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| RESEARCH ARTICLE

Optimizing Radiation Safety Protocols in Industrial Radiography Using Linear Programming and Simulation

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| ABSTRACT
Industrial radiography puts non-destructive testing (NDT) technicians at risk of high photon dose rates during inspection activities. Old methods of scheduling and assigning tasks are based on guesses and do not provide equal distribution of doses, leading to inefficient means of operation and avoidable exposures. In this article, an integrated operations research (OR) framework has been offered to optimize radiation safety measures in industrial radiography, based on linear programming (LP) and the Monte Carlo simulation. The model will reduce the collective dose and enhance the efficiency of the workflow in realistic field conditions. In the case study of ten radiographic jobs and three technicians, the optimized schedule has resulted in a total collective dose that is less by 25 %, the highest dose that is less by 34 %, and an improvement in operational time by 15 %. Monte Carlo simulation ensures the ability to resist variation of dose rates and the length of the job. These results demonstrate opportunities for the OR-based decision support systems to optimize the ALARA implementation and increase the safety performance of the industrial radiography practice.

| KEYWORDS

Industrial radiography, radiation safety, linear programming, Monte Carlo simulation, occupational exposure, ALARA principle, operations research

| ARTICLE INFORMATION

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1. Introduction

Industrial radiography is also vital in the industry, like pipeline construction, aerospace, and petrochemical engineering, yet the technicians are exposed to high dose rates due to sources such as Ir-192, Se-75, or high-energy X-ray generators. Even though IAEA and NCRP offer exposure optimization interventions, they are largely qualitative and do not offer quantitative tools to schedule, allocate tasks, and distribute doses [International Atomic Energy Agency, 2018], [National Council on Radiation Protection and Measurements, 2015]. Radiography work is affected by the choice of variable geometry, scattered field, shield limits, and variable work time, which result in disproportionate exposure and unproductive working hours. Research in medical imaging and occupational protection also points to optimizing dose quantitatively through simulation and machine learning and OR-based methods [Alemayehu et al., 2023], [ICRP PUBLICATION, 2023], [Lee, 2024], [Tsapaki, 2020]. Although OR techniques, linear programming, metaheuristics, and discrete-event simulation are tools to enhance the range of UHC scheduling and radiology modelling [Ala et al., 2021], [Chen et al., 2022], [Vieira et al., 2021], they have not been applied extensively to industrial radiography. This paper fills this gap using an optimisation dose objective based on OR.

2. Literature Review

The radiation dose optimization has emerged as an increasing field of concern in the medical and industrial fields. The European ALARA Network places emphasis on the prerequisites of realistic optimization strategies that are not limited to qualitative types of recommendations, but advanced planned tools of dose reduction [4]. In their turn, the ICRP identifies the problems of radiological protection in digital imaging and suggests more organized optimization schemes [ICRP PUBLICATION, 2023]. It is shown in several works that simulation methods, namely Monte Carlo methods, are accurate methods for modeling radiation transport and predicting dose in complex environments [Guembou et al., 2022], [Lee et al., 2024], [Moon et al., 2024].

The use of OR in radiation safety has increased tremendously. Ala et al. optimized the healthcare appointment systems with metaheuristic algorithms, which enhance fairness and efficiency [Ala et al., 2021]. Vieira et al. have proved that the use of OR can radically enhance the quality of scheduling at radiotherapy centers [Vieira et al., 2021]. Chen et al. used simulation-optimization in augmenting ultrasound workflow scheduling and room allocation [Chen et al., 2022]. The approaches are aligned with the radiographic setting where the complexity in scheduling and dynamic demand would affect overall dose and efficiency.

A study by Joel et al. investigated factors of shielding and layout in radiography plants in the industry, highlighting the role of geometry, which shapes the dose to the worker [Joel et al., 2019]. Moon et al. proposed a new system of Monte Carlo dose calculations to assist in emergency source retrieval scenarios. They demonstrated that high-fidelity modeling can be useful in the context of radiographic safety [Moon et al., 2024]. Combined, these publications confirm the effectiveness and need for the combination of OR and simulation in terms of a significant dose reduction during field radiography.

3. Methodology

This study formulates a linear programming model to reduce the number of technicians and ensure that the job is completed on time. These factors include technician assignment, workload allocation, exposure limits, and shift limits as a part of the model.

3.1 Linear Programming Model

Let:

- *i* = technician
- *j* = job
- *D*_j = dose rate for job *j* (mSv/hr)
- *T*_j = required duration of job *j*
- *t*_{ij} = time technician *i* spends on job *j*
- *E*_{max,i} = maximum allowable dose per technician
- *S*_i = maximum working hours per shift

Objective Function

Minimize $Z = \Sigma_i \Sigma_j (D_j * t_{ij})$

Constraints

1. Job Completion:

$\Sigma_i t_{ij} = T_j \; \forall j$

2. Technician Dose Limit:

$\Sigma_j (D_j * t_{ij}) \leq E_{max,i} \; \forall i$

3. Shift Duration:

$\Sigma_j t_{ij} \leq S_i \; \forall i$

4. Logical Assignment Constraint:

$t_{ij} = 0$ if technician i is not assigned to job j

3.2 Monte Carlo Simulation

A Monte Carlo model was carried out to take into consideration the variability in dose rates as a result of scatter, geometry, and environmental factors. Dose rates were allowed to vary by ±15%:

$D'_j = D_j (1 + X)$ Where $X \sim N(0, 0.15)$

Ten thousand simulation iterations ensured the robustness of the optimized schedule.

4. Case Study and Results

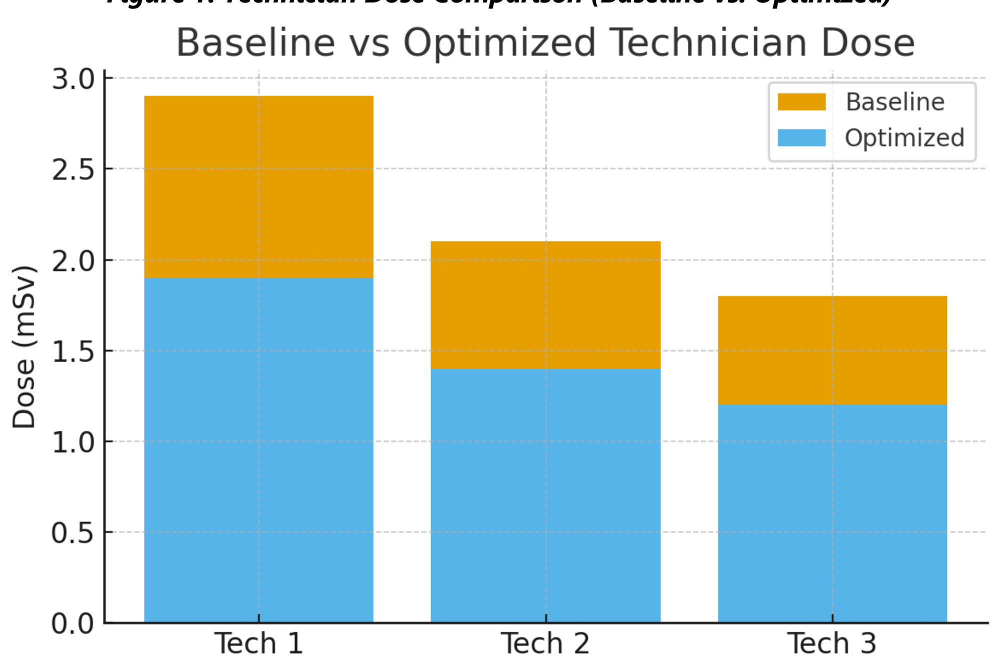
To test the performance of the model, a simulated industrial radiography operation where ten jobs with three technicians were considered was evaluated. Dose rate was between 0.2 mSv/h and 1.1 m Sv/h, and hours of work were between 0.5 and 2 hours. The situation was the case of manual scheduling that was common in field practice.

Table 1. Baseline vs. Optimized Metrics

Metric	Baseline	Optimized	Improvement
Total dose (mSv)	6.8	5.1	−25%
Highest Individual Dose (mSv)	2.9	1.9	−34%
Total Duration (hrs)	19.4	16.5	−15%

Time management is basically the reduction in dose and improved time-effectiveness. There was no centralization of tasks for technicians to perform.

Figure 1. Technician Dose Comparison (Baseline vs. Optimized)



This figure demonstrates the reduced dose among all technicians, which is more just and adheres to the alternatives of ALARA.

5. Discussion

The study has already proven that the quantitative optimization has a significant influence on the radiation protection practice in the industrial radiography sector. The model has significantly reduced the quantity of dose accumulated, as well as the quantity of dose administered by each technician via a combination of linear programming and Monte Carlo simulation. The enhancement meets well with the international standards of operational radiation protection systems, especially those presented by the IAEA and the NCRP, which have a formal, quantitative methodology for applying the ALARA concepts to practice [International Atomic Energy Agency, 2018], [National Council on Radiation Protection and Measurements, 2015]. The fact that the highest individual dose decreased by 34 % is particularly interesting since dose concentration among individual technicians is considered to be one of the risk factors involved in occupational overexposure.

The strength of the optimized schedule in different conditions of scatter and geometry is supported by the Monte Carlo study, which is reiterated in the literature of the past, showing the importance of stochastic modeling in dose estimation and risk management of radiology [Guembou et al., 2022], [Lee, et al., 2024], [Moon, et al., 2024]. These results also correspond to successful OR implementation in clinical practice, where optimization of the schedule has also been demonstrated to enhance safety and efficiency of operations [Ala et al., 2021], [Chen et al., 2022], [Vieira et al., 2021]—industrial radiography gains such benefits in terms of less idle time, fewer bottlenecks, and predictable workflow.

Nonetheless, several restrictions should be admitted. The model assumes the technician's competency to be equal, whereas in the real world, the crew can vary in terms of experience, speed, or the level of certification. The same can be said of the other kinds of logistic consideration that may affect dose distribution, schedule achievability, such as travel time between discharging position/re-shoot position, ease of site access, or time. What is more, multi-site or multi-source operations are not reflected in the existing model since they occur in large-scale projects. These shortcomings suggest potential improvements in the future, such as the optimization of multifunctional, real-time dosimetry and adaptive organizational structure.

6. Conclusion

This study illustrates the fact that occupational radiation protection of industrial radiography operations can be greatly enhanced by linear programming and Monte Carlo simulation. The proposed model will offer an effective, quantitative implementation of the principles of ALARA by reducing collective and individual dosage levels and enhancing efficiency. Multi-objective optimization, multi-site scheduling, multi-objective optimization-based dosimetry feedback, and multi-site database in conjunction with AI-based dose predictivity may also be incorporated into future work.

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