



Revenue Optimization in Higher Education under Price Dependent Demand: A Scholarship Allocation and Tuition Pricing Model

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ARTICLE INFO

Article history:

Received 28 June 2026
Received in revised form 11 September 2026
Accepted 6 October 2026
Available online 10 October 2026

Keywords:

Enrollment Management; Tuition Pricing;
Mixed-Integer Programming; Scholarship
Allocation; Revenue Optimization

ABSTRACT

Higher education institutions operate in increasingly competitive environments where student demand and institutional revenue are strongly influenced by scholarship policies and tuition fees. Under price-dependent demand, this study proposes an optimization framework for revenue management in colleges based on the optimal allocation of scholarship categories across multiple academic programs. Demand is modeled using piecewise-linear demand functions derived from observed price-demand data. The resulting model integrates capacity constraints, institutional scholarship policies, and demand elasticity within a mixed-integer optimization framework. Computational experiments using data from multiple academic programs demonstrate how tuition levels and scholarship allocation interact with demand elasticity to determine optimal enrollment and revenue outcomes. The proposed framework provides decision support for college administrators seeking to balance financial sustainability with student access objectives.

1. Introduction

Higher education institutions are increasingly competitive; therefore, pupil demand and institutional revenue are very much shaped by tuition prices and scholarship programs. Rising operating expenses and increasing rivalry among universities have caused institutions to look for more data-driven strategies for admissions management. Especially in this regard, scholarship distribution helps students access while also influencing financial sustainability.

Methods from the area of operations research offer a helpful structure for tackling such trade-offs. In sectors like airlines and hospitality, where constrained capacity must be distributed among clients with varying willingness to pay, these techniques have been successfully utilized. In greater education, where courses have set capacities and pupils react differently to tuition rates and financial aid options, similar difficulties develop.

Even with rising interest in quantitative enrollment management, most current techniques depend on heuristic decision-making or view student demand as homogeneous throughout academic disciplines. Though, universities provide several kinds of scholarships, including complete

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<https://doi.org/10.67334/cds31202642>

scholarships, partial scholarships, and full tuition placements, each linked with different demand behavior. Ignoring these variations can produce poor enrollment and financial results.

This study presents an optimization-based framework for enrollment management that maximizes institutional revenue by distributing pupils across scholar-ship categories, therefore resolving this disconnect. The suggested model considers several academic programs with limited capacity and integrates price-dependent demand functions developed from actual price–demand statistics. The framework also considers institutional rules mandating a minimum ratio of totally funded students.

The problem is formulated as a mixed-integer optimization model that integrates scholarship allocation decisions, program capacities, and demand constraints. By explicitly modeling the interaction between tuition pricing, scholarship policies, and demand behavior, the proposed framework provides a systematic decision-support tool for university administrators.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the mathematical model. Section 4 presents computational experiments and results. Finally, Section 6 concludes the paper and discusses directions for future research.

2. Literature Review

Revenue management has been widely studied in the operations research literature as a framework for allocating limited resources among heterogeneous customers with different willingness to pay. Revenue management started in the airline business, where seat inventory had to be split across different fare classes in the face of an unknown demand. Littlewood's [1] study, which first used the idea of safeguarding capacity for more lucrative clients, is a cornerstone in this field. Commonly referred to as Littlewood's rule, this idea started off several later improvements in models for revenue management.

Further investigation applied these concepts to dynamic pricing and inventory management under random demand. Gallego and Van Ryzin [2] showed that to maximize income, pricing and capacity allocation choices should be decided together for goods with limited capacity and price-sensitive demand, hence creating dynamic pricing models for such items. Later additions included network revenue management models, stochastic control, and dynamic demand learning to broaden revenue management systems. Talluri and Van Ryzin [3] and Phillips [4], who show mathematical models for pricing, capacity allocation, and demand forecasting in revenue management systems, offer thorough theoretical treatments of these techniques.

Originally designed for sectors like airlines, hospitality, and retail, revenue management approaches are now increasingly used in other industries with capacity limits and varied customer demand. Higher education establishments exhibit a number of these features: academic programs have set capacities; prospective students vary in their readiness and ability to pay tuition. Consequently, tuition pricing and financial help policies may be viewed as types of price differentiation akin to those seen in conventional revenue management situations.

For decades, economics literature has been looking at how colleges and universities set prices. Early studies by Jenny [5] and Rothschild and White [6] looked at the financial foundation of university pricing and resource distribution. They showed how selective scholarships and tuition cuts could be used as price discrimination tools to change student demand. Subsequent studies examining institutional income plans and resource distribution systems in colleges [7] expanded this perspective.

More recent research has focused particularly on financial aid policies, tuition costs, and tuition discounts as calculated approaches to draw more pupils to register. Ehrenberg [8] gives a complete analysis of the variables affecting rising tuition prices and the expanding function of institutional aid

in judging student demand. Hillman [9] and Parrott [10] investigate tuition discounting policies in a similar vein, exposing how colleges maintain net tuition income by using institutional scholarships and grants to regulate enrollment levels. Most people see these strategies as ways that colleges control their finances by varying the fees they levy on various student categories.

Yet another field of research examines strategic enrollment management and mathematical decision models. DesJardins and McCall [11] say that financial aid policies greatly influence student choices and the quantity of them enrolling. Aulck *et al.*, [12] suggests that under capacity constraints, early optimization-based techniques for college enrollment management can support admissions and financial aid decisions by means of mathematical programming.

Studies done recently have also looked at computer-based and data-driven ways to plan enrollment and allocate scholarships. Rebbapragada *et al.*, [13] explore the application of data mining and revenue management strategies in college admissions. Aulck *et al.*, [12] suggest using machine learning and genetic algorithms to maximize scholarship distribution to boost enrollment yield in a similar way. Highlighting the need of modeling student demand as a function of price and financial aid, Wang [14] extends mathematical optimization models for scholarship allocation.

Notwithstanding these developments, not many studies combine scholarship distribution, resource limitations, and price-dependent demand inside a single optimizing framework. Many current methods either view student demand as external or presume set scholarship structures, hence limiting the possibility to jointly maximize scholarship distribution and enrollment choices. More integrated models are required to reflect the relationship among pricing policies, financial aid policies, and institutional capacity limits, as recent studies on enrollment optimization and tuition discounting [15] emphasize.

By combining these aspects into a single optimization framework, the model presented in this research advances the body of knowledge. The suggested approach especially combines several academic programs, category-specific demand functions based on price-demand data, and institutional scholarship regulations requiring a minimum ratio of fully funded students. The framework offers a methodical way to find the best enrollment mix across scholarship types and maximize institutional income by using demand modelling with mixed-integer optimization.

3. Mathematical Model

The mathematical formulation of the suggested enrollment optimization model is given in this section. The goal of the model is to maximize the university's overall tuition revenue by finding the best distribution of students across scholarship categories for several academic programs. The model considers program capacities, scholarship policies, and price-dependent student demand. Including these components into a unified optimization framework helps the model to decide the ideal enrollment distribution throughout scholarship categories. In higher education systems, optimization techniques have already been used to solve issues with resource allocation and enrollment planning [16, 17].

3.1 Sets and Indices

The proposed enrollment optimization model considers a university offering multiple academic programs and several scholarship categories. Let D denote the set of academic programs offered by the university, where each program corresponds to a department or field of study with a fixed enrollment capacity. In addition, let S represent the set of scholarship categories available for student admissions. These categories correspond to different tuition payment levels and therefore generate different revenue contributions for the institution. In this study, three scholarship categories are considered: full scholarship (100% tuition waiver), partial scholarship (50% tuition discount), and full

tuition (no scholarship). Such tuition discounting mechanisms are commonly used by universities as pricing strategies to influence student demand and enrollment composition [18]. The index $d \in D$ is used to represent academic programs, while $s \in S$ denotes scholarship categories. These sets and indices define the structure of the enrollment allocation problem and allow the model to determine the optimal number of students admitted to each program under different scholarship categories.

3.2 Parameters

The model includes several parameters that describe program capacities, tuition levels, and demand conditions for each scholarship category. Let T_d denote the enrollment capacity of program d , representing the maximum number of students that can be admitted to that program [1, 19]. The parameter P_d represents the full tuition price associated with program d . The scholarship kind affects the real tuition price since students can enrol under many scholarship divisions. Particularly, full scholarship students don't pay any tuition; partly funded students pay half of the tuition price; full tuition students pay the whole tuition amount [9].

The function $D_{d,s}(p)$ reflects student demand; it indicates the demand for programme d under scholarship category s at tuition price p . Based on price–demand statistics [4, 18], this demand function illustrates how student demand varies with tuition levels.

Furthermore, the model uses an institutional policy variable to indicate the least ratio of fully financed students needed in every field of study. Representing university policies meant to guarantee accessibility and aid academically deserving students with financial need, γ marks this parameter. In this study, the value of this parameter is set to $\gamma = 0.05$, meaning that at least five percent of the seats in each program must be allocated to students receiving full scholarships.

3.3 Decision Variables

The decision variables represent the number of students admitted to each academic program under different scholarship categories. Let $x_{d,s}$ denote the number of students admitted to program d under scholarship category s , where $d \in D$ represents academic programs and $s \in S$ represents scholarship categories. These variables determine the enrollment composition across programs and scholarship types. Since the number of admitted students must be a non-negative integer, all decision variables are defined as integer and non-negative. The optimization model determines the optimal values of these variables in order to maximize total tuition revenue while satisfying program capacity constraints, demand limitations, and institutional scholarship policies.

Formally, the decision variable is defined as:

$$x_{d,s} \geq 0 \quad (1)$$

number of students admitted to program d under scholarship category s , where

$$d \in D, s \in S \quad (2)$$

and

$$x_{d,s} \in \mathbb{Z}_+ \quad (3)$$

3.4 Objective Function

The objective of the proposed optimization model is to maximize the total tuition revenue generated from student enrollments across all academic programs and scholarship categories. Since different scholarship categories correspond to different tuition payment levels, the revenue contribution of each admitted student depends on the scholarship type.

Let $r_{d,s}$ denote the tuition revenue obtained from admitting a student to program d under scholarship category s . The value of this parameter depends on the effective tuition paid by the student. Students receiving full scholarships do not generate tuition revenue, whereas partially funded students pay a reduced tuition amount and full tuition students pay the entire tuition fee. Accordingly, the revenue parameters for each scholarship category are defined as follows:

$$r_{d,100} = 0, r_{d,50} = 0.5P_d, r_{d,F} = P_d \quad (4)$$

where P_d represents the full tuition price of program d .

The objective function of the model can therefore be expressed as:

$$\max Z = \sum_{d \in D} \sum_{s \in S} r_{d,s} x_{d,s} \quad (5)$$

This objective function determines the optimal enrollment composition across programs and scholarship categories in order to maximize the total tuition revenue while satisfying the constraints of the model. Similar revenue-maximization formulations are commonly employed in admission and scholarship allocation models where institutions determine optimal financial aid and admission policies to balance enrollment demand and institutional revenue objectives [17, 18].

3.5 Capacity Constraints

Each academic program has a limited enrollment capacity that determines the maximum number of students that can be admitted. Therefore, the total number of students admitted to program d across all scholarship categories must not exceed the capacity of that program.

Formally, the capacity constraint is expressed as follows:

$$\sum_{s \in S} x_{d,s} \leq T_d \quad \forall d \in D \quad (6)$$

This constraint ensures that the total number of admitted students in each program does not exceed the available capacity.

3.6 Demand Constraints

Student demand for each scholarship category is limited and depends on the tuition level associated with that category. Therefore, the number of students admitted to program d under scholarship category s cannot exceed the corresponding demand.

Let $D_{d,s}(p)$ denote the demand for program d under scholarship category s at price p . The demand constraints are defined as follows:

$$x_{d,s} \leq D_{d,s}(p_{d,s}) \quad \forall d \in D, s \in S \quad (7)$$

where $p_{d,s}$ represents the effective tuition price associated with scholarship category s .

These constraints ensure that enrollment decisions remain consistent with the estimated demand for each scholarship category.

3.7 Minimum Scholarship Policy

Many universities implement institutional policies that require a minimum proportion of students in each program to receive full scholarships. Such policies aim to promote accessibility and support academically qualified students with financial need.

To incorporate this requirement into the model, a minimum scholarship constraint is introduced. Let γ denote the minimum proportion of students receiving full scholarships in each program. The constraint is defined as follows:

$$x_{d,100} \geq \gamma T_d \quad \forall d \in D \quad (8)$$

In this study, the value of the policy parameter is set to:

$$\gamma = 0.059 \quad (9)$$

which means that in every academic program, at least five percent of the seats must be reserved for completely funded students.

3.8 Demand Modeling

Enrollment optimization in higher education depends on an honest reflection of student demand. Tuition rates and financial aid availability affect student interest in academic courses. Demand related to each scholarship type can differ greatly as various categories match different effective tuition rates. Therefore, in order to record students' varied willingness to pay, modeling demand independently for every scholarship category is absolutely vital.

This study uses price–demand observations from historical enrollment data or market analysis to predict demand for every scholarship category and academic program. These data reveal the link between tuition rates and the quantity of pupils prepared to attend at those pricing points.

Let q_{dsk} stand for the corresponding observed demand and let p_{dsk} stand for the tuition pricing connected with observation k for program d under scholarship category s . For each program and scholarship category, a set of price–demand observations is available:

$$(p_{dsk}, q_{dsk}), k = 1, 2, \dots, K10 \quad (10)$$

where, p_{dsk} represents the observed tuition price level, q_{dsk} represents the corresponding demand.

These observations capture how demand changes as tuition prices vary. By collecting demand observations at multiple price points, it is possible to estimate the sensitivity of student demand to tuition levels.

To incorporate demand behavior into the optimization model while maintaining computational tractability, demand functions are represented using piecewise linear approximations. Piecewise linear demand functions provide a flexible way to approximate nonlinear relationships between tuition prices and student demand.

For two consecutive price–demand observations (p_{dsk}, q_{dsk}) and $(p_{ds(k+1)}, q_{ds(k+1)})$, demand is interpolated linearly as follows:

$$D_{d,s}(p) = q_{dsk} + \frac{q_{ds(k+1)} - q_{dsk}}{p_{ds(k+1)} - p_{dsk}} (p - p_{dsk}) \quad 11 \quad (11)$$

for

$$p_{dsk} \leq p \leq p_{ds(k+1)} \quad 12 \quad (12)$$

This formulation generates a continuous piecewise linear demand curve that approximates the relationship between tuition price and student demand.

Different scholarship categories correspond to different effective tuition levels and therefore exhibit distinct demand characteristics. In general, demand for fully funded scholarships is significantly higher than demand for partially funded or full tuition placements. This reflects the fact that fully funded opportunities attract a larger pool of applicants

The demand functions described above are integrated into the optimization model through demand constraints that limit the number of admitted students under each scholarship category. For each academic program, the model ensures that the number of admitted students does not exceed the estimated demand corresponding to the effective tuition level.

While keeping the linear form needed for effective mixed-integer optimization, this method lets the model capture the interaction among tuition pricing, scholarship distribution, and student demand.

4. Results

This section shows the computer simulations done to see how well the suggested enrollment optimization model works. Under capacity, demand, and policy restrictions, the aim of these tests is to show how the model maximizes institutional income while guiding the best distribution of students throughout scholarship categories. The computer simulations depend on a synthetic dataset meant to show a university with several academic courses. The university is believed in the studies to have 30 academic courses, each with 100 fixed-enrollment capacity. There are three scholarship tiers thought about for every program: complete scholarship (100% scholarship), partial scholarship (50% scholarship), complete tuition (no scholarship). P_d is used to represent the total cost of each program's tuition. While fully funded students pay no tuition, those partially supported pay half of the tuition fee. Students paying full tuition cover the total cost. Price–demand observations are used to create piecewise linear demand functions, which help estimate student demand for every scholarship category. These demand equations show how the number of pupils willing to register varies with the cost of tuition. With an Intel Core i7 CPU on a workstation, Gurobi Optimizer version 12.0 was used to solve the model. Given the somewhat limited model size, the solver could find the best solution nearly right away.

4.1 Revenue Distribution Across Programs

Figure. 1 illustrates the revenue generated by each academic program under the optimal solution. The results reveal that because of variations in demand for full tuition and partially financed students, revenue varies among programs. Programs with more full tuition students have considerably more income. For instance, the first several departments admit a relatively large number of full tuition students, resulting in higher program-level revenue. The model progressively raises the proportion of partially funded students to keep enrollment levels consistent as demand for entire tuition declines across programs. This pattern shows how the optimization model helps to strike a balance between revenue generation and practicality of enrolment. The model substitutes partially funded students to guarantee that program capacity stays completely used when demand for more costly students is low. The findings generally support the idea that variations in demand elasticity and willingness to pay are the main causes of income disparities among programs.

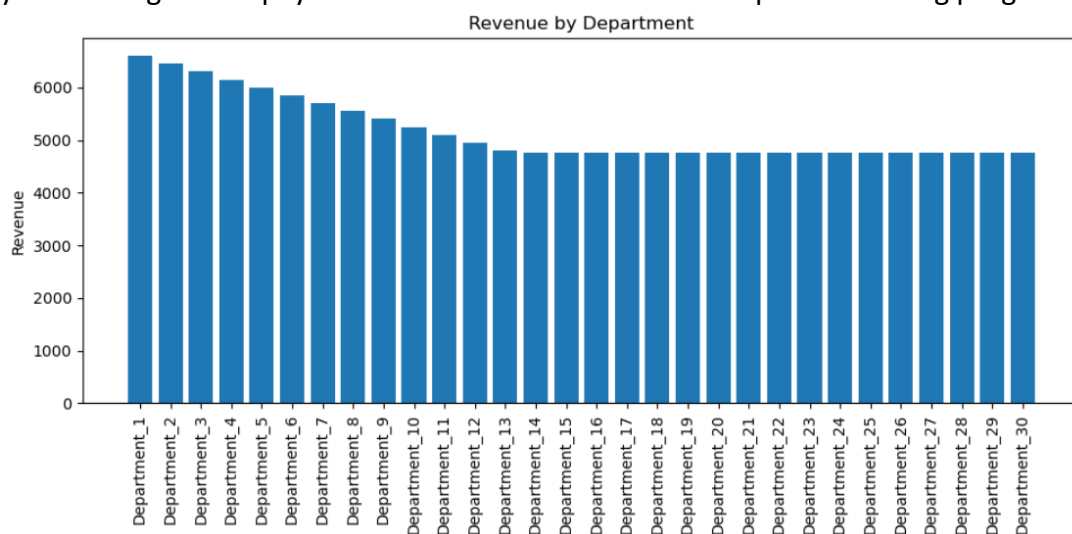


Fig. 1. Revenue generated by each academic program

4.2 Optimal Scholarship Composition

Figure 2 shows the best scholarship mix for every course of study. The chart depicts the division of students among the three scholarship categories: full scholarships (100%), partial scholarships (50%), and full tuition placements. Every program shows a consistent trend. Every program sets aside precisely five percent of its resources for full scholarships, therefore meeting the institutional policy need for a minimum proportion of fully supported students. Beyond this requirement, the remaining seats are distributed among full tuition and partially funded students depending on demand conditions. Programs with lower full tuition demand depend more significantly on partly sponsored students; those with greater demand for full tuition students accept a greater number of such students. This finding emphasizes a crucial management understanding: partly sponsored scholarships provide a flexible tool for keeping enrollment numbers up when full tuition demand isn't enough. The model guarantees full utilization of program capacity and income generation by varying the mix of scholarship types.

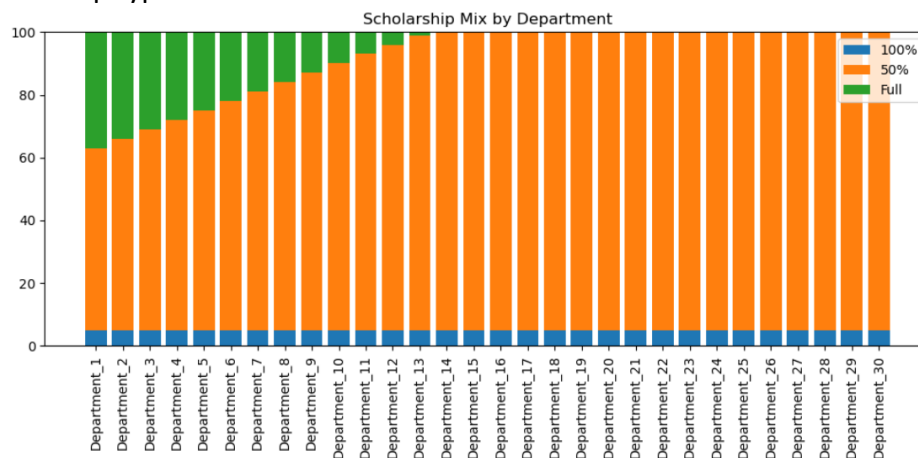


Fig. 2. Optimal scholarship composition across programs

4.3 Sensitivity to Minimum Scholarship Requirements

The minimum scholarship requirement parameter's sensitivity analysis results are shown in Figure 3. The study examines how variations in the minimum ratio of completely paid students impact overall university income. The findings clearly point to an inverse correlation between the scholarship requirement and overall income. Total income consistently drops as the minimum scholarship ratio rises from 5% to 20%. This result is predictable as scholarships that are entirely supported do not bring in tuition income. Raising the necessary quantity of these scholarships hence lowers the quantity of revenue-generating students. The study does show, though, that reasonable scholarship guidelines do not significantly lower income. Increasing the scholarship requirement from, say, 5% to 10% leads to a fairly modest revenue drop compared to more significant policy adjustments. For university officials trying to strike financial stability with access objectives, these findings offer insightful direction.

4.4 Price Sensitivity Analysis

Figure 4 illustrates how variations in tuition cost affect general income. To calculate tuition rates in this study, 0.8 to 1.2 was used. According to the findings, which reflect the increased contribution per full tuition student, revenue normally increases together with tuition prices. But the relationship is not quite linear as in price-sensitive areas, more prices reduce demand. Increasing tuition by roughly 20% generates the most revenue in the experiment. This suggests that the starting price level of the synthetic dataset is somewhat low; a slight price increase can help to improve sales results.

This conclusion emphasizes the need to consider demand elasticity when evaluating tuition pricing strategies from a management standpoint.

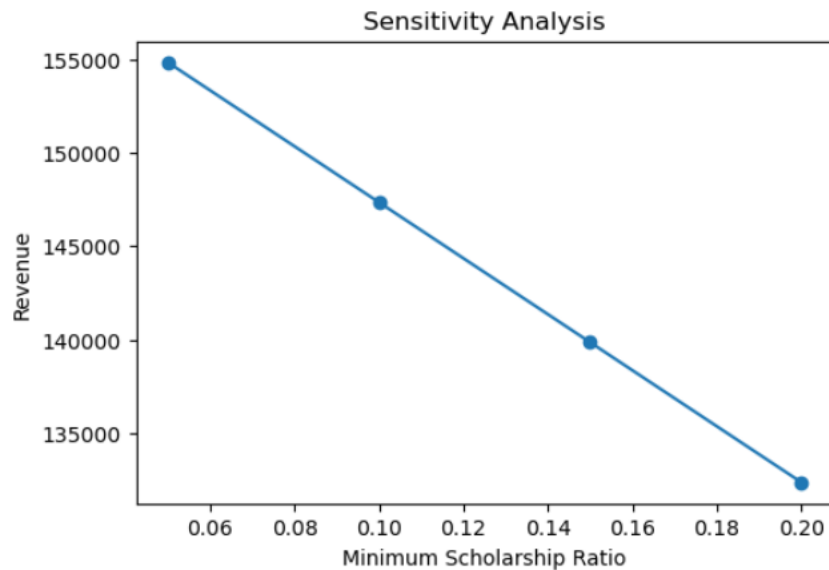


Fig. 3. Impact of minimum scholarship requirements on total revenue

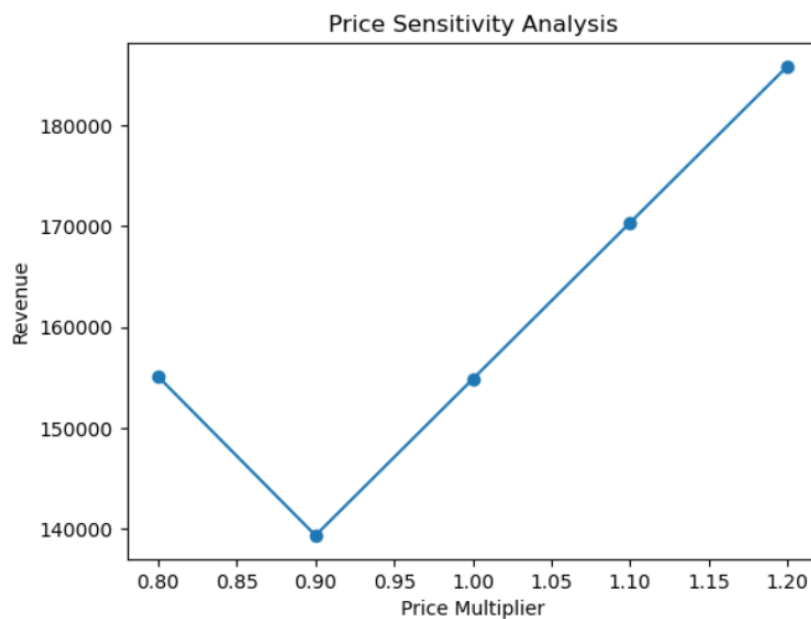


Fig. 4. Impact of tuition price changes on total revenue

4.5 Demand Shock Analysis

Changes in student demand affect total revenue, as shown in Figure 5. The factors between 0.8 and 1.1 multiplied the demand levels. Rising demand shows the university's ability to fill program capacity with more affluent students as income increases. Fewer enrolment opportunities, on the other hand, translate to less revenue if demand declines. Still, in comparison to changes in capacity or pricing, the overall income shift is fairly small. This suggests that the scholarship mix in the optimization model provides some degree of freedom to adjust to changes in demand. For example, the model makes up for a drop in demand by moving chairs between different scholarship types to maintain enrollment levels as close to feasible.

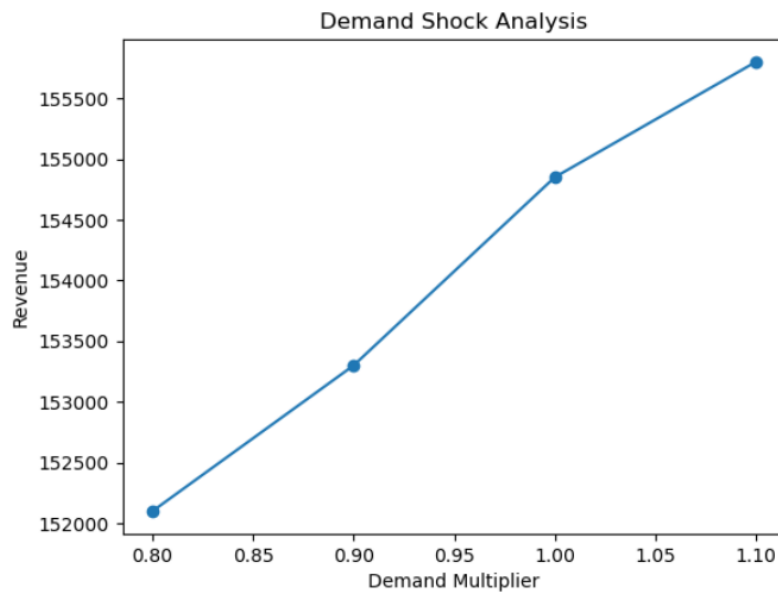


Fig. 5. Revenue sensitivity to demand fluctuations

4.6 Capacity Sensitivity Analysis

Program capacity variations affect overall income as shown in Figure 6. The study looks at capacity multipliers of 0.8, 1.0, and 1.2. The data reveal a clear positive link between income and capacity. Increasing the university's program capacity lets it take more revenue-generating students, which leads to major income increases. For example, a 20% rise in capacity produces a notable rise in overall income. On the other hand, cutting capacity 20% causes a significant income loss.

This result underlines the need of enrolment management in capacity planning. Increasing institutional income can come from growing capacity in in-demand programs.

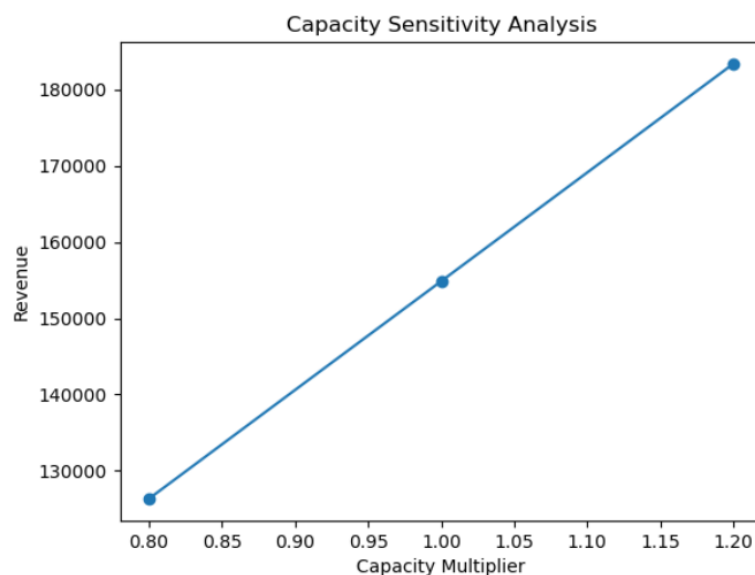


Fig. 6. Revenue sensitivity to program capacity

5. Conclusion

This study offers an optimization-based approach for managing college enrollment that maximizes institutional revenue by deciding the best distribution of students throughout scholarship categories. Within a single mixed-integer optimization framework, the suggested model combines scholarship policies, price-dependent demand functions, and program capacity limits.

The suggested framework precisely simulates the interplay among tuition pricing, scholarships distribution, and student demand whereas conventional enrollment planning methods depend on heuristic policies or past behaviors. The model offers a systematic decision-support tool for balancing financial sustainability and accessibility goals by including category-specific demand functions and institutional scholarship rules.

The computer simulations done in this investigation reveal a few very important observations. Scholarship distribution rules first have a major impact on institutional income. Raising the minimum ratio of fully funded students lowers income; however, somewhat generous scholarships have rather small financial effect. Second, income production is quite dependent on tuition rules. The price sensitivity study shows that slight price variations might have a significant influence on the profitability of businesses. Third, program capacity seems to be the most significant factor affecting income results. Including program capacity with great demand will significantly boost overall income.

Another significant finding is that, if demand for full tuition students is low, partially funded scholarships act as a flexible instrument for maintaining enrollment levels up. The scholarship mix is dynamically changed by the optimization model to ensure full use of program capacity and maximum revenue.

From a management standpoint, the suggested framework gives university administrators a way to quantitatively assess scholarship policies and enrollment plans. The model may help with wise choices about program capacity planning, scholarships distribution, and tuition pricing. Universities may enhance financial performance and policy transparency by moving from heuristic decision-making to data-driven optimization.

The study has several flaws that point to directions for future research even if it contributes. First of all, the demand functions that are used in computer-based experiments are based on made-up data for price and demand. More realistic demand models can be found in future research by including actual enrollment and application data. Second, the current system treats demand as fixed, but student demand can be unpredictable. Including either stochastic demand or strong optimization approaches into the model would give a more realistic depiction of enrollment uncertainty. Third, more study might look at more scholarship types, changing prices, or multi-period enrollment options.

In conclusion, the suggested optimization framework shows how effectively operations research approaches may help strategic enrollment management in universities. The model offers a thorough method to revenue-oriented enrollment decision-making by combining demand modeling, scholarship distribution, and capacity planning.

Acknowledgement

This research was not funded by any grant

Conflicts of Interest

The authors declare no conflicts of interest.

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