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ORIGINAL ARTICLE

Managing the patient portfolio using mathematical programming: decision support guidelines using a real-world use case at a university hospital

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Abstract
Many hospitals in Germany are facing escalating economic pressures. After several years of stagnation, the number of inpatient hospital treatments dropped by 13% in 2020 compared to the previous year. This negative tendency can also be seen in operating theaters (OTs). Strategic management of the case mix in hospital OTs now necessitates a solid data foundation. The case mix and the case mix index have become central economic indicators in contemporary hospital operations. In this work, we develop a mathematical model for case mix optimization at Augsburg University Hospital in Germany, which is based on an extensive data analysis with descriptive methods. The optimization model is subject to rigorous testing and evaluation through an extensive series of scenario analyses. The primary objective is to calculate a revenue-maximizing patient mix while respecting the available scarce personnel resources in the OT and intensive care unit. This research marks a pioneering effort in delineating the practical integration of case mix planning into a hospital's routine operations using mathematical optimization. The analyses reveal a strong correlation between an upsurge in revenue and an increased number of cases. Furthermore, the results demonstrate that strategic planning of the patient mix has the potential to enhance revenue with existing resources. Even though the optimal patient mix may not be directly implementable in practice, the findings yield valuable insights for managerial decision-making. A critical examination of these results also fosters a nuanced discourse on the utilization of optimization models as decision support tools within hospital management.

Keywords Case mix · Mathematical optimization · OT planning · Hospital · Decision support

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1 Introduction

Numerous hospitals in Germany are facing increased economic pressure. After years of stagnation, the number of inpatient hospital treatments declined by 13% in 2020 compared to the previous year, primarily due to the COVID-19 pandemic. Similarly, the total number of surgeries performed dropped by 10% to 6.4 million (Statistisches Bundesamt 2021). Furthermore, the growing shortage of medical professionals poses an increasingly daunting challenge for German hospital management (Osterloh 2018). Quantitative Operations Research/Management Science (OR/MS) methods offer a potential solution to support hospital management in dealing with these complex issues.

Active strategic management of the service portfolio, commonly referred to as case mix, can help hospitals maintain a sustainable and economically viable service offering despite stagnant case numbers and limited (personnel) resources. The key challenge lies in identifying the optimal mix and volumes of patient categories, a complex planning task known as the case mix planning problem (CMPP) (Hof et al. 2017). The core of the CMPP is the optimal allocation of scarce resources (e.g., operating theater (OT) capacity) to strategically manage the case mix. The basic objective of strategic case mix planning is to fulfill the service mandate, increase the quality of care, and/or maximize (personnel) revenue (Hof et al. 2017; Waeschle et al. 2016). The specific planning objectives vary depending on the management perspective guiding the strategic control of the service portfolio.

This paper examines the application of quantitative OR/MS methods for strategic service portfolio planning. Alongside in-depth analyses, the paper delves into the potential and limitations of applying these methods in real hospital practice. The insights gained are illustrated using the Augsburg University Hospital (UKA) as a practical case study. OR/MS is an interdisciplinary field concerned with developing and applying mathematical optimization models for decision support (Hulshof et al. 2012; van Wassenhove and Besiou 2013). In healthcare, OR/MS models and methods find diverse applications across various complex planning problems, including OT planning, shift scheduling, or service range planning (Erhard et al. 2018; Heider et al. 2022; Hof et al. 2017).

Given the predominantly isolated consideration of surgical hospitals, making a universally applicable statement about resource allocation within a hospital is challenging. This study addresses this issue by systematically comparing personnel expenses and revenues for the entire hospital. Assuming that OT and intensive care unit (ICU) capacities remain relatively stable in the short to medium term, the optimized increase or reduction of specific surgery types and the distribution of available OT resources provide a redistribution of the surgical service portfolio. From a strategic management perspective, the results may signal the need to selectively reduce less profitable surgeries over the medium to long term. However, it should be noted that such reduction measures would require external cooperation, such as transferring patients to other hospitals as part of a cooperation model, while controlling patient inflow via referring parties.

To implement CMPP through mathematical optimization models at the operational level, revenues generated from inpatient surgeries can be allocated to corresponding cost categories, including personnel, material costs, and infrastructure, based on the *Institut für das Entgeltsystem im Krankenhaus* (InEK) matrix (Deutsche Krankenhausgesellschaft et al. 2016). Hospital information systems' OT control tools, commonly used in practice, facilitate the comparison of directly assignable personnel expenses with these revenues. Through this data preparation and analysis, along with the help of optimization techniques, it becomes feasible to quantify the extent to which personnel expenses are covered by the revenues for various surgery types. These results can be calculated both for individual surgical departments and aggregated across the entire hospital.

The purpose of this work is to introduce a mathematical optimization method that incorporates case mix planning seamlessly into the daily operation of hospitals and to develop decision support guidelines based on a use case at a university hospital.

Our work is structured as follows. In Sect. 2, we introduce our case study and data, while Sect. 3 outlines our case mix optimization method. In Sect. 4, we provide the computational analysis results at the UKA. A discussion of the findings and decision support guidelines is provided in Sect. 5. Section 6 includes a summary and an outlook to future research.

2 Introducing the case study and data

The model is built on a dataset comprising 22,657 cases encompassing 2,100 distinct surgery types. Various data cleaning steps were implemented to enhance patient flow control. The greater objective of this refinement process is to ensure greater efficiency. An overview of the data preparation process is presented in Fig. 1. Given the existence of numerous surgery types with minimal occurrences in the reference year, these types underwent categorization using an ABC analysis. For the further course of the study, solely surgery types falling within the A group are utilized. This group encompasses all surgery types that collectively represent 80% of case numbers, ordered in descending order of frequency. Consequently, $15{,}609$ cases and 433 surgery types are included in the analysis. The determination of available scarce resources is then carried out based on the considered cases, as outlined in Sect. 2. A total of 12 different departments are considered.

3 Developing a simple mathematical model formulation for the CMPP

The strategic management of the patient mix presents itself as a mathematical optimization challenge, with a detailed model provided below. The primary objective of case mix optimization is to ensure an economical service portfolio in the long term while increasing the quality of care. The framework for these decisions is shaped by the available resources, demand, and the hospital's care mandate.

Strategic case mix management operates on an aggregate annual basis, considering both resources and case numbers. Although Diagnosis-Related Groups (DRG) serve as a suitable classification system for retrospective analysis of the case mix,

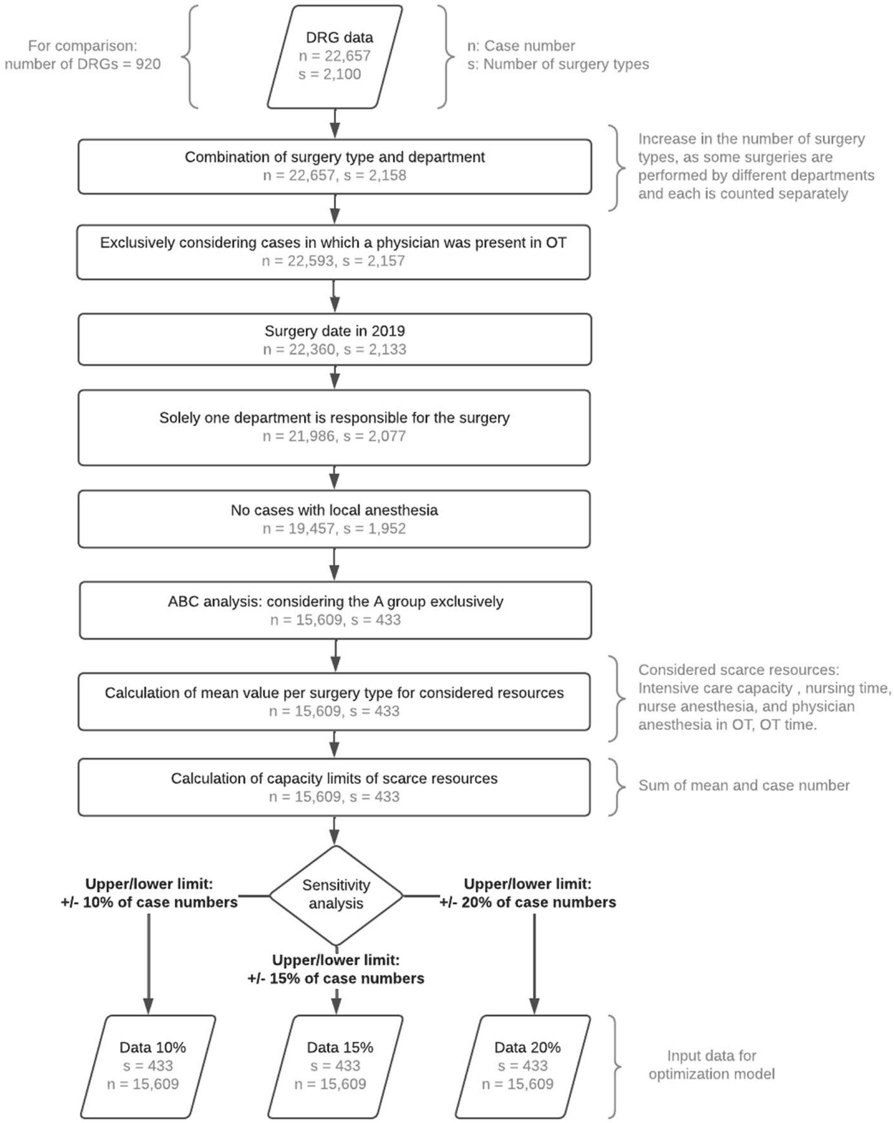

Fig. 1 Data preparation for the model

they prove unsuitable for actively managing the service portfolio (Salge and Vera 2012). This is because assigning a surgery to a DRG group typically occurs retrospectively, and practical portfolio management based on DRG groups is challenging. Consequently, patient groups are characterized for optimization purposes using the surgery types commonly employed in internal surgical planning. These in-house surgery types, numbering more than $2{,}000$, effectively capture the treatment intent. Examples of the surgery types are reimplantation of a pacemaker, lung resection and pulmonary resection. The reimbursement, resource demands, and costs associated with patients in a surgery type are estimated based on the relative distribution of DRGs within that surgery type.

In our study, we focus on maximizing the revenue generated from staffing. From the hospital's perspective, material and infrastructure costs, often referred to as throughput costs, are considered temporary, and maximizing revenue or case mix points does not necessarily increase contribution margin. The rationale for this is that material and infrastructure costs can fluctuate in response to changes in patient demand and operational procedures, and are frequently adjusted to accommodate short-term requirements. Furthermore, certain medical procedures are associated with exceptionally high material costs (e.g. cochlear implants), which can distort the overall cost analysis if not carefully considered. In contrast, personnel costs have a significant impact on overall expenditure and are more stable over time (Statistisches Bundesamt 2023). Personnel revenue is determined based on the proportionate personnel revenue according to the InEK cost calculation as pursuant to Section 17b (5) KHG (Hospital Care Act) and the state prime rate. In the next step, the personnel revenue per surgery type is estimated based on the historical relative distribution of DRGs within each surgery type. The optimization of the case mix, as well as for the personnel revenue model, operates within the constraints defined by scarce resources. These resources encompass OT nursing, OT anesthesia nursing, OT physician anesthesia, OT time, and ICU staffing capacity. In this context, surgeon time is not considered a scarce resource because allocating personnel resources for the OT always takes precedence for surgeons, with other tasks outside the OT considered lower in priority. The capacity allocated per resource for a patient is approximated by the respective mean value of the observed resource commitments per surgery type. Furthermore, the available capacity per resource during the observation period, in this case, a calendar year, is determined. The sum of case numbers per surgery type and the previously determined committed capacity per surgery type is calculated for each scarce resource. This is based on the observation that scarce resources have not experienced significant idle times during the observation period.

In addition to resource constraints, upper and lower limits on the number of patients per surgery type define the framework within which the case mix can be optimized. Upper limits are typically determined by demand, while lower limits are influenced by both the hospital's service mandate and the need for quality assurance in services where treatment outcomes depend on service volume. For individual services, the lower limits are predefined based on the minimum quantity regulation pursuant to Section 136b (1) Sentence 1 Number 2 German Social Code V (SGB V).

The described situation can be depicted using a mathematical CMPP model. Table 1 defines the sets, indices, parameter, and decision variables.

The deterministic mathematical model contains an objective function with three constraints, and it can be formulated as follows.

$$Max \quad \sum_{s \in S} p_s \cdot X_s \tag{1}$$

Table 1 Sets, indices, parameter, and decision variables

Sets and indices	
$s \in S$	Set of surgery types
$r \in R$	Set of resource types
Parameter	
p_s	Average personnel revenue per surgery with surgery type s
d_{rs}	Average resource requirement per surgery per resource type r and surgery type s
u_s	Case upper limit per surgery type s
l_s	Case lower limit per surgery type s
c_r	Capacity limit per resource r
Decision variable	
X_s	Case number per surgery type s

$$s.t. \quad \sum_{s \in S} d_{rs} \cdot X_s \leq c_r \quad \forall\ r \in R \tag{2}$$

$$X_s \leq u_s \quad \forall\ s \in S \tag{3}$$

$$X_s \geq l_s \quad \forall\ s \in S \tag{4}$$

$$x_s \geq 0 \quad \forall\ s \in S \tag{5}$$

The objective function (1) maximizes the total product of (proportionate) personnel revenue and the number of cases per surgery type. This optimization is aimed at maximizing personnel revenue across all departments. Constraints (2) guarantee compliance with capacity limits per resource type, preventing any deviation in the case mix from causing the defined scarce resources to exceed their available capacities. Constraints (3) and (4) set upper and lower limits on the resulting number of cases for each surgery type. It is also possible to define individual limits for each surgery type if the necessary data is accessible. Constraints (5) are the non-negativity constraints.

4 Solving the CMPP at Augsburg University Hospital

This section discusses the results of the case study described in Sect. 2. It considers three scenarios involving potential deviation of 10%, 15%, and 20% from the case numbers of the reference year. In our model, these percentages of 10%, 15%, and 20% are represented by the upper and lower limits u_s and l_s. For example, in the 10% scenario, the number of cases per surgery type can vary between 90% and 110% of the number of cases in the reference year. In other words, any number of cases between these two limits can be realized if the hospital plans for it. For example, if a surgery type originally has a case number of 505, the lower limit in the 10% scenario is 454, and the upper limit is 556. This means that any case number between 454 and 556 can theoretically be realized for this surgery type. The model selects the number of cases that is most profitable according to the objective function. A distinction is made between personnel revenue, proportionate revenue, and case mix.

4.1 Personnel revenue

Figure 2 illustrates that the application of the optimization model yields higher values for both the overall number of cases to be treated and personnel revenue in all three scenarios when compared to the current status. Depending on the specific scenario, the increase in total personnel revenue ranges from $+2.3\%$ and $+4.5\%$, while the total number of cases increases by a margin of $+3.4\%$ and $+6.7\%$, across the scenarios, all while maintaining the same or lower capacity utilization when compared to the reference year's values.

An increase in the total number of cases and personnel revenue does not necessarily translate to an increase for each department. Figure 3 shows the relative changes in the number of cases and personnel revenue per department in the 10%scenario. While most departments experience growth in both case numbers and personnel revenue, there are also departments where, from an overall optimization perspective, it would be more economically sound to reduce case numbers and personnel revenue. One of the primary factors contributing to these reductions is the elevated material costs associated with surgeries at these departments. Although material costs positively impact case mix points per department, they represent solely temporary expenses not factored in this model. Another contributing factor is an unfavorable ratio of personnel revenue to committed capacity per scarce resource when compared to other types of surgeries. In the developed optimization model, this ratio per surgery type is assessed across departments and optimally employed with the objective of maximizing personnel revenue for the entire hospital.

Nonetheless, changes in both key metrics are not solely confined to increases or decreases. Considering department 10, for example, it would be possible to decrease the case numbers by adjusting the case mix without affecting the department's personnel revenue. A detailed overview of the evolution of personnel revenues per department can be found in the left part of Table 2. To enable the monitoring of the proposed changes at the department level, the results have been organized for each department and scenario $(10\%, 15\%, 20\%)$.

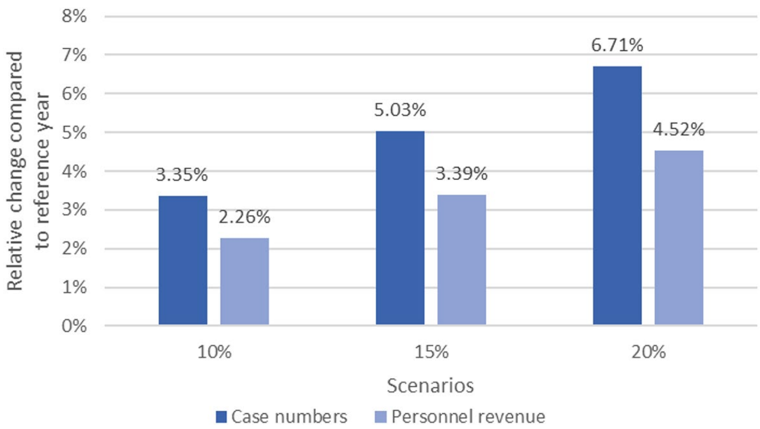

Fig. 2 Total relative change in number of cases and personnel revenue per scenario

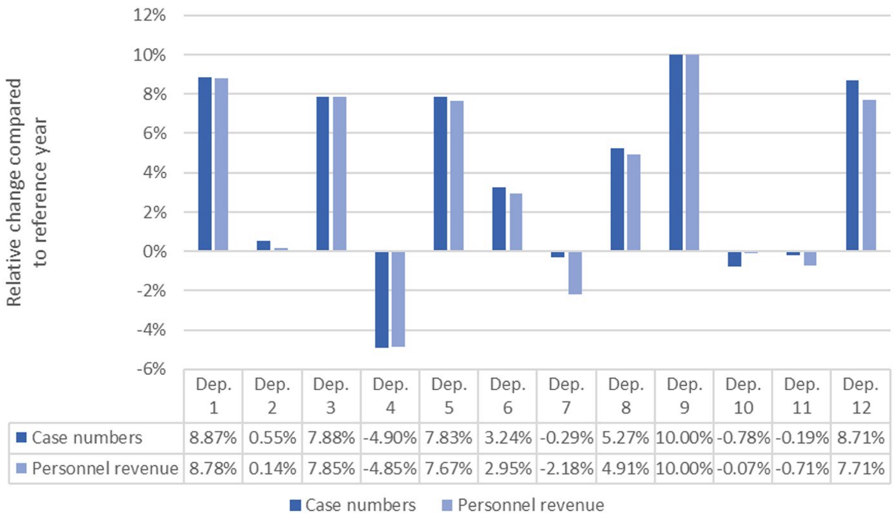

Fig. 3 Relative change in case numbers and personnel revenue per department in 10% scenario (Dep.: Department)

Table 2 Development of personnel revenue per department and scenario (personnel revenue model)

	Personnel revenue			Proportionate personnel revenue		
	±10%	±15%	±20%	±10%	±15%	±20%
Dep. 1	+8.78%	+13.17%	+17.56%	+8.45%	+12.67%	+16.90%
Dep. 2	+0.14%	+0.22%	+0.29%	–0.68%	–1.01%	–1.35%
Dep. 3	+7.85%	+11.77%	+15.69%	+7.78%	+11.68%	+15.57%
Dep. 4	–4.85%	–7.27%	–9.70%	–5.47%	–8.20%	–10.94%
Dep. 5	+7.67%	+11.50%	+15.34%	+6.57%	+9.85%	+13.13%
Dep. 6	+2.95%	+4.42%	+5.90%	+0.61%	+0.92%	+1.22%
Dep. 7	–2.18%	–3.27%	–4.36%	–3.73%	–5.60%	–7.47%
Dep. 8	+4.91%	+7.37%	+9.83%	+3.51%	+5.27%	+7.03%
Dep. 9	+10.00%	+15.00%	+20.00%	+10.00%	+15.00%	+20.00%
Dep. 10	–0.07%	–0.10%	–0.14%	–0.70%	–1.04%	–1.39%
Dep. 11	–0.71%	–1.07%	–1.42%	–1.52%	–2.27%	–3.03%
Dep. 12	+7.71%	+11.56%	+15.41%	+5.09%	+7.63%	+10.17%
Total	**+2.26%**	**+3.39%**	**+4.52%**	**+0.32%**	**+0.47%**	**+0.63%**

Figure 4 presents an excerpt of the outcomes provided to the respective department, using one department as an illustrative example. In this representation, both the various scenarios and the different surgery types are displayed. For each type of surgery, it is evident whether there should be an increase or decrease in the number of cases within the department. For example, personnel revenue is more advantageous to have a higher number of pacemakers implanted in the department than in the reference year. Thus, it is apparent that for each scenario and each department, a customized decision is made regarding the ideal case mix. The model optimally adjusts the number of cases per surgery type to either the upper or lower limit (i.e. either exactly

	10% Case number: -0.29% Revenue: -2.18%		15% Case number: -0.44% Revenue: -3.27%	
	Surgery type	**Perc.**	**Surgery type**	**Perc.**
1	;[HLM, coronary surgery];	-10%	;[Pacemaker, reimplantation];	15%
2	;[Pacemaker, reimplantation];	10%	;[HLM, coronary surgery];	-15%
3	;[Pulmonary resection, atypical, VATS];	10%	;[Pulmonary resection, atypical, VATS];	15%
4	;[Pleura, effusion, VATS];	10%	;[Pleura, effusion, VATS];	15%
5	;[Pacemaker, change (without intervention on probes)];	10%	;[Pacemaker, change (without intervention on probes)];	15%
6	;[ICD, reimplantation];	10%	;[ICD, reimplantation];	15%
7	;[TAVI,transfemoral];	-10%	;[TAVI,transfemoral];	-15%
8	;[HLM, valve surgery, aortic valve];	-10%	;[HLM, valve surgery, aortic valve];	-15%
9	;[Pacemaker, ICD, probe revision];	-10%	;[Pulmonary resection, lobectomy, VATS];	15%
10	;[Pulmonary resection, lobectomy, VATS];	10%	;[Pacemaker, ICD, probe revision];	-15%
11	;[HLM, valve surgery, mitral valve];	-10%	;[HLM, coronary surgery and valve surgery (aortic valve)];	15%
12	;[HLM, coronary surgery and valve surgery (aortic valve)];	10%	;[HLM, valve surgery, mitral valve];	-15%
13	;[Anesthesia for transcatheter aortic valve implantation transfemoral (1MD)];	-10%	;[Chest wall, stabilization, combined VATS+open];	15%
14	;[Pleura, pleurectomie-decortication, VATS];	-10%	;[Anesthesia for transcatheter aortic valve implantation transfemoral (1MD)];	-15%
15	;[Chest wall, stabilization, combined VATS+open];	10%	;[Pleura, pleurectomie-decortication, VATS];	-15%
16	;[ICD, CRT, change (without intervention on probes)];	-10%	;[ICD, CRT, change (without intervention on probes)];	-15%
17	;[Lung resection, lobectomy, open];	-10%	;[Lung resection, lobectomy, open];	-15%
18	;[CRT, reimplantation];	-10%	;[CRT, reimplantation];	-15%

Fig. 4 Exemplary output for a department based on the optimized personnel revenue (10% and 15% scenario)

$+10\%$ or -10%, as in Fig. 4, for example). This decision-making process is driven by the economic viability of each surgery type. When it is financially advantageous, the model maximizes the number of cases for the most profitable surgery types; otherwise, it minimizes them. Such a strategy ensures that resources are allocated in a manner that maximizes personnel revenue while adhering to capacity constraints.

4.2 Proportionate personnel revenue

In addition to the previously outlined objective function, a further analysis aimed to maximize only the personnel revenue of the medical and functional services within the OT and anesthesia area. This analysis was conducted using the same dataset, with the only difference being that the personnel revenue per surgery type was substituted with the proportional personnel revenue of the aforementioned areas. Similarly, three scenarios involving 10%, 15%, and 20% permissible deviation in case numbers per surgery type were examined in this context. The rationale behind the second analysis relates to the significant cost factor associated with OT during a patient's overall stay and the limited availability of qualified personnel resources in this domain. Depending on the type of surgery, approximately one-third of the costs and revenues are generated in a matter of hours. The remaining costs and revenues extend over several days in the ICU or general ward. While individual cases may yield differing results between the two analyses, the overall trends are quite similar. The outcomes of the second analysis are detailed in Table 3.

In both analyses, the impact on the other objective function was also assessed, as evidenced in Tables 2 and 3. This facilitates a transparent comparison between the two objectives. Additionally, decision-makers were provided with additional key metrics not directly incorporated into the model but influenced by the model's solution. These metrics include the expected length of stay in general wards, which can vary depending on the chosen solution.

4.3 Case mix

In a third analysis, a conventional case mix optimization was conducted using the developed model. Similar to the proportional personnel revenue model, the only modification made was to replace the target weights. In this case the target weights are replaced with the average total revenue per surgery type, derived from the DRG flat rates per case. When considering personnel revenue, proportional personnel revenue, and case mix in the 10% scenario, the results depicted in Fig. 5 were generated.

As seen in the above figures, the relative variations in key metrics are displayed and compared against the reference year. It is evident that in each respective model, the key metric being optimized demonstrates the most significant relative change. Upon examining the target metrics, it becomes apparent that the case mix also exhibits the second-largest percentage change in the two personnel revenue models. Importantly, all considered metrics exhibit exclusively positive changes across all models. The case mix model achieves the most substantial relative change, with a 2.64% increase in case mix. The potential reasons for this increase in the case mix model are multifaceted. Firstly, it is possible that exclusive control of surgeries with regard to the case mix parameter has not been conducted in the past. Additionally, the

Table 3 Development of personnel revenue per department and scenario (proportionate personnel revenue model)

	Personnel revenue			Proportionate personnel revenue		
	10%	15%	20%	10%	15%	20%
Dep. 1	−2.56%	−3.84%	−5.12%	−0.21%	−0.32%	−0.43%
Dep. 2	−1.00%	−1.50%	−2.00%	0.00%	0.00%	0.00%
Dep. 3	+4.37%	+6.55%	+8.73%	+5.30%	+7.95%	+10.60%
Dep. 4	−5.03%	−7.54%	−10.05%	−4.66%	−6.99%	−9.32%
Dep. 5	+3.49%	+5.23%	+6.97%	+3.74%	+5.61%	+7.48%
Dep. 6	−3.31%	−4.96%	−6.61%	−0.79%	−1.19%	−1.59%
Dep. 7	+3.46%	+5.18%	+6.91%	+5.07%	+7.60%	+10.14%
Dep. 8	−3.47%	−5.21%	−6.94%	−0.88%	−1.32%	−1.76%
Dep. 9	+4.30%	+6.44%	+8.59%	+5.34%	+8.01%	+10.68%
Dep. 10	−0.75%	−1.12%	−1.49%	−0.57%	−0.86%	−1.14%
Dep. 11	+3.04%	+4.56%	+6.07%	+3.39%	+5.09%	+6.78%
Dep. 12	+1.12%	+1.68%	+2.24%	+3.72%	+5.59%	+7.45%
Total	**+0.46%**	**+0.69%**	**+0.91%**	**+1.67%**	**+2.50%**	**+3.34%**

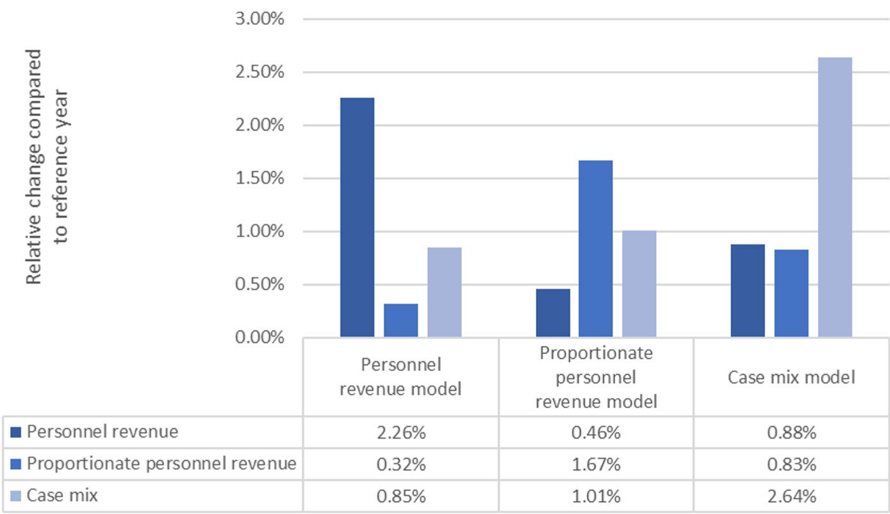

Fig. 5 Relative change in total and proportionate personnel revenue and case mix (10% scenario)

availability of such a comprehensive dataset for further analysis and optimization has been unprecedented until now.

5 Discussion

The results were practically implemented at UKA and subjected to analysis with various stakeholders to assess their informativeness and control possibilities. Based on these analyses, both the calculation basis and the mathematical optimization model were iteratively refined.

The case mix, along with the case mix index, serves as a central metric for controlling budget planning in individual departments within a hospital. Both indicators provide transparent comparability within a hospital and across different hospitals. For example, university hospitals typically exhibit a higher average case severity (case mix index) compared to smaller hospitals. In practice, and in some models discussed in the literature, it is often simplistically assumed that maximizing revenue is a suitable objective for hospital economic management due to the substantial portion of fixed costs in hospitals (Fügener 2015; Gupta 2007). However, a drawback of this approach is that per-case payments encompass non-personnel costs, which are essential pass-through costs for hospitals. Maximizing case mix alone can favor hospitals and surgeries with high non-personnel costs, inflating revenue without a corresponding increase in contribution margin. To counteract these distortions, the developed model maximizes personnel revenue to cover personnel costs, focusing on contribution margins rather than just case mix. Due to the model's generic structure, the target can be easily tailored to specific needs, as shown in Sect. 3. The ongoing debate in recent months on reforming or eliminating the fee-per-case system (Deutscher Ärzteverlag GmbH, Redaktion Deutsches Ärzteblatt 2022) underscores the necessity for such flexibility in surgeries.

Examining personnel revenues in isolation also allows for the identification of surgeries, such as those in cardiac surgery, that may initially seem profitable due to high total revenues but lose their profitability when material costs are excluded. This can lead to cooperative arrangements in which pacemaker implantations are performed in hospitals with cooperation partners, deliberately reducing capacities for TAVI surgeries. Notably, the fact that high material requirements do not necessarily lead to lower personnel revenues can be observed in vascular surgery, where complex endovascular surgeries also yield substantial personnel revenues. However, as the ranking of all surgeries by profitability in terms of personnel revenues relates to the entire surgical portfolio of all departments, the results and evaluations provided as examples for each hospital should be viewed with consideration for the entire service portfolio.

The described model inherently addresses the objectives of enhancing the quality of care and treatment. Although the weighting of cases based on personnel revenues can provide a rough indication of prioritizing severe cases, leading to improved quality of care, it is crucial to remember that the valuation ratios, cost, and revenue allocations in the DRG system primarily describe economic expenses, not the medical significance or case severity of treatment. The introduction of explicit lower limits in the model can ensure that the hospital's care mission is adequately covered. The values derived from the models cannot be directly implemented in practice. One reason for this is that our current model is deterministic, which simplifies the optimization process but does not fully capture the variability in real-world data. High variance within certain surgery types could significantly impact the results (McRae and Brunner 2020). The selected scenarios of $10\%, 15\%$, and 20% represent a potential solution to this limitation, as they allow for relative changes in case numbers relating to all surgery types. For increased significance, one would have to determine the maximum available demand as well as the maximum potential reduction per surgery type. These values do not have to be symmetrical and can be represented in the model. In practice, however, gathering such data can be challenging, and, in some cases, associations may exist across case groups. Furthermore, optimal values of the algorithm are only found at the extreme points of the solution space. This explains the continuous increase or reduction of all surgeries up to the allowable maximum in all scenarios, as can be seen in Fig. 4. Nevertheless, the developed model provides a more nuanced perspective on generated revenues and committed personnel at each department at a strategic level, facilitating comparisons.

Numerous factors must be taken into account in case mix planning. The optimization model developed, and the results obtained represent an additional factor for chief physicians to assess whether specific types of surgeries contribute to increased personnel revenue. Hospital boards can also use these results to determine the allocation of capacity to different departments within the hospital. Again, a multifaceted perspective is essential, and the developed optimization model is just one facet among many. It is important to note that case mix optimization has its advantages and disadvantages. By applying case mix optimization, the benefits of the DRG system can be utilized to ensure efficient and transparent billing of services, optimize resource utilization, and promote competition among facilities. Modeling various scenarios also allows for a better understanding of potential impacts of policy changes or new reimbursement systems. However, challenges such as distortions in billing due to incentives for profit maximization, neglect of quality aspects, and the complexity of models and data requirements can hinder effective implementation (Hof et al. 2017). Additionally, ethical concerns may arise regarding the prioritization of profitability over patient needs, even though current practice sometimes optimizes case mix points. Comparing with personnel revenue optimization shows that both approaches offer different pros and cons. While case mix optimization prioritizes patient care and treatment quality, personnel revenue optimization promotes financial transparency and efficiency. A balanced strategy considering both approaches could ensure optimal resource utilization and patient care.

The implementation of patient portfolio management also has implications for both patients and the healthcare system as a whole. The effects on patients may vary depending on the approach. In the case of case mix optimization, an overemphasis on cost efficiency could lead to a reduction in resources for complex cases, potentially compromising the quality of care (McRae et al. 2020). However, focusing on personnel revenue may enable faster treatment for patients as resources are utilized more efficiently. Nevertheless, there is a risk that emphasizing financial incentives may affect the quality of care. A balanced strategy is crucial to ensure that the needs and quality of patient care are adequately addressed. The overall impact on the healthcare system is multifaceted. Through the optimization of case mix or personnel revenue, efficiency gains can be achieved by more effective resource utilization, potentially leading to better capacity utilization and improved financial stability of hospitals. However, inadequately balanced incentives may compromise the quality of care and lead to undesirable behaviors, such as avoiding complex cases or those with high material costs. Additionally, such optimization strategies could impact social equity by limiting access to high-quality healthcare for certain population groups. It is important to consider the long-term effects on the efficiency, quality, and accessibility of the healthcare system to ensure that optimization measures improve overall healthcare delivery (Hof et al. 2017). These findings can already be leveraged by policymakers to prevent the avoidance of complex cases and to incorporate all significant costs through a combination of models, thus mitigating potential misaligned treatment incentives. Overall, policymakers can utilize optimization models to simulate and assess various scenarios, examining how different reimbursement structures affect hospital behavior and resource allocation, thereby identifying potential mismatches and inefficiencies (Hof et al. 2017). This facilitates informed adjustments to ensure that financial incentives promote equitable and efficient patient care. Furthermore, extending case mix optimization to cover all hospitals per state could significantly influence bed capacity planning at the regional level.

The case in Augsburg has highlighted that it is not the case mix, but rather the personnel revenue, that holds importance. Consequently, the emphasis is not on optimizing the case mix but rather on optimizing personnel revenue or proportionate personnel revenue. This analysis yields valuable decision support guidelines, offering a comprehensive perspective on operational management within the OT. Notably, the centrality of case mix in Germany's billing system underscores its significance, urging managers to prioritize understanding and optimizing this metric. The findings suggest that optimizing based on case mix may not always be the most suitable approach, while focusing on (proportionate) personnel revenue could offer a more viable alternative. Moreover, the widespread application of case mix across the nation provides a transparent basis for inter-hospital comparisons. Regular benchmarking against similar institutions emerges as a key strategy, facilitating the identification and implementation of potential improvements. The ongoing discourse surrounding the reform or elimination of the fee-per-case system emphasizes the imperative for flexible management models. Administrators are urged to be adaptable, adjusting economic targets in response to evolving industry practices and regulatory changes. Simple mathematical optimization models emerge as valuable tools in aiding such decisions, offering adaptability to specific situations. The inherent objective of the model is to enhance the quality of care and treatment, providing a guide for prioritizing serious cases. It is imperative for managers to recognize this function and strike a balance between economic considerations and maintaining high standards of care. Collaborative decision-making is underscored as significant, emphasizing the value of partnerships and collaborations to optimize resource utilization. Particularly in scenarios where material costs impact profitability, exploring cooperative arrangements becomes essential. Lastly, the provided results and assessments should be viewed within the broader context of the overall service portfolio. Managers are cautioned against isolated decision-making, encouraging them to consider the comprehensive impact on the entire hospital operation. In essence, these insights advocate for a strategic, adaptive, and collaborative approach in navigating the complexities of OT management.

6 Conclusion

This work introduces a mathematical optimization approach for incorporating case mix planning into the daily operations of hospitals. The findings demonstrate that revenue rises with an increase in case numbers. Additionally, strategic planning of the case mix has the potential to enhance revenue. In summary, the analysis offers valuable insights for medical decision-makers.

Future research has the potential to address these limitations by broadening the scope to encompass multiple hospitals in Germany. Furthermore, it could involve engaging with additional decision-makers to assess the applicability of the model. Regarding the mathematical model, future models could incorporate stochastic elements to account for variability and uncertainty, leading to more robust and reliable optimization outcomes. Moreover, future research could investigate the potential for case mix optimization across all hospitals in a state, with the objective of supporting bed capacity planning.

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Declarations

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