs required for and the days of each scheduled surgery are recorded. Despite its small size, the data allows for narrowing down of instruments and surgery days to 39 and 18 respectively. An overview of this data, save for costs, is given is given in Appendix B and C. Analyzing the data before feeding the program reduces the complexity significantly. Also, due to the low amount of instruments needed, it can be assumed that non-used instruments have been excluded.

Surgery planning is crucial in the suggested methodology as it restrains the shared level capacity, because the asynchronous needs are only derivable from there. This means that if two types of surgeries share some instruments in the same net, this net can only be used for both surgeries under a certain condition. Namely, the surgeries cannot be scheduled on the same day, or to be more precise until the CSSD has cleaned and returned them to the hospital.

4.1 Hybrid solutions

Table 1 summarizes the results of obtaining the hybrid solution where the RMDs with potential shared level are identified. Overall there a 36 different thresholds of benefit, but not all are shown in table 1. The results clearly show that the two extremes, $N1$ - one net for one surgical case, and $N3$ - one net for one RMD, can be outperformed by the hybrid grouping choices with different thresholds of benefit. $N1$ has performed the worst, as it does not allow for instrument sharing. Instrument sharing is of importance and is especially apparent in this data set. In particular, the net storage costs are relatively high compared to the usage and storage cost of the instruments. Even though with high net storage costs, less nets are assumed to be profitable. 211 nets yield the optimal solution of this hybrid. From this solution it becomes clear, that with this data set individually packaged instruments are preferred over nets that contain all instruments needed for a surgery. This explains why the optimal threshold of benefit led to a decrease of about 12% when compared to $N1$, and only to about 2% when compared to $N3$. When using the optimal hybrid solution instead of $N3$, €5.748 can be saved. This however leads to 4 more instruments being included in the nets, than minimally needed. Thus more RMDs need to be sterilized.

	$N1$: **TB = 14.946**	$N3$: **TB < 0**	**TB = 0**	**TB = 500**	**TB = 550**	**TB = 1.000**	**TB = 10.000**
Number of nets (N)	56	226	218	212	211	208	88
Overall Cost (€)	274.083	246.832	243.632	241.484	241.084	244.588	259.747
Decrease compared to N1 (%)	-	9,94	11,11	11,89	12,04	10,76	5,23
Decrease compared to N3 (%)	-11,04	-	1,30	2,17	2,33	0,91	-5,23

Table 1: Hybrid Solution for RMDs with potential shared level for different threshold of benefit (TB)

The best threshold of benefit is at $TB = 550$. The overall cost difference of the threshold $TB = 550$ to $TB = 500$ has an absolute difference of €400. Not only does the marginal cost difference supports using $TB = 550$ as a threshold of benefit, but also this threshold corresponds to 211 nets in the optimal solution, as opposed to 212 nets. This might seem as a negligible difference but the choice of 211 nets does reduce the complexity of the problem.

The results of the hybrid solution for surgeries with potential shared RMDs based on the hybrid solution of RMDs with potential shared level are summarized in table 2. This methodology has further decreased the cost by €9.660 and the number of RMDs remained the same compared to the previous hybrid solution. This is mainly explained as 28 less nets are used, while the amount of instruments remained the same. Again, another advantage of those net compositions is, that the nets with multiple RMDs are not necessarily assigned to a single surgery and thus the reduction in nets further reduces the complexity of the overall grouping and partitioning problem.

	HS: RMD with potential shared level	HS: surgeries with potential shared RMD
Number of nets (N)	211	183
Overall Cost (€)	241.084	231.424
Decrease (%)	-	4,01

Table 2: Hybrid Solution (HS) for surgeries with potential shared RMDs based on the hybrid solution of RMDs with potential shared level

4.2 Optimization of hybrid solution

Both, SA and TS have been low performing in improving the mixed hybrid solutions. In the best performing case only 133 instruments were packaged individually. The best performing results are summerized in Appendix D and Appendix E, where the partitioning of the nets and the surgeries assigned to the nets are represented respectively. In Appendix D it can be seen that a net contains at most 4 RMDs. Generally, having less than 4 instruments is impractical, as it requires a logistical effort beyond the occupational routine within hospitals. Thus, the result will most likely not lead to immediate success when implemented in reality.

For SA the control parameter was chosen to be 0 for the first 2.000 iterations, which means that no worse solution was allowed for those iterations. As a consequence the costs decreased by €4.373. This, however, is not in line with the characteristics of SA as it excludes the option of more expensive net compositions immediately. When actually using control parameters for the next 2.000 iterations three choices were made. Firstly, a T was chosen that linearly decreases to 0. Secondly, a T was chosen that decreases in an exponential manner and thus tends to 0 towards the last iterations and lastly, a T was chosen that decreases in a logarithmic manner to 0. The results of SA are summarized in table 3:

	Hybrid Solution	$\mathbf{T = 0}$	$\mathbf{T = 1 - 0{,}0005 \times q}$	$\mathbf{T = e^{1-q}}$	$\mathbf{T = \log\left(e - \frac{e-1}{1999} \times (q-1)\right)}$
Number of iterations (q)	-	2.000	1.500	1.500	1.500
Number of nets (N)	183	175	175	175	175
Overall Cost (€)	231.424	227.051	226.592	226.592	226.592
Cost decrease (%)	-	1,89	2,09	2,09	2,09

Table 3: Simulated annealing with different control parameter (T)

As the same seed has been used for all different control parameters not equal to 0, it can be seen that the type of control parameter has not affected the outcome. SA only led to a decrease in cost of $0,20\%$, in comparison to the outcome after T has been set to 0.

Even though SA, has not had a significant effect on cost reduction, it still outperformed TS. This is in line with the paper of Antosiewicz et al. (2013) which stipulates that SA finds the best solution. This, however, cannot be generalized for this data, as it depends on the seed chosen.

When comparing TS to the hybrid solution, only 3 nets decreased and €330 were saved. This can be explained by the fact that again 4 more instruments are present then minimally needed, and thus the net compositions did not allow for a fully efficient use of RMDs. The results are summarized in table 4, where the length (L) of the tabu list varied and the number of iterations were set to 40.000.

	Hybrid Solution	**L = 2**	**L = 5**	**L = 10**	**L = 15**	**L = 20**
Number of iterations (q)	-	40.000	40.000	40.000	40.000	40.000
Number of nets (N)	183	180	180	180	180	
Overall Cost (€)	231.424	231.094	231.094	231.094	231.094	231.094
Cost decrease (%)	-	0,14	0,14	0,14	0,14	0,14

Table 4: Tabu search with different tabu list lengths (L)

Again, a seed has been used, which shows that the tabu list lengths of L = 2, 5, 10, 15 or 20 did not affect the result. TS lead to a cost reduction of about 0,14%. Thus, SA has outperformed TS by €4.043 which corresponds to $1,78\%$ in this case.

Both SA and TS have found a solution where additional RMDs were included in the nets. The costs associated to not using a RMD, were set to the usage cost of this instrument. This has the disadvantage, as can be seen in Appendix E, that the nets are assigned to the surgeries even if they are not needed. That is, with the objective to minimize costs, it does not make a difference whether the non-used RMDs are or are not included when partitioning the nets to surgeries, even though this means that the CSSDs have to clean more RMDs in reality.

5 Conclusion and future work

Even though the decrease in cost appears minimal, a proper conclusion cannot be drawn, as the original partitioning of nets is unknown. According to Beer (2015), Koch (2015) and Warken (2015) most hospitals are very inefficient when looking at their composition of nets. Thus, if this method is applied, this model will likely result in significant cost reductions compared to the original partitioning of nets.

Making use of the two hybrid solutions led to a superior starting solution, when optimizing over the threshold of benefit. On the downside the metaheuristics SA and TS do not have a significant impact on the cost reduction when trying to obtain the optimal net compositions. The fact that the metaheuristics have not led to a significant cost reduction, supports the efficiency of the mixed hybrid solutions. For future work, it might be valuable to apply column generation to further optimize the net compositions as also suggested by Reymondon et al. (2008).

Considering that the hybrid solution is a net composition with mostly individually packaged RMDs constitute a problem in reality. It is simply not a good idea to spend much time on picking the nets during the stressful surgeries. Thus, it might be beneficial to introduce a penalty for individually packaged instruments, by changing the net storage cost. This can be done by increasing the net storage cost in a sensible manner, which makes less nets more profitable. Applying this method and recalculating the cost with the true net storage figures likely leads to a more costly solution. This, however, can be justified based on higher practical applicability.

The problem of non needed nets in partitioned to surgeries, can be tackled by setting the costs of non used RMDs to 0 after obtaining the solution. In other words, before it did not make a difference whether an instrument was used or not, as the usage cost was always incurred under the cost function. In reality however, the amount of RMDs cleaned by the CSSDs does depend on whether the net has been indeed used. Thus, it follows that whether non-used nets are included or excluded will affect the overall cost. Also, in case the objective is to decrease the amount of non used instruments having to be cleaned by the CSSDs, it is advisable to set the costs associated to non used RMDs even higher than the usage of them.

Additionally, to obtain compositions of nets with more than 4 RMDs, it might have been better to use different types of neighborhoods. The neighborhood used in SA and TS only allowed for a single change of RMDs - either to subtract and/or add a RMD. In order to have a higher chance of more RMDs in the nets, bigger neighborhoods can be used instead. For instance, by using multiple RMDs or generally further randomizing the neighborhood.

As already mentioned, the data available was limited. Thus, it was not sensible to include constraints such as that the instruments that are stored for more than 6 months are considered contaminated. Also, as the surgeries were only given per day, it was not possible to optimize over different delivery times of CSSDs. This is interesting as it can lead to large cost reductions if the instruments needed for the surgeries in the morning would also be needed for the surgeries at night. The aforementioned would allow for the sharing of nets on the same day but during different blocks of surgeries. It is advisable for future papers to take these suggestions into consideration in case the available data set allows to do so.

Even though the data available was insufficient to optimize over the factors mentioned above. Generally speaking, it is quite rare to have data concerning this topic. In practice, hospital information systems are currently less developed than information systems in industrial companies (Reymondon et al., 2008). Thus, to utilize the existing potential for optimizing the net compositions for surgeries, a better data collection is essential. There are however, only a limited number of countries which record this data properly. Netherlands for example is among them, whereas its neighboring country Germany has only recently initiated the process. Also, even though the matheamatical approach of tackling this problem is promising, field studies should not be underestimated. Thus, when carrying out the optimization of nets, it would be advisable to first carry out a field study, and in the second step apply the methods used in this paper. Thus, although rising medical costs can be a daunting reality, and hospital modernization is a complex endeavour, quantitative optimization ascertains that possible solutions are not far behind.

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Appendices

A Pseudocode for the hybrid solution

Here 3 external functions are made use of. BUILD($N3$) packages each instrument individually and BUILD($N1$) packages the nets needed for each surgery. Lastly, the function EXTRACT_RMD(r) called, which removes the instrument from the $N1$ and packages it individually. As soon as the algorithm is finished, the hybrid solution $N4$ is created.

Algorithm 4: Pseudocode for the hybrid solution

```
Data: instruments needed for each type of surgery and all individual instruments
begin
    Call BUILD(N3)
    for r = 1 to R do
        C1_N3(r) = C1(r)
    end
    Call BUILD(N1)
    for r = 1 to R do
        C1_N1(r) = C1(r)
    end
    for r = 1 to R do
        DC1(r) = C1_N1(r)-C1_N3(r)
    end
    Set TB
    for r = 1 to R do
        if DC1(r) > TB then
            Call EXTRACT_RMD(r)
        end
    end
    Return N4
end
```

B RMDs required of each surgery

	S 1	**S 2**	**S 3**	**S 4**	**S 5**	**S 6**	**S 7**	**S 8**	**S 9**	**S 10**
RMD 3								2	2	2
RMD 4								8	8	8
RMD 7								1	1	1
RMD 8	1	1	1	1	1	1	1			
RMD 9								2	2	2
RMD 13	2	2	2	2	2	2	2			
RMD 15	2	2	2	2	2	2	2			
RMD 18	1	1	1	1	1	1	1			
RMD 26								4	4	4
RMD 29								1	1	1
RMD 34								6	6	6
RMD 35	4	4	4	4	4	4	4			
RMD 37								5	5	5

	S 11	**S 12**	**S 13**	**S 14**	**S 15**	**S 16**	**S 17**	**S 18**	**S 19**	**S 20**
RMD 1										4
RMD 3	2	2	2	2	2	2	2	2	2	
RMD 4	8	8	8	8	8	8	8	8	8	
RMD 7	1	1	1	1	1	1	1	1	1	
RMD 9	2	2	2	2	2	2	2	2	2	
RMD 12										4
RMD 15										2
RMD 26	4	4	4	4	4	4	4	4	4	
RMD 29	1	1	1	1	1	1	1	1	1	
RMD 34	6	6	6	6	6	6	6	6	6	
RMD 37	5	5	5	5	5	5	5	5	5	
RMD 38										4

	S 21	**S 22**	**S 23**	**S 24**	**S 25**	**S 26**	**S 27**	**S 28**	**S 29**	**S 30**
RMD 1	4	1	1	1	1					
RMD 4		1	1	1	1					2
RMD 5		8	8	8	8	8	8	8	8	1
RMD 6						3	3	3	3	3
RMD 7						4	4	4	4	2
RMD 8						3	3	3	3	1
RMD 9		2	2	2	2	1	1	1	1	

RMD 10		2	2	2	2	2	2	2	2	
RMD 12	4									
RMD 15	2					2	2	2	2	
RMD 16		1	1	1	1					
RMD 17		4	4	4	4					
RMD 18		1	1	1	1					
RMD 24						2	2	2	2	
RMD 36		1	1	1	1					
RMD 38	4									

	S 31	**S 32**	**S 33**	**S 34**	**S 35**	**S 36**	**S 37**	**S 38**	**S 39**	**S 40**
RMD 1					1	1	1	1	1	
RMD 2										3
RMD 4	2	2	2	2	4	4	4	4	4	
RMD 5	1	1	1	1	3	3	3	3	3	
RMD 6	3	3	3	3						2
RMD 7	2	2	2	2	1	1	1	1	1	2
RMD 8	1	1	1	1						
RMD 9					3	3	3	3	3	
RMD 11					2	2	2	2	2	
RMD 12					1	1	1	1	1	
RMD 17					3	3	3	3	3	
RMD 19										2
RMD 22					1	1	1	1	1	
RMD 30					2	2	2	2	2	

	S 41	**S 42**	**S 43**	**S 44**	**S 45**	**S 46**	**S 47**	**S 48**	**S 49**	**S 50**
RMD 1										4
RMD 2	3	3	3	3	3	3	3			
RMD 5								1	1	
RMD 6	2	2	2	2	2	2	2	4	4	
RMD 7	2	2	2	2	2	2	2			
RMD 8										2
RMD 14										1
RMD 19	2	2	2	2	2	2	2			
RMD 23										2
RMD 25								3	3	
RMD 27										2

RMD 32										1
RMD 33										5
RMD 39										7

	S 51	**S 52**	**S 53**	**S 54**	**S 55**	**S 56**
RMD 1	4	4			3	1
RMD 3			1	1		
RMD 5			3	3		
RMD 7					2	
RMD 8	2	2				
RMD 9			3	3		
RMD 12					2	
RMD 14	1	1				
RMD 16						2
RMD 18					1	
RMD 20						2
RMD 21					1	
RMD 23	2	2	3	3		
RMD 27	2	2				
RMD 28					1	
RMD 29						3
RMD 31			1	1		
RMD 32	1	1				
RMD 33	5	5				
RMD 39	7	7				

Table 5: Type of RMD required for each surgery (S)

C Surgery schedule

	D 1	**D 2**	**D 3**	**D 4**	**D 5**	**D 6**	**D 7**	**D 8**	**D 9**	**D 10**
S 3								1		
S 5			1							
S 6		1								
S 7	1									
S 9						1				
S 11									1	
S 13				1						
S 14	1									
S 15									1	
S 18						1				
S 20									1	
S 21									1	
S 27			1							
S 29					1					
S 31							1			
S 33										1
S 34									1	
S 35	1									
S 36				1						
S 37						1				
S 38					1					
S 40			1							
S 41		1								
S 42									1	
S 43									1	
S 44					1					
S 45							1			
S 47				1						
S 48			1							
S 49									1	
S 51							1			
S 52			1							

	D 11	D 12	D 13	D 14	D 15	D 16	D 17	D 18	D 19	D 20
S 1					1					
S 2							1			
S 4						1				
S 8									1	
S 10						1				
S 12				1						
S 16				1						
S 17							1			
S 19				1						
S 22	1									
S 23						1				
S 24							1			
S 25						1				
S 26									1	
S 28		1								
S 30		1								
S 32									1	
S 39		1								
S 46							1			
S 50					1					
S 53								1		
S 54				1						
S 55							1			
S 56					1					

Table 6: Type of surgery (S) scheduled per day (D)

D Optimal net compositions

	N 1	N 2	N 3	N 4	N 5	N 6	N 7	N 8	N 9
I 1	13	38	38	36	36	24	11	2	2
I 2	13	38	38			24	22		2
I 3		38	38						
I 4		38							

	N 10	N 11	N 12	N 13	N 14	N 15	N 16	N 17	N 18
I 1	25	32	31	21	20	33	16	1	1
I 2				28	20	39		1	
I 3								1	

	N 19	N 20	N 21	N 22	N 23	N 24	N 25	N 26	N 27
I 1	4	3	23	4	3	3	3	4	4
I 2							34	9	

	N 28	N 29	N 30	N 31	N 32	N 33	N 34	N 35	N 36
I 1	4	4	4	4	30	4	4	4	4

	N 37	N 38	N 39	N 40	N 41	N 42	N 43	N 44	N 45
I 1	4	4	9	4	4	4	4	4	4
I 2					7				

	N 46	N 47	N 48	N 49	N 50	N 51	N 52	N 53	N 54
I 1	4	4	5	10	5	5	5	5	1
I 2			5		10	5			5

	N 55	N 56	N 57	N 58	N 59	N 60	N 61	N 62	N 63
I 1	5	5	5	1	5	29	2	6	25
I 2		5	5	5			6		
I 3							6		
I 4							6		

	N 64	N 65	N 66	N 67	N 68	N 69	N 70	N 71	N 72
I 1	6	6	6	6	6	6	6	7	7
I 2	25					8			7

	N 73	N 74	N 75	N 76	N 77	N 78	N 79	N 80	N 81
I 1	7	27	7	2	7	18	8	8	15
I 2						35		14	

	N 82	N 83	N 84	N 85	N 86	N 87	N 88	N 89	N 90
I 1	8	26	9	34	9	9	26	9	5
I 2			26						

	N 91	N 92	N 93	N 94	N 95	N 96	N 97	N 98	N 99
I 1	10	17	10	11	12	1	12	12	12
I 2						1		12	15
I 3						12		38	

	N 100	N 101	N 102	N 103	N 104	N 105	N 106	N 107	N 108
I 1	12	12	8	16	17	17	17	17	17
I 2		15	15						

	N 109	N 110	N 111	N 112	N 113	N 114	N 115	N 116	N 117
I 1	17	17	18	18	2	19	19	23	23
I 2					19				
I 3					19				

	N 118	N 119	N 120	N 121	N 122	N 123	N 124	N 125	N 126
I 1	9	37	26	37	26	26	7	26	26
I 2	9					37			

	N 127	N 128	N 129	N 130	N 131	N 132	N 133	N 134	N 135
I 1	26	9	29	29	30	33	33	33	33

	N 136	N 137	N 138	N 139	N 140	N 141	N 142	N 143	N 144
I 1	34	34	34	34	34	34	3	34	3
I 2							34		

	N 145	N 146	N 147	N 148	N 149	N 150	N 151	N 152	N 153
I 1	34	34	26	34	26	34	3	34	35
I 2				34			34		

	N 154	**N 155**	**N 156**	**N 157**	**N 158**	**N 159**	**N 160**	**N 161**	**N 162**
I 1	35	35	37	37	37	37	37	37	26
I 2									37

	N 163	**N 164**	**N 165**	**N 166**	**N 167**	**N 168**	**N 169**	**N 170**	**N 171**
I 1	37	37	37	34	4	37	4	8	39
I 2							37	39	

	N 172	**N 173**	**N 174**	**N 175**
I 1	39	39	27	39
I 2			39	

Table 7: Instrument types assigned to each net (N)

E Nets assigned to the surgeries

	Surgery 1	Surgery 2	Surgery 3	Surgery 4	Surgery 5	Surgery 6
Part 1	N 1	N 1	N 1	N 1	N 1	N 1
Part 2	N 78	N 78	N 78	N 78	N 78	N 78
Part 3	N 81	N 81	N 81	N 81	N 81	N 81
Part 4	N 102	N 102	N 102	N 102	N 82	N 102
Part 5	N 153	N 153	N 153	N 153	N 99	N 153
Part 6	N 154	N 154	N 154	N 154	N 153	N 154
Part 7	N 155	N 155	N 155	N 155	N 154	N 155
Part 8					N 155	

	Surgery 7	Surgery 8	Surgery 9	Surgery 10	Surgery 11	Surgery 12
Part 1	N 1	N 19	N 20	N 19	N 25	N 22
Part 2	N 78	N 24	N 25	N 24	N 28	N 27
Part 3	N 81	N 26	N 27	N 26	N 31	N 29
Part 4	N 102	N 28	N 30	N 27	N 35	N 30
Part 5	N 153	N 35	N 33	N 28	N 37	N 31
Part 6	N 154	N 42	N 35	N 37	N 38	N 34
Part 7	N 155	N 43	N 37	N 41	N 39	N 37
Part 8		N 47	N 40	N 45	N 40	N 46
Part 9		N 71	N 43	N 84	N 43	N 83
Part 10		N 84	N 44	N 127	N 47	N 88
Part 11		N 126	N 77	N 130	N 60	N 118
Part 12		N 127	N 84	N 144	N 83	N 119
Part 13		N 130	N 89	N 146	N 120	N 123
Part 14		N 144	N 120	N 147	N 123	N 124
Part 15		N 146	N 126	N 148	N 124	N 127
Part 16		N 147	N 130	N 149	N 128	N 130
Part 17		N 148	N 140	N 150	N 139	N 136
Part 18		N 149	N 145	N 152	N 140	N 140
Part 19		N 150	N 146	N 161	N 141	N 144
Part 20		N 152	N 148	N 163	N 142	N 145
Part 21		N 161	N 152	N 164	N 149	N 151
Part 22		N 163	N 156	N 165	N 157	N 152
Part 23		N 164	N 159	N 166	N 159	N 157
Part 24		N 165	N 161	N 168	N 160	N 159
Part 25		N 166	N 162	N 169	N 165	N 166
Part 26		N 168	N 165		N 166	N 168

Part 27		N 169

	Surgery 13	Surgery 14	Surgery 15	Surgery 16	Surgery 17	Surgery 18
Part 1	N 24	N 24	N 24	N 24	N 22	N 19
Part 2	N 28	N 26	N 26	N 26	N 24	N 31
Part 3	N 29	N 28	N 27	N 33	N 29	N 34
Part 4	N 31	N 37	N 29	N 39	N 35	N 38
Part 5	N 40	N 41	N 30	N 40	N 41	N 39
Part 6	N 42	N 43	N 36	N 43	N 42	N 41
Part 7	N 44	N 44	N 41	N 44	N 44	N 42
Part 8	N 77	N 45	N 45	N 45	N 84	N 45
Part 9	N 84	N 84	N 84	N 60	N 87	N 60
Part 10	N 87	N 127	N 85	N 75	N 123	N 121
Part 11	N 127	N 130	N 122	N 120	N 130	N 122
Part 12	N 130	N 144	N 126	N 121	N 144	N 123
Part 13	N 144	N 146	N 130	N 126	N 146	N 125
Part 14	N 146	N 147	N 138	N 139	N 148	N 128
Part 15	N 147	N 148	N 143	N 141	N 149	N 136
Part 16	N 148	N 149	N 145	N 142	N 150	N 137
Part 17	N 149	N 150	N 150	N 146	N 152	N 141
Part 18	N 150	N 152	N 151	N 147	N 162	N 142
Part 19	N 152	N 163	N 161	N 148	N 164	N 143
Part 20	N 163	N 164	N 162	N 162	N 165	N 149
Part 21	N 164	N 165	N 164	N 164	N 166	N 151
Part 22	N 165	N 166	N 168	N 165	N 167	N 163
Part 23	N 166	N 168	N 169	N 167	N 168	N 164
Part 24	N 167	N 169		N 169	N 169	N 169
Part 25	N 168					
Part 26	N 169					

	Surgery 19	Surgery 20	Surgery 21	Surgery 22	Surgery 23	Surgery 24
Part 1	N 19	N 2	N 2	N 5	N 4	N 5
Part 2	N 23	N 3	N 18	N 18	N 16	N 17
Part 3	N 25	N 17	N 54	N 53	N 36	N 26
Part 4	N 28	N 58	N 81	N 55	N 49	N 39
Part 5	N 35	N 95	N 96	N 56	N 51	N 49
Part 6	N 36	N 97	N 98	N 57	N 52	N 52
Part 7	N 38	N 99	N 101	N 59	N 53	N 53

Part 8	N 41	N 100		N 90	N 54	N 55
Part 9	N 42	N 102		N 91	N 55	N 56
Part 10	N 47			N 93	N 56	N 57
Part 11	N 84			N 103	N 91	N 59
Part 12	N 85			N 107	N 92	N 90
Part 13	N 87			N 108	N 106	N 91
Part 14	N 122			N 109	N 108	N 93
Part 15	N 125			N 110	N 110	N 103
Part 16	N 129			N 112	N 112	N 107
Part 17	N 137			N 118	N 118	N 108
Part 18	N 138			N 128		N 109
Part 19	N 143			N 167		N 110
Part 20	N 149					N 112
Part 21	N 150					
Part 22	N 156					
Part 23	N 158					
Part 24	N 160					
Part 25	N 161					
Part 26	N 163					

	Surgery 25	**Surgery 26**	**Surgery 27**	**Surgery 28**	**Surgery 29**	**Surgery 30**
Part 1	N 5	N 6	N 6	N 6	N 6	N 41
Part 2	N 22	N 50	N 50	N 50	N 48	N 45
Part 3	N 39	N 51	N 51	N 51	N 50	N 48
Part 4	N 48	N 55	N 52	N 52	N 52	N 67
Part 5	N 50	N 56	N 53	N 53	N 53	N 68
Part 6	N 57	N 57	N 57	N 56	N 55	N 69
Part 7	N 58	N 67	N 66	N 62	N 57	N 71
Part 8	N 59	N 68	N 68	N 65	N 59	
Part 9	N 89	N 70	N 69	N 70	N 65	
Part 10	N 90	N 72	N 72	N 72	N 67	
Part 11	N 93	N 73	N 75	N 73	N 68	
Part 12	N 103	N 77	N 79	N 79	N 71	
Part 13	N 104	N 79	N 90	N 81	N 72	
Part 14	N 105	N 81	N 93	N 82	N 73	
Part 15	N 107	N 82	N 101	N 89	N 77	
Part 16	N 109	N 93	N 102	N 90	N 79	
Part 17	N 111	N 102	N 124	N 93	N 81	
Part 18		N 118	N 128	N 102	N 82	

Part 19				N 124	N 86	
Part 20					N 91	
Part 21					N 93	
Part 22					N 102	

	Surgery 31	**Surgery 32**	**Surgery 33**	**Surgery 34**	**Surgery 35**	**Surgery 36**
Part 1	N 41	N 41	N 47	N 33	N 7	N 7
Part 2	N 47	N 52	N 67	N 34	N 17	N 18
Part 3	N 62	N 62	N 68	N 56	N 18	N 19
Part 4	N 65	N 65	N 70	N 65	N 32	N 22
Part 5	N 66	N 69	N 77	N 66	N 34	N 26
Part 6	N 77	N 75	N 82	N 69	N 40	N 32
Part 7	N 82	N 167	N 90	N 71	N 47	N 41
Part 8	N 90		N 124	N 75	N 57	N 57
Part 9	N 167	N	N 167		N 59	N 59
Part 10					N 72	N 89
Part 11					N 86	N 90
Part 12					N 87	N 94
Part 13					N 90	N 97
Part 14					N 94	N 100
Part 15					N 97	N 108
Part 16					N 100	N 109
Part 17					N 108	N 110
Part 18					N 109	N 118
Part 19					N 110	N 131
Part 20					N 128	
Part 21					N 131	
Part 22					N 167	

	Surgery 37	**Surgery 38**	**Surgery 39**	**Surgery 40**	**Surgery 41**	**Surgery 42**
Part 1	N 7	N 7	N 7	N 9	N 9	N 8
Part 2	N 18	N 18	N 17	N 61	N 67	N 9
Part 3	N 26	N 26	N 18	N 65	N 68	N 61
Part 4	N 29	N 32	N 19	N 71	N 70	N 70
Part 5	N 32	N 41	N 26	N 76	N 76	N 72
Part 6	N 46	N 46	N 30	N 77	N 77	N 73
Part 7	N 47	N 47	N 32	N 114	N 114	N 114
Part 8	N 57	N 51	N 39	N 115	N 115	N 115

Part 9	N 59	N 56	N 47		N 124	
Part 10	N 86	N 89	N 48			
Part 11	N 87	N 94	N 55			
Part 12	N 90	N 97	N 59			
Part 13	N 94	N 100	N 77			
Part 14	N 97	N 108	N 86			
Part 15	N 100	N 109	N 94			
Part 16	N 108	N 110	N 100			
Part 17	N 109	N 118	N 108			
Part 18	N 110	N 131	N 109			
Part 19	N 124	N 167	N 110			
Part 20	N 131		N 131			

	Surgery 43	**Surgery 44**	**Surgery 45**	**Surgery 46**	**Surgery 47**	**Surgery 48**
Part 1	N 9	N 9	N 8	N 9	N 9	N 10
Part 2	N 61	N 62	N 9	N 67	N 68	N 55
Part 3	N 72	N 70	N 68	N 68	N 70	N 62
Part 4	N 76	N 72	N 70	N 70	N 72	N 63
Part 5	N 77	N 75	N 72	N 72	N 76	N 64
Part 6	N 113	N 76	N 76	N 73	N 114	N 67
Part 7		N 114	N 114	N 76	N 115	N 70
Part 8		N 115	N 115	N 114	N 124	
Part 9			N 124	N 115		

	Surgery 49	**Surgery 50**	**Surgery 51**	**Surgery 52**	**Surgery 53**	**Surgery 54**
Part 1	N 10	N 11	N 11	N 11	N 12	N 12
Part 2	N 53	N 15	N 15	N 15	N 21	N 20
Part 3	N 62	N 17	N 17	N 17	N 57	N 21
Part 4	N 63	N 58	N 18	N 18	N 59	N 57
Part 5	N 64	N 74	N 74	N 74	N 90	N 59
Part 6	N 67	N 80	N 80	N 80	N 116	N 86
Part 7	N 68	N 116	N 116	N 116	N 117	N 89
Part 8		N 117	N 117	N 117	N 118	N 90
Part 9		N 132	N 132	N 132	N 128	N 116
Part 10		N 133	N 133	N 133	N 144	N 117
Part 11		N 134	N 134	N 134		N 128
Part 12		N 135	N 135	N 135		
Part 13		N 170	N 170	N 170		

Part 14		N 171	N 171	N 171
Part 15		N 172	N 172	N 172
Part 16		N 173	N 173	N 173
Part 17		N 174	N 174	N 174
Part 18		N 175	N 175	N 175

	Surgery 55	**Surgery 56**
Part 1	N 13	N 14
Part 2	N 17	N 16
Part 3	N 71	N 18
Part 4	N 75	N 60
Part 5	N 96	N 103
Part 6	N 100	N 129
Part 7	N 111	N 130

Table 8: Nets (N) assigned to each surgery (S)