Case study: Mobile X-ray equipment selection for a traumatology department using value engineering and multi-criteria decision methods

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Abstract. The methodology for a selection of medical devices was created within the study "Utilization of value engineering and multi-variate decision making in health technology assessment". This case study presents the pilot implementation of the methodology. The aim was to select mobile X-ray equipment for a hospital de- partment of traumatology. The study consists of two parts. First, a suitable type of the X-ray device was chosen, and in the second step, its particular brand was selected. The methodology takes into consideration clinical outcomes (e.g. radiation exposure of the patient and the staff), cost data (procurement of the appliance, service, spare parts, training, routine operation, etc.), and also technical parameters of the particular device. Device specifications and clinical outcomes were evaluated by the TOPSIS method combined with Saaty´s method. Saaty´s method is used for objectivization of the weights of individual criteria. On the basis of the obtained weights, the TOPSIS method ranks the variants in an ideal order taking into account real values of the vari- ants. These values are subsequently used as the "effects" in the denominator of the cost-effectiveness ratio, while the cost calculation/estimation is used in the numerator. This study has proved the applicability of this methodology. In a case of a selection of a suitable type and brand of medical equipment, it provides us with a possibility of a complex view.

Keywords: HTA methodology · medical devices · multi-criteria decision analysis · roentgen.

1 Introduction

The study addresses the issues of the acquisition of a suitable X-ray apparatus for the Department of Traumatology of a university hospital. First, the types of skiagraphs are analysed – an analogue type, a type with indirect and direct digitization. The cost-effectiveness analysis of the above types was made in relation to respective healthcare facilities. The assessment was calculated for university hospitals, regional hospitals and outpatient facilities. Due to the fact that a university hospital was involved in this case, the option of direct digitization was analysed as a more suitable option. This primarily results form a large number of presumed examinations. Detailed market research was also conducted. With the help of an expert group in the given field (clinicians-radiologists, physicists-radiologists, technicians-radiologists), the essential specifications for the purchase of a digital skiagraph were identified and subsequently assessed using Saaty's matrix. In conclusion, the cost-effectiveness analysis was made and a suitable skiagraph that should be purchased by the Depart-

ment of Traumatology was chosen. The evaluation process is illustrated in the figure below.

The exchange rate for January 31, 2014:

1 EUR = 27.50 CZK

2 Data

The data acquired within this study were collected directly from healthcare facilities working in different radiographic modes - analogue or digital. Also, they were collected with the help of leading distributors and manufacturers of medical equipment operating on the Czech market. Data were obtained to identify the prices of film-based operation, the prices of digital and analogue systems, and to analyse data in the digital archive.

Radiation burden of radiographic systems

The radiation burden of different radiographic modalities was compared in two different ways: first, by measuring the input surface kermas on phantoms and, subsequently, by comparing clinical dose values obtained from the KAP meter. The patient's radiation dose associated with a radiographic examination was evaluated for two frequently performed X-ray scans – the chest (PA projection) and the abdomen (PA projection) scans. The reason for selecting these examinations was their frequency and the radiation burden magnitude.

The data were collected at the Clinic of Imaging Methods of the 2nd Faculty of Medicine of Charles University and the Motol University Hospital. The Clinic annually performs over 250 thousand examinations, and a complex digitization of the workplace was underway there at the time of data collection; therefore, dose related data from all compared methods (SFR, CR and DR) were available.

Measurements on phantoms

A tissue-equivalent phantom with a water thickness of 20 cm was selected for the abdominal examination, and that of 15 cm for lungs. The phantom is made of synthetic acrylic glass (PMMA), as a water-filled rectangular prism with external dimension of 25×25 cm. The measurement of the input surface kerma was made using an ionization chamber, which was placed in the middle of the upper surface of the phantom. The PMMA phantom was always positioned so that it would overlap the active chambers of the exposure machine.

KAP meter measurements in clinical practice

To assess the radiation burden in clinical practice, 10 patients were always selected for each type of examination using the given image detector. Based on clinical recommendations, dose related data of 10 patients for the respective examination are sufficient for the determination of local diagnostic reference levels (LDRL). LDRL are identified as the arithmetic mean from easily measurable dose quantities of 10

standard patients weighing 70±5 kg. The LDRL value for skiagraphy is expressed in terms of KAP values.

Results

modality	Lungs PA (mGy)	Abdomen PA (mGy)
DR	0.126	0.579
CR	0.146	0.669
SFR	0.491	1.231

Table 1: Comparison of measured input surface kermas for different types of image detectors

modality	Lungs PA (μGy.m^2)	Abdomen PA (μGy.m^2)
DR	0.062	0.570
CR	0.087	0.863
SFR	0.173	1.587

Table 2: Comparison of average KAP values for different image detectors according to examinations

The results of the input surface kerma measurement in the input plane of the phantom show that digitization has significantly reduced the patient's radiation dose. Considering the dose required for obtaining a radiographic image for a film - foil detector as 100%, the other radiographic modalities require lower input doses (Table **3**). This finding is confirmed by the results of measurements with the KAP meter in clinical practice.

modality	ø reduction (%)
DR	53.1
CR	51.5

Table 3: Average percentage reduction in the input surface kerma for digital detectors

Purchasing price and operating costs for radiographic systems

The information on the purchasing prices and operating costs for different digital or analogue radiographic systems was obtained from Philips, FOMA and ORCZ companies.

The calculation is based on a basic identification of three different workplaces with different operation modes. The first workplace is an imaginary outpatient facility with 25 patients per day. The second workplace represents a facility of a regional hospital type with medium operation of 50 patients per day. The last type of workplace is a large university hospital with 75 patients examined per day.

An average radiographic examination of 1 patient consists of two images, taking up 0.144 m^2 of film in analogue systems or 5-10 MB of disk space in the case of digital systems. For workplaces with a higher number of images, a higher number of evaluation diagnostic stations needs to be included in the calculation.

Other items necessary for the calculation of the total costs over the estimated service life of a device of 8 years in digital systems include an increase in costs for the HW data storage renewal after the third year of operation amounting to 5 % of the purchasing price. Moreover, CR foils in CR systems must be replaced after 20 000 exposures.

Analogue operation of SFR

Device	Purchase price	Operating costs/year
skiagraphy (50 examin.)	1 290 000.00 CZK	120 000.00 CZK
skiagraphy (100 examin.)	1 690 000.00 CZK	120 000.00 CZK
skiagraphy (150 examin.)	1 690 000.00 CZK	120 000.00 CZK

Table 4: Basic prices of self-contained radiographic devices for workplaces with different operation modes

Darkroom	Purchase price	Operating costs/year
automatic machine	140 000.00 CZK	20 000.00 CZK
table	25 000.00 CZK	-
light	10 000.00 CZK	-

Table 5: Basic prices related to darkroom equipment

Negatoscope	Purchase price
1 (50 examin.)	40 000.00 CZK.
2 (100 examin.)	90 000.00 CZK
3 (150 examin.)	130 000.00 CZK

Table 6: Basic prices of negatoscopes for workplaces with different operation modes

Disposable materials (incl.chemistry)	Operating costs/year
skiagraphy (50 examin.)	414 000.00 CZK
skiagraphy (100 examin.)	828 000.00 CZK
skiagraphy (150 examin.)	1 242 000.00 CZK

Table 7: Basic prices for disposable materials for workplaces with different operation modes

Digital operation of CR

Device	Purchase price	Operating costs/year
skiagraphy (50 examin.)	1 290 000.00 CZK	120 000.00 CZK
skiagraphy (100 examin.)	1 690 000.00 CZK	120 000.00 CZK
skiagraphy (150 examin.)	1 690 000.00 CZK	120 000.00 CZK

Table 8: Basic prices of self-contained radiographic devices for workplaces with different operation modes

CR reader	Purchase price	Operating costs/year
CR 1 slot (50 examin.)	900 000.00 CZK	90 000.00 CZK
CR 1 slot (100 examin.)	900 000.00 CZK	90 000.00 CZK
CR 4 slots (150 examin.)	1 650 000.00 CZK	120 000.00 CZK

Table 9: Basic prices of CR readers for workplaces with different operation modes

CR foils	Purchase price
4x (50 examin.)	100 000.00 CZK
6x (100 examin.)	150 000.00 CZK
10x (150 examin.)	250 000.00 CZK

Table 10: Basic prices of CR foils for workplaces with different operation modes

PACS	Purchase price	Operating costs/year
PACS + 1 station (50 examin.)	2 000 000.00 CZK	150 000.00 CZK
PACS + 2 stations (100 examin.)	3 000 000.00 CZK	250 000.00 CZK
PACS + 3 stations (150 examin.)	4 000 000.00 CZK	300 000.00 CZK

Table 11: Basic prices of data storage for workplaces with different operation modes

Digital operation of DR

Device	Purchase price	Operating costs/year
1xFPD (50 examin.)	3 500 000.00 CZK	350 000.00 CZK
2x FPD (100 examin.)	5 200 000.00 CZK	450 000.00 CZK
2x FPD (150 examin.)	5 200 000.00 CZK	450 000.00 CZK

Table 12: Basic prices of full digital radiographic devices for workplaces with different operation modes

PACS	Purchase price	Operating costs/year
PACS + 1 station (50 examin.)	2 000 000.00 CZK	150 000.00 CZK
PACS + 2 stations (100 examin.)	3 000 000.00 CZK	250 000.00 CZK
PACS + 3 stations (150 examin.)	4 000 000.00 CZK	300 000.00 CZK

Table 13: Basic prices of data storage for workplaces with different operation modes

Speed of work with the system

The data related to the speed of work with radiographic systems were obtained directly from clinical radiographic workplaces in the Motol University Hospital, KOLF outpatient facility in Pardubice and X-ray outpatient facility in Poděbrady.

Data collection methodology

To determine the speed of work with a given modality, the time needed to obtain a full-value radiogram, which is subsequently handed over to a doctor for evaluation, was measured. To avoid the reliance on patients' variability in the assessment of the speed of work with the respective radiographic modality, only the time from the start of exposure (pressing the button) until the exit of the developed film from the developing machine in SFR systems, or until sending off the image to the diagnostic station in the case of digital systems was measured. For conservative reasons, the time required for obtaining a radiogram in the maximum size used in conventional radiographic examinations, 35x43, was selected. This format is most commonly used for examinations of the chest or the abdomen.

Results

modality	ø time for obtaining image (s)
DR	17
CR	163
SFR	220

Table 14: Average times necessary for obtaining an image for different modalities

The results of measuring the time needed for obtaining a radiogram imply that digitization accelerates operation under the considered conditions. Considering the time required for obtaining a radiographic image for a film – foil detector as 100 %, the other radiographic modalities require shorter times (Table 15).

modality	ø reduction (%)
DR	-92.3
CR	-22.7

Table 15: Percentage reduction in time necessary for obtaining an image for digital detectors

3 Data Analysis

Data analysis is based on the basic subdivision into three different workplaces with different operation modes. The first workplace is an imaginary outpatient facility with 50 examinations per day, i.e. 25 patients/day. The second workplace is a healthcare facility with medium operation of a regional hospital type with 100 examinations per day, i.e. 50 patients/day. The last type of workplace is a large university hospital with 150 examinations per day, i.e. 75 patients/day. (This assumption was already used in obtaining the data for specifying the acquisition costs and operating costs of work-places.)

Cost minimization analysis (CMA)

The first economic analysis represents the assessment of the total financial costs for the acquisition of medical devices and the workplace operation for the recommended service life of the X-ray devices of 8 years. The costs related to personnel were not considered during the application. The calculation is based on the experience of analysed healthcare facilities that neither the composition, nor the remuneration of the personnel depends on the type of radiographic workplace (SFR, CR, DR). It is further assumed that the whole system is under warranty during the first two years, so that no annual service costs (excluding film material) are incurred to the workplace in this period. Source data for the graphical presentation are listed in the Annex.

Small workplace (outpatient facility)

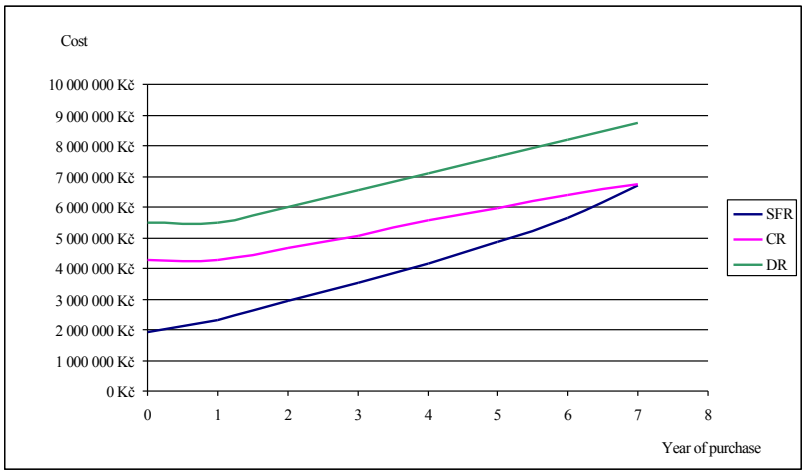

Chart 1: Cost development for running a small radiographic workplace

Medium workplace (regional hospital)

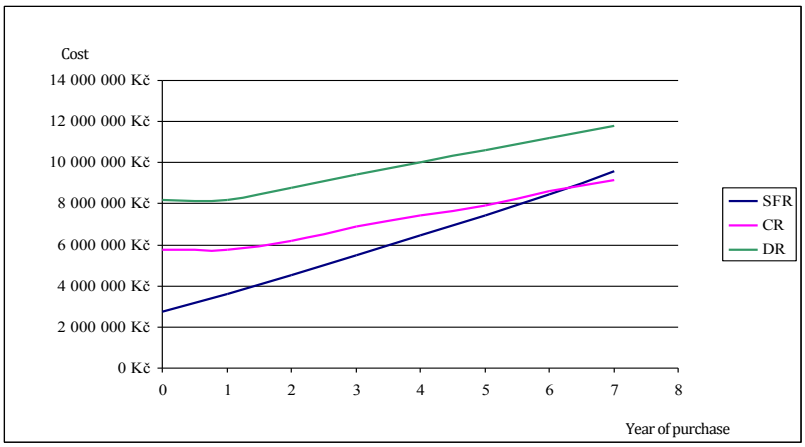

Chart 2: Cost development for running a medium radiographic workplace

Large workplace (university hospital)

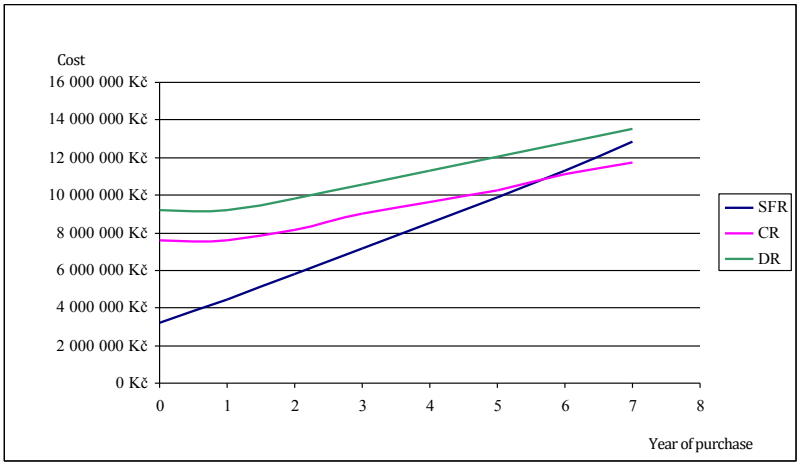

Chart 3: Cost development for running a large radiographic workplace

Multiple-criteria decision analysis (MDA)

Multiple-criteria decision analysis consists of more steps. In the first phase, the objective of the analysis must be defined. The objective of this analysis is to sort out individual methods of the acquisition of an X-ray image (SFR, CR, DR) according to the preferences of different types of healthcare facilities (outpatient facility, regional hospital, university hospital). The result of MDA will also serve for the CEA calculation.

As already mentioned in the theoretical part, the weighted sum method was selected for data analysis. There are 3 alternatives available (SFR, CR, DR), which are assessed according to three main criteria: total costs over a period of 8 years, the time required to make an image, and the mean dose per image. All these criteria are minimizing criteria; hence, the method that is minimal in the respective parameter is given the value 1. The values for the other methods are proportionally related to it.

Subsequently, the weight of individual criteria must be identified. It is evident that different workplaces will have essential criteria differing by their weight. The weights for individual workplaces were consulted with experts in medical technology, in particular with Jiří Petráček, head of the Department of Investments and Medical Technology.

Outpatient facility	Weight
costs for 8 years	0.8
time/image	0.1
KAP/image	0.1
	1

Table 16: Weights for small workplaces (50 examin.)

Regional hospital	Weight
costs for 8 years	0.6
time/image	0.3
KAP/image	0.1
	1

Table 17: Weights for medium workplaces (100 examin.)

University hospital	Weight
costs for 8 years	0.4
time/image	0.3
KAP/image	0.3
	1

Table 18: Weights for large workplaces (150 examin.)

Thanks to identified weights, the weighted sum may be calculated, and the order of the suitability of individual modalities for the particular workplace made. The weighted sum is obtained from Equation 1.

$$w_i = \sum_{j=1}^{k} r_{ij} v_j, i = 1,2,...,n$$

Equation 1: Formula for weighted sum calculation

First, a normalized criteria matrix (Tables 25, 27, 29) whose elements express the values of the benefit of respective alternatives according to a particular criterion is created using the transformation formula. In practice, the values of individual criteria are multiplied by their weights, and the resulting values are finally summed up. Thus, the result is the weighted sum of individual criteria. The resulting order is made starting from the largest value to the smallest one.

Small workplace (outpatient facility)

modality	**costs for 8 years**	**time/image (s)**	**dose/image (µGy.m^2)**
SFR	5 202 000.00 CZK	220	0.88
CR	2 460 000.00 CZK	163	0.475
DR	3 250 000.00 CZK	17	0.316

Table 19: Criteria for a small workplace

weight	0,8	0,1	0,1	weighted sum	order
modality	costs for 8 years	time/image	dose/image		
SFR	0.47	0.08	0.36	0.421951887	3
CR	1.00	0.10	0.67	0.876955764	1
DR	0.76	1.00	1.00	0.805538462	2

Table 20: Multiple-criteria decision analysis for a small workplace

Medium workplace (regional hospital)

modality	**costs for 8 years**	**time/image (s)**	**dose/image (µGy.m^2)**
SFR	7 624 000.00 CZK	220	0.88
CR	3 410 000.00 CZK	163	0.475
DR	3 600 000.00 CZK	17	0.316

Table 21: Criteria for a medium workplace

weight	0,6	0,3	0,1	weighted sum	order
modality	acquisition costs	time/image	dose/image		
SFR	0.45	0.08	0.36	0.327453973	3
CR	1.00	0.10	0.67	0.697814659	2
DR	0.95	1.00	1.00	0.968333333	1

Table 22: Multiple-criteria decision analysis for a medium workplace

Large workplace (university hospital)

modality	costs for 8 years	time/image (s)	dose/image (µGy.m^2)
SFR	10 846 000.00 CZK	220	0.88
CR	4 140 000.00 CZK	163	0.475
DR	4 300 000.00 CZK	17	0.316

Table 23: Criteria for a large workplace

Weight	0,4	0,3	0,3	weighted sum	order
modality	costs for 8 years	time/image	dose/image		
SFR	0.38	0.08	0.36	0.283592108	3
CR	1.00	0.10	0.67	0.630867291	2
DR	0.96	1.00	1.00	0.985116279	1

Table 24: Multiple-criteria decision analysis for a large workplace

Cost effectiveness analysis (CEA)

Having completed the multiple-criteria decision analysis of the methods (SFR, CR, DR) for different types of workplaces (outpatient facility, regional hospital, university hospital), the obtained weighted sums are divided by the acquisition costs of individual methods. The CEA result is presented in Tables 23–25.

Small workplace (outpatient facility)

Modality	Acquisition costs	CEA criterion (x10^{-6})	order
SFR	1 505 000.00 CZK	0.2803667022303	1
CR	4 290 000.00 CZK	0.2044185929236	2
DR	5 500 000.00 CZK	0.1464615384615	3

Table 25: CEA for a small workplace

Medium workplace (regional hospital)

Modality	Acquisition costs	CEA criterion (x10^{-6})	order
SFR	1 955 000.00 CZK	0.1674956384140	1
CR	5 740 000.00 CZK	0.1215704981442	2
DR	8 200 000.00 CZK	0.1180894308943	3

Table 26: CEA for a medium workplace

Large workplace (university hospital)

Modality	Acquisition costs	CEA criterion ($x10^{-6}$)	order
SFR	1 995 000.00 CZK	0.1421514324258	1
CR	7 590 000.00 CZK	0.0831182201484	3
DR	9 200 000.00 CZK	0.1070778564206	2

Table 27: CEA for a large workplace

4 Discussion

Cost minimization analysis (CMA)

In terms of CMA, CR is the most promising technology in all studied types of workplaces. On the contrary, the most expensive on a long-term basis appears to be film-based operation, which, despite of its low acquisition costs, incurs enormous costs for operating and disposable material. By comparing the resulting charts, we may conclude that if the number of examinations rises, film operation will become significantly more demanding from the economic perspective.

In a small outpatient facility, the CR technology will pay off after 7 years, while in a medium workplace the CR technology will pay off after 6 years. In the case of a large university hospital, the investment in the CR technology will pay off already after 5 years.

This result holds true provided that this large hospital possesses only one diagnostic instrument. If the hospital is equipped with a larger number of digital modalities, such as e.g. CT, MR, ultrasound, etc., the costs for the operation of a PACS digital archive will be proportionally distributed among all modalities and the introduction of digital radiography (CR, DR) will pay off already after a shorter period of use.

For facilities of the "university hospital" type, the acquisition of the latest technology (DR) may also be presumed despite of the not very favourable result of the CMA analysis.

Multiple-criteria decision analysis (MDA)

The acquisition of a radiographic system (SFR, CR, DR) need not be bound only on the minimum purchasing price as is mostly the case of public tenders, but other criteria may also be considered (depending on the client's preferences), such as total operating costs, the time required for making an image and the average dose per image. The selection criteria have different weights for different types of workplaces. According to designed weights, recommended by an expert, the most suitable system for an outpatient facility is the CR, for a medium workplace the DR system and for a large hospital also the DR. The comparison of the results using MDA implies that the

DR technology will pay for the busiest workplaces. A higher number of examined patients results in a higher difference between the film and digital operation, CR and DR.

Cost effectiveness analysis (CEA)

MDA must be necessarily completed as the first step, in order to calculate CEA correctly. It should be noted that MDA differs for workplaces of different size and, therefore, CEA brings different results, too. CEA has preferred film operation regardless of the workplace size because of the lowest acquisition costs. In general terms, however, it is evident that the larger the workplace, which means a large number of patients examined, the smaller the difference between the film and full digital operation in the CEA result. The table below presents theoretic data where full digital operation is equivalent to film operation even in terms of CEA analysis.

workplace	patients/day
Outpatient facility	71
Regional hospital	83
University hospital	146

Table 28: The lower threshold of daily number of examined patients at the workplace where full digital operation matches film operation, in terms of CEA analysis

For comparison, the table below presents necessary numbers of patients examined per day so that the CEA analysis preferred the CR indirect digital operation.

workplace	patients/day
Outpatient facility	44
Regional hospital	71
University hospital	358

Table 29: The lower threshold of daily number of examined patients at the workplace where full digital operation matches film operation in terms of CEA analysis

Comparing the tables we can see that for smaller facilities of an outpatient type, the transition to digital operation should be done rather by CR indirect digitization, while for large facilities, on the contrary, direct digitization with a flat panel detector (FPD) is the preferred option.

Acknowledgement. The authors acknowledge financial support for the development of HTA methods for medical devices by the Ministry of Health Services of the Czech Republic under the Grant No. NT11532 “Medical Technology Assessment”.

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