Restructuring Degree Roadmaps To Improve Timely Graduation in Higher Education

- Purpose

Faced with declining government funding support and rising student loan debt, recently timely graduation in higher education has become a focal point of discussion at many institutions, particularly public universities. Timely graduation requires a student to successfully enroll in and complete a set of required and elective courses, the relationship of which are bound by the courses' prerequisite requirements. However, due to the fact that class capacity is oftentimes limited and wrongly timed, many students find it challenging to stay on track. A well-structured degree roadmap that takes all factors into consideration and specifies the right courses to take by semester will better guide students' course selection and thus increase their chance of earning their degrees within the four-year time window. Additionally, it will also allow administrators to do better capacity planning, and hence increase course accessibility to students.

- Design/methodology/approach

In this research, some operational techniques such as line balancing and simulation are applied to restructure and improve degree roadmaps, and assess the resulting outcomes. Some innovative methods are proposed to improve the processes on which students proceed to degree.

- Findings

The results based on historical data that contains millions of student records spanning over eight-year time window demonstrate that the improved degree roadmaps can substantially increase students' chance of completing the degree in a four-year time window. The research findings provide university administrators with cost-effective solutions.

- Originality/value

Our research breaks a new ground in literature due to its unique approach and focus. To the best of our knowledge, our research is one of the first attempts to systematically study the impact of degree roadmap on timely graduation. Our research focuses on finding solutions that are within the institution's control, hence the proposed solutions are implementable and will provide university administrators with new tools and perspectives to enhance student success.

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Abstract

Faced with declining government funding support and rising student loan debt, recently timely graduation in higher education has become a focal point of discussion at many institutions, particularly public universities. Timely graduation requires a student to successfully enroll in and complete a set of required and elective courses, the relationship of which are bound by the courses' prerequisite requirements. However, due to the fact that class capacity is oftentimes limited and wrongly timed, many students find it challenging to stay on track. A well-structured degree roadmap that takes all factors into consideration and specifies the right courses to take by semester will better guide students' course selection and thus increase their chance of earning their degrees within the four-year time window. Additionally, it will also allow administrators to do better capacity planning, and hence increase course accessibility to students. In this research, we view the higher education institution as an operations system, apply operations research techniques to restructure and improve degree roadmaps, and assess the resulting outcomes. We propose innovative methods to improve the processes on which students proceed to degree. The results based on historical data that contains millions of student records spanning over eight-year time window give promising results and allow university administrators to find cost-effective solutions.

Key Words:

Timely graduation, higher education, degree roadmaps, simulation

1. Introduction and Literature Review

With the aspiration of transforming American higher education and economy, President Obama introduced the American Graduation Initiative in summer 2009 which calls for five million additional graduates by 2020 in order that the United States will have the highest graduation rate among nations in the world (Brandon, 2009). According to a study by the Public Policy Institute of California (PPIC), California will have a shortage of 1.1 million college graduates to meet its economic needs by 2030 (Bliss and Pottinger, 2015). The projected workforce shortage is expected to have an adverse impact on California's future economic development. In the last decade, considerable institutional resources were spent on boosting the graduation rate and some higher education institutions have even implemented intrusive advising programs to achieve this goal. Nonetheless, the national data paint a grim picture of the four-year graduation rate. The U.S. National Center for Education Statistics (Ginder et al., 2018) reports that the four-year graduation rate for first-time, full-time undergraduate students seeking a baccalaureate degree at four-year degree-granting institutions in the 2009 starting cohort was 34% at public institutions and 53% at nonprofit private institutions. The four-year graduation rate at the national level has remained relatively stagnant all the way back to the 2000 starting cohort. Most strikingly, California State University's (CSU) four-year graduation rate is one of the lowest in the nation, an alarming 19%.

As the largest public university system in the United States that enrolls almost half million students with over 50,000 faculty and staff on 23 campuses, the California State University (CSU) system strives to provide affordable higher education to California residents and increase accessibility to a diverse student population, particularly those low-income and first-generation students. The current system-wide tuition fee is $5,742 per academic year for undergraduate students enrolling in more than six units per term, which is 19% cheaper than the national average public four-year tuition of $7,056 and 75% cheaper than the average California tuition of $23,377 for four-year colleges. CSU highly relies on state funding to run such a giant public system and fulfill its mission to provide high-quality, affordable education to California people. However, state funding support has declined dramatically as a share of the total budget in the past four decades. Such shift has increasingly created more pressure on each campus and forced administrators to manage capacity and enrollments more effectively. California has to expand access to CSU schools and holds public higher education institutions more accountable for bolstering the four-year graduation rate. Confronting such daunting low figures, CSU's Board of Trustees approved its most ambitious initiative yet: Graduation Initiative 2025, launched in 2009, which aims to increase system-wide four-year graduation rates to 40% by 2025 and to close the achievement gap for all 23 campuses without comprising academic integrity or educational quality (https://www2.calstate.edu/csu-system/news/Documents/GI2025-Fact-Sheet.pdf). California also supports the notion that state funding will connect to an increased percentage of freshman graduating within four years at public universities (Megerian and Gordon, 2013). Further, on September 21, 2016, Senate Bill 412 (SB 412) was signed into law by Governor Jerry Brown to further bolster CSU's four-year graduation rate by committing to more advising support and providing priority registration to full-time students (https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB412). Given this context, and using eight years' curriculum and graduation data at the California State University Long Beach, our research aims to systematically investigate the factors that cause the low graduation rate. Further, we construct mathematical model and use simulation to quantify the impact of such factors, which prescribe solutions that would effectively improve timely graduation rate in a cost-effective way.

Timely graduation has been a focal point of discussion in the higher education environment over the last decade. Constructing a longitudinal examination of the 118-year retention and graduation records at U.S. public universities, Boden (2011) documents an alarming fact: the four-year graduation rate—as compared to the six-year rate—declined by 1.9% per decade. Many prior studies have aimed to identify indicators that can be used to explain why or why not students graduate on time. For instance, Yue ad Fu (2017) track more than 10,000 first-time freshman from 2002 to 2014 at one large California State University. Students' academic performance indicators (term GPA, cumulative units earned at beginning of term, and cumulative GPA at beginning of term) and their decisions on majors (such as double majors and minors) are the top two factors that improve their odds of degree attainment. Interestingly, the pre-college characteristics (for example, high school GPA, first-generation student, Pell Grant eligibility, etc.) contribute to less than 1% of total variation in graduation after controlling students' academic performance and major choices. By examining graduation rates among different ethnicities, Mooring and Mooring (2018) find that GPA at 4-year colleges becomes the most pronounced timely graduation predictor for Asian transfer students. Enrolling in a 4-year transfer program at community colleges is an effective timely degree indicator for African-American transfers. Bengesai and Paideya (2018), following an eight-year graduation period after initial 2009 cohort freshman, report that the engineering students at South African University who graduated on time are likely to be non-African students with high admission scores, and who pass more than 75% of courses in the first year. In addition, the financial aid also exhibits a positive effect on four-year graduation rate.

Some research examine how external factors influence student behavior, which in turn affect timely graduation rate. DeShields, Kara and Kaynak (2005) suggest that students' satisfaction about their college experience would improve retention. Class schedule is one of the factors which contributes to students' college experiences. Advancing the "warehouse hypothesis," Chen and Yur-Austin (2016) suggest that students use schools as warehouses to shield themselves from the deteriorating job market. Their study undertakes to explain college students' mindsets during the 2008 financial crisis. Some prior studies (Bowen and Rudenstine, 1992 and Hakkinen and Uusitalo, 2003) suggest the timely completion of degree is, to some extent, is driven by financial incentives or punishments. Garibaldi et al. (2012) presents the evidence in support of the notion that students exert more efforts to graduate on time if they expect to pay higher tuition due to late graduation. Their data shows the probability of late graduation is reduced by 5.2% for 1,000 additional euro increase in continuation tuition at Bocconi University in Italy, when the average late graduation probability is 80%

There have been case studies that assess the impact of policy and practice changes on timely graduation. Robertson and Pelaez (2016) present a case study reporting a 16-point increase in timely graduation within 4 years at Florida International University which implements the Graduation Success Initiative (GSI). GSI applies behavior analytic concepts to initiate changes in its organization such as explicitly declaring major at admission, integrating academic advising and career development, etc. Rowley (2003) concludes that an effective communication between different parts of the university and a detailed student record system will fortify the university infrastructure to achieve satisfactory students' retention results. Othman, Mohamad and Barom (2019) analyze different factors that can influence students' decision for class selection and enrollment. Five significant factors identified include the lecturer, time-space, ease and comfort, course mate and commitment factor. Johnson and Stage (2018) investigate the rapport between 10 high-impact practices (e.g., internships, writing intensive courses, first-year seminars and experiences, etc.) and graduation rates at 101 participating 4-year public colleges and universities in U.S. However, Johnson and Stage fail to establish a strong predictive connection between improving students' engagements because of high-impact practices and timely college completion.

Our research breaks a new ground in literature due to its unique approach and focus. We view the higher education institution as an operations system, which consists of various processes in which students progress to degree. The processes can be depicted as degree roadmaps, which are driven by the degree curricular structure, but can be shaped by pacing the courses differently. The goal of the higher education administrators is to improve the processes, i.e. degree roadmaps so as to better match capacity with demand for course seats, which will lead to improved graduation rate. Obviously, given a degree requirement, the central pillars that support timely graduation are: (1) successful enrollment (taking the right courses at the right time); (2) successful course completion (get a passing grade). We examine various factors that affect the probability of successful enrollment including aggregate capacity (overall seats availability), and structural demand and capacity (seats availability of specific courses). Our research focuses on finding solutions that are within the institution's control, hence the proposed solutions will be implementable. Our study focuses on students who are willing and able to follow a suggested degree roadmap. Nonetheless there are some students who may not follow a predetermined roadmap due to personal choices or behaviors. The paper proceeds as follows. Section 2 describes current situation of aggregate capacity; Section 3 defines structural demand and degree map; Section 4 describes the quantitative research model and analysis; Section 5 presents the recommendations based on sensitivity analysis; and Section 6 concludes and suggests future research direction.

2. Assessing the Aggregate Capacity

As the largest public university system in the United States, CSU system enrolls almost half million students. Because state funding support has declined dramatically as a share of the total budget in the past four decades, CSU constantly faces budget challenge. To fulfill its mission to provide high-quality and affordable education to California people, tuition increase is in general not a viable option. Such shift has increasingly created more pressure on each campus and forced administrators to manage capacity and enrollments more effectively. While not desirable the limited budget has led to higher enrollment caps and higher class fill rates.

All CSU campuses are governed by CSU chancellor's office. They follow similar policies and practices and face similar challenges. CSU Long Beach (CSULB) is the third largest campus with more than 32,000 enrolled students in 2016 (http://www.calstate.edu/as/stat_reports/2016-2017/f16_01.htm). In our study, we examined the class level data for the entire campus at CSULB over the past eight years from academic year 2009-2010 to academic year 2016-2017. The dataset includes over 93,000 class session information and over 2,000,000 student level records. Figure 1 shows the total number of seats offered as well as the number of students enrolled over the past eight years. Since the last US economic recession in 2008, the entire campus has witnessed a steady increase in student enrollment (12.5% increase in eight years). To accommodate such increased demand, the university has gradually increased the capacity (9.2%). Due to budget constraint, capacity expansion fell behind the speed of enrollment growth. This led to significantly higher class fill rates today campus-wide, over 90% as compared to 85.5% eight years ago, as shown in figure 2. College of Business, in particular, has reached an average class fill rates of 96.2%, which leaves very little space for students to access their desired classes.

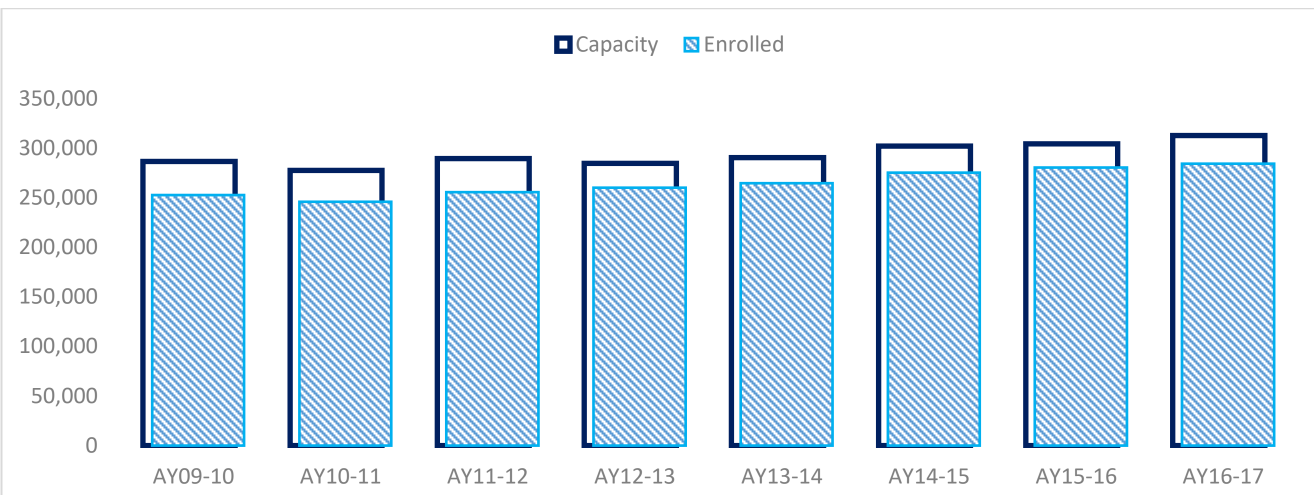


Figure 1: Total Number of Seats Offered/Students Enrolled over the Past Eight Years

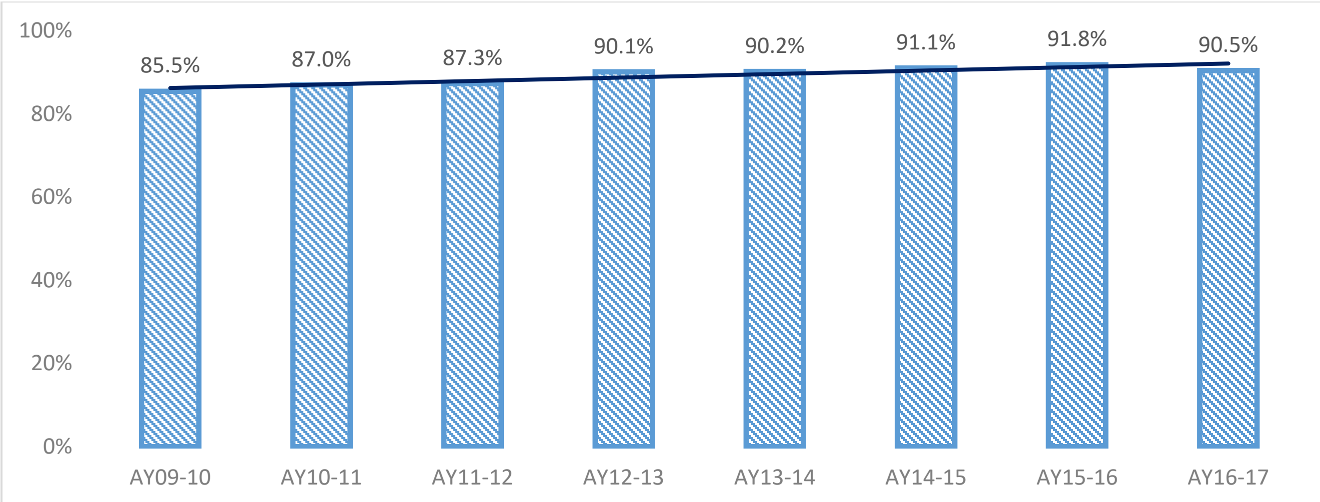


Figure 2: Class Fill Rates Over the Past Eight Years

According to Higher Education Scheduling Index 2016, a report published by Ad Astra Information Systems (a computer software company specializing in course scheduling for higher education) based on more than 1,000 higher education campuses they collaborated, CSULB faces huge challenge in striking the balance between meeting student course needs and managing campus financial resources efficiently. Apart from a number of other metrics, the report provides the average class fill rates, the percent of overloaded courses (fill rates exceeding 95%), the percent of balanced courses (fill rates between 70% and 95%) and the percent of under-utilized courses (fill rates under 70%), for all institutions combined, four-year public universities, four-year private universities, and two-year colleges respectively. Figure 3 shows a comparison between CSULB and its peers on these four metrics. As clearly indicated in Figure 3, the class fill rates and the percent of overloaded courses at CSULB is much higher than its peers while the percent of under-utilized courses is much lower than its peers.

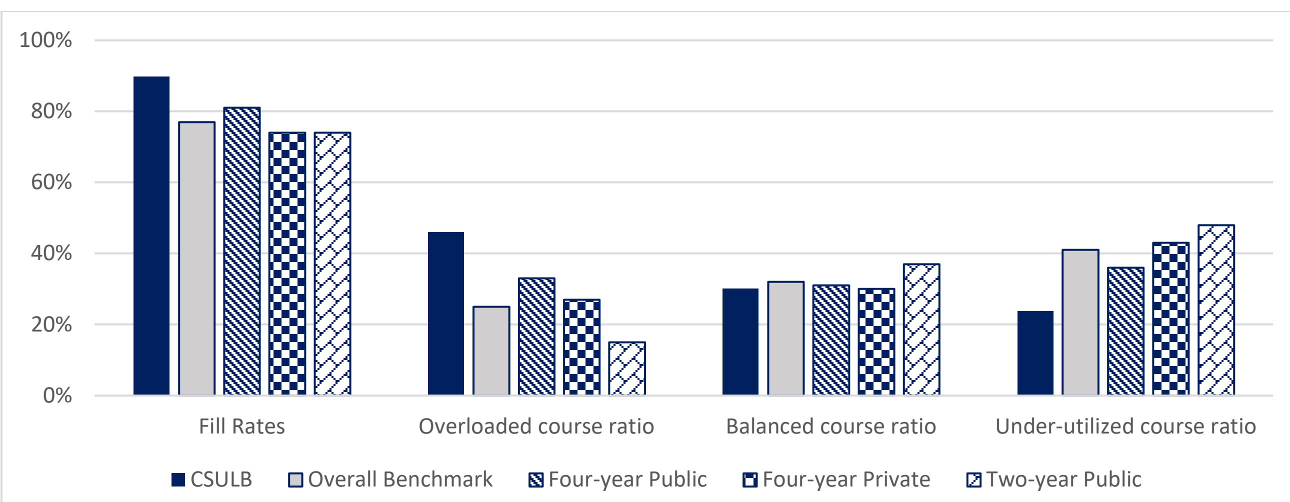


Figure 3: Comparison of Class Fill Rates between CSULB and Other Institutions

In addition, the average class cap at CSULB is much higher than its peers, 36 as opposed to 29. A significant percent of classes, particularly lower-division classes, are taught in large lecture halls. Figure 4 shows the class size distribution at different levels. Close to 20% of the classes at the 100 level (freshman level class) have a class cap of 51 or more. This has led to, apart from other reasons, poor student performance, as demonstrated in Table 1. As clearly evidenced in Table 1, student performance is highly correlated with class size and student perform much worse in classes offered in large lecture halls, particularly at the lower-division level (100 and 200 level classes). The DFW (D, F, and Withdraw) rates at the lower-division classes with capacity 101 or more exceed 17.1%. This has caused many students to drop out from the university in the first couple of years and made others to retake the classes, and hence delayed their graduation time. Faced with declining state financial support and public pressure not to increase the tuition, CSULB administrators have been left no choice but to come up with innovative ways by completely restructuring the system in order to manage capacity more efficiently and improve student success.

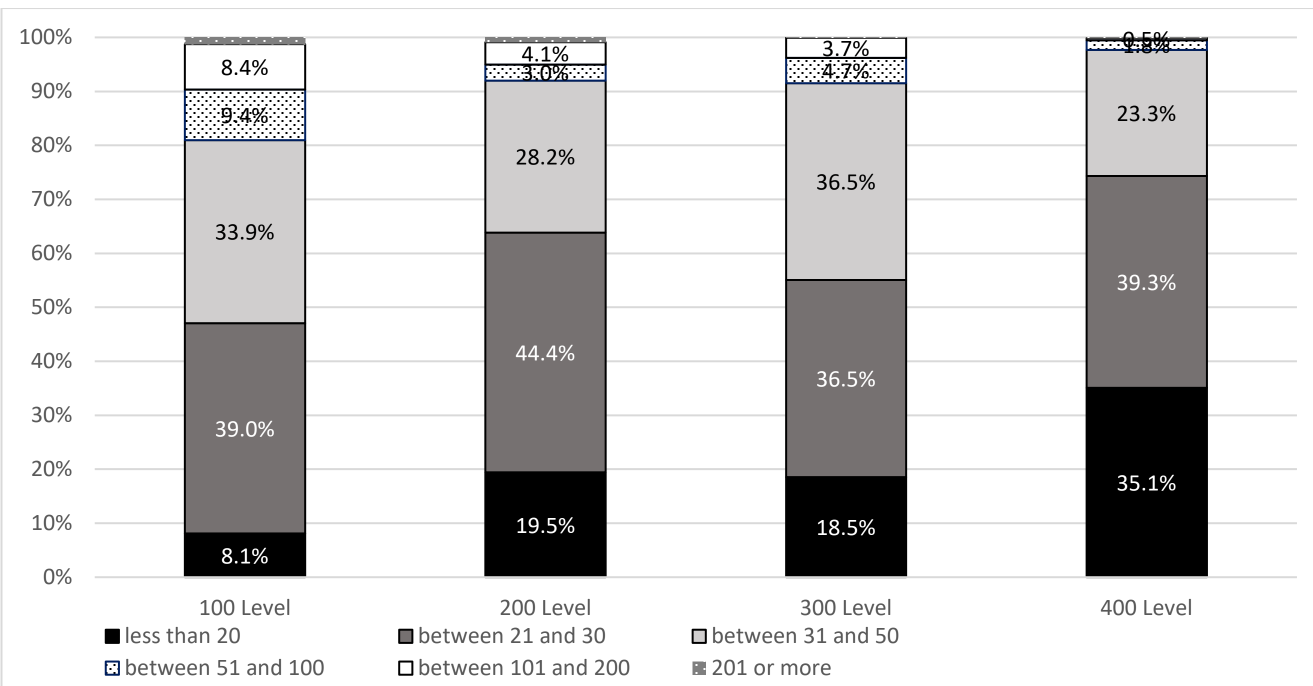


Figure 4: Class Size Distribution at Different Levels

Table 1: Student performance at different class levels.

	100 Level			200 Level			300 Level			400 Level		
Class Size	# Sessions	GPA	DFW Rate	# Sessions	GPA	DFW Rate	# Sessions	GPA	DFW Rate	# Sessions	GPA	DFW Rate
20	1448	3.13	9.6%	1589	3.45	5.9%	4173	3.29	6.0%	7431	3.49	4.7%

30	6975	3.12	9.1%	3626	3.08	10.9%	8215	3.09	8.8%	8323	3.30	6.0%
50	6058	3.14	11.6%	2301	3.00	11.7%	8205	3.01	9.6%	4943	3.15	6.0%
100	1678	2.99	11.2%	241	2.82	15.6%	1050	2.88	12.9%	376	3.08	8.6%
200	1508	2.62	17.1%	336	2.52	20.0%	842	2.68	13.0%	96	3.19	4.5%
201 or more	223	2.60	18.8%	75	2.34	20.4%	16	2.93	9.4%	21	3.49	2.9%

3. Structural Demand and Degree Roadmap

Since course capacity at the aggregate level is very tight, we need to dig deeper into the structure of the demand for courses so that we can better utilize limited capacity. Students in different majors often need the same subset of courses to fulfil their degree requirements. We call them the “common core courses”. For instances, in the Colleague of Business, there are ten such upper division common core courses, and usually, those courses become full quickly after registration window opens. On an ongoing basis, academic advisors hear from multiple students the same story that a graduating senior just needs one last class before degree but couldn’t get a seat. Academic advisors often petition on students’ behalf to request instructors to add students beyond class cap. Other times, they request administration to open one more session of that class. When department chairs open the same number of sessions for the following semester, they often find out that too many seats are offered and some classes do not fill. They call it demand waves. When we closely examine the enrollment in a full class with a waiting list, we find that some students on the waiting list need that class badly/immediately for graduation on time, while other students who are already enrolled, although also need the class, do not need the class immediately. They can actually wait one, even two or three semesters without delaying their degree.

After some investigation, we find three culprits for this phenomenon as well as the so called demand waves: (1) Students don’t have a clear understanding of the path to degree and choose classes that are easy, fit their schedule, have a nice instructor, or simply because their friends take it. This causes students to end up in a class they don’t actually need or don’t need immediately, while missing the best window to take classes that are critical to their degree progress. (2) The decision on the number of sessions/seats offering is based on the seat and session offering of the previous semester and/or one year ago, without paying much attention to admission growth, even less to the shifting of admission changes across different majors in a college. This structural changes in demand, if ignored, can throw capacity planning off much more than the demand change at the aggregate level. The reason is that aggregate level demand change is more incremental and controllable. (3) The current registration priority rule is not effective at differentiating the needs as “no need”, “need” and “immediate need”.

We believe that a well-crafted degree roadmap for every major is the first step to understand structural demand for individual courses. It is also the foundation for tackling the three problems mentioned above. In our exploratory study, we drew degree roadmaps for a wide variety of academic majors on campus, which make further in-depth analyses possible. Sample roadmaps are shown below in Figures 5 and 6.

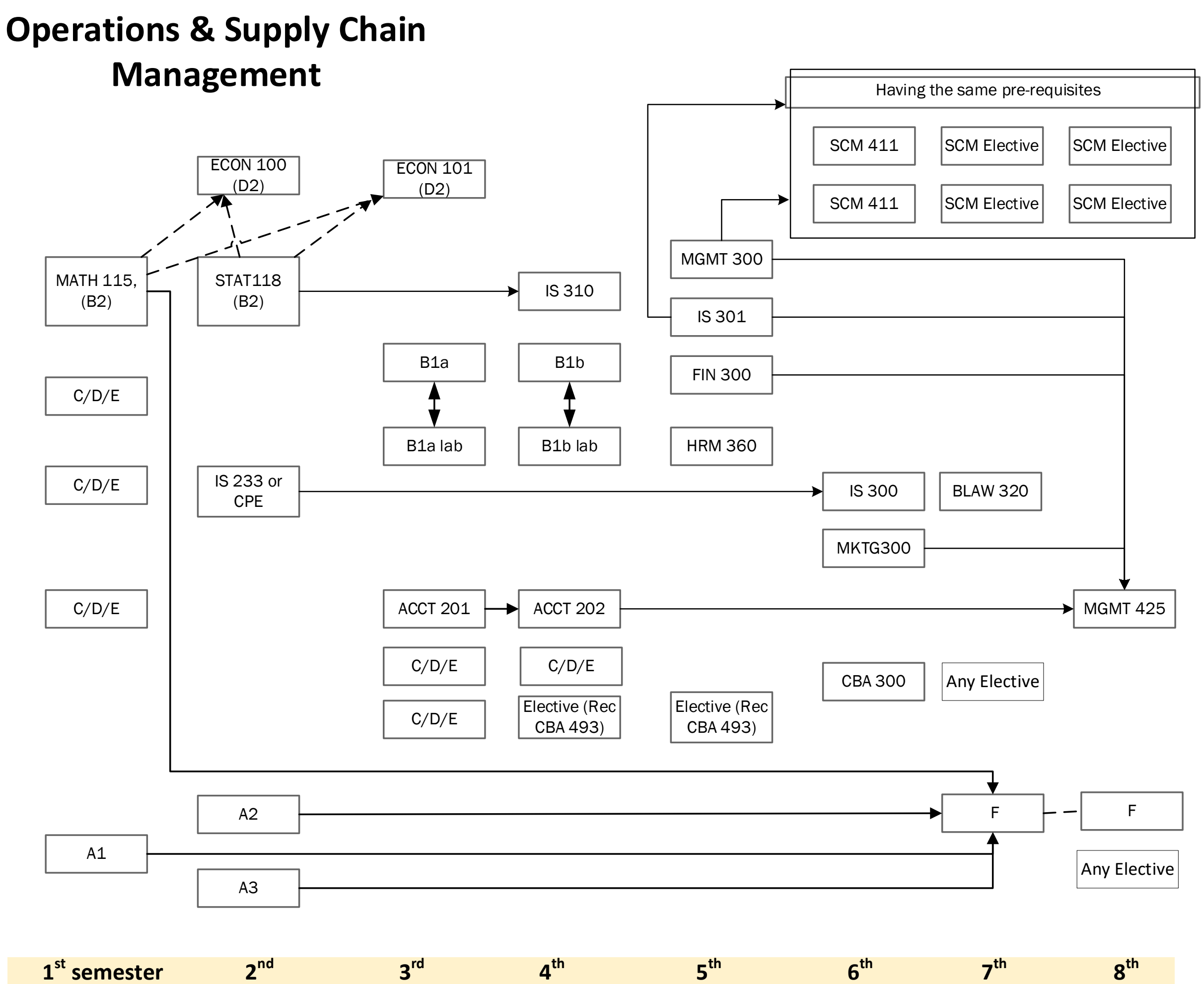


Figure 5: Degree Roadmap for Operations & Supply Chain Management in College of Business at CSULB

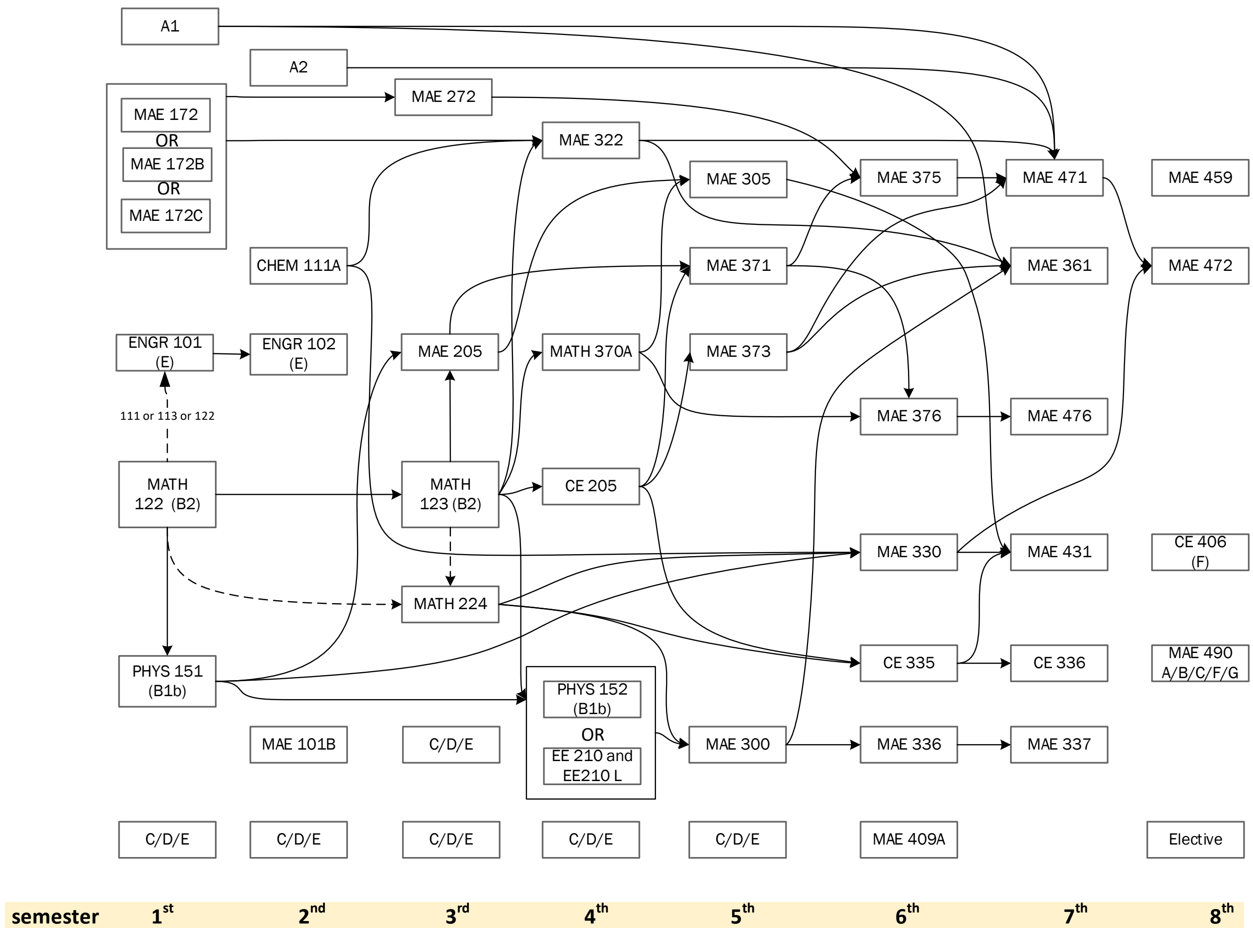


Figure 6: Degree Roadmap for Mechanical Engineering Major in College of Engineering at CSULB

The visual degree roadmap provides students with a clear map towards degree attainment, showing all required courses as well as the timing of those courses in a straightforward way. According to Albert (Bandura, 1995 and 1997), self-efficacy is the belief in one's capabilities to organize and execute the courses of action required to manage prospective situations. This visual roadmap provides a clearly charted courses of action for students, which serves as the information foundation that supports students' self-efficacy. Research clearly shows that if students clearly understand their status or position on their academic journey, they have a better chance to stay on track and succeed (Besterfield-Sacre et. al., 1996; Lent et. al., 1987 and 2003; Hackett et. al, 1992). The University of Hawaiʻi at Mānoa has a great success story of implementing the 4-year degree roadmaps. Their 4-year graduation rate has increased from 21.2% to 34% in the five years from 2013-2017, a solid 62% increase. On their white paper, they say "the 4-year plan, along with the STAR degree audit system has had more impact on students' perception about the university's commitment to their success than anything else….." Academic advisers identify the 4-year academic plans as the most important factor in that success. Having a set of individual degree roadmaps is a starting point for crafting a coordinated system-wide course scheduling plan, which is necessary for improving student course accessibility. The visual roadmap also provides a foundation for the following quantitative analysis.

3.1 Roadmap Design

At CSULB, for almost all degrees, students need to complete 120 units, which is equivalent to 40 3-unit courses. The 40 courses can be further categorized into general education (GE) courses, lower division core, upper division core, capstone, and elective courses. Some lower division core courses, oftentimes double counted as GE, need to be completed before students can matriculate into a major officially. They are so-called major declaration courses. Upper division core course are normally only available to matriculated students, and some upper division core courses serve as pre-requisites for major specific capstone and elective courses. For full-time students, the task of 4-year roadmap design is to assign 40 courses into eight (8) sequential semesters (time buckets) so that all the degree requirements can be completed in four years, and the sequence should be such that all milestones (e.g. major declaration) are hit at the right time, and all pre-requisites for a course get cleared in a timely manner so that students can progress to degree smoothly. This problem can be solved with line balancing technique in process and layout design, combined with the CPM (Critical Path Method) in project management.

The starting point of the roadmap design is to identify all the course requirements of a degree and draw all the sequential paths based on prerequisite requirements. A path is the sequence/chain of courses that have pre-requisite relations. Please note that some courses can sit on multiple paths, while others are free floating, not on any path. We further examine the number of paths as well as the length of each path (in terms of number of semesters) to determine which path(s) are critical to students' timely graduation. For instance, by tracing all prerequisite requirements, the roadmap for the Mechanical Engineering major (MAE) ends up having 37 paths total in addition to stand-alone courses, among them three paths are 7-semester long. They are MATH122->MATH123->MAE205->MAE371->MAE375 -> MAE471->MAE 472; MATH122->MATH123->CE205->MAE371->MAE375->MAE471-> MAE 472; and MATH122->PHYS151->MAE205->MAE371->MAE375 -> MAE471->MAE 472 respectively. Note that normally students cannot take a course before successfully completing all prerequisites. However, there are exceptions. For example, although MATH123 is one of the prerequisites for MAE 205, the policy allows students to take MATH123 and MAE 205 simultaneously. The same exception applies to PHYS 151 which has MATH 122 as a prerequisite. The roadmap also contains six 6-semester long paths among others. Although all paths as well as stand-alone courses on the degree roadmap need to be completed before graduation, obviously, the three 7-semester long paths, specifically, the courses on them, are critical to timely degree completion, and the six 6-semester long paths should be closely watched for as well. It should be alarming that the current roadmap design schedules the three 7-semester long paths to be competed exactly at the end of semester #8. Any disruptions to any of the five courses—CE 205, MAE371, MAE 375, MAE 471 and MAE 472—will push the graduation beyond four years.

3.2 Roadmap Optimization with Line Balancing Technique

The task of roadmap design is to determine the sequence and timing of those courses required for a degree. Since the 40 courses should be completed in eight (8) semesters, it makes sense to balance student work load by assigning five classes to each semester, this is where line balancing technique can be helpful. We propose using four metrics to measure a course's importance, and hence assignment priority, in the roadmap. Define

A – the longest path branching out from this course

B – the number of followers

C – number of paths branching out from this course

D – the average of length of following paths branching out from this course

Taking Math 224 as an example, we can see that Math 224, MAE 300, MAE336 and MAE 337 constitute the longest path, so A=4. Math 224 has nine followers total, so B=9. Math 224 has six paths branching out from this course, so C=6. Finally, the average length for the six paths is 3.2 semesters, so D=3.2. Please refer to figure A-1 in the Appendix for a complete list of Importance metrics for all courses required for the degree.

We can come up these four measures for each course, then starting with semester #1, we assign a course with highest A measure. If there is a tie, assign a course with highest B measure. If tie again, assign a course with highest C measure. We rarely run into a case where there are ties twice, but D measure is the backup to solve any additional ties. During this process, the precedence relationship for each path has to be monitored. After the first semester is loaded with the first five courses, we can proceed to load semester #2 using the same rules and tie breakers. Blow is the revised roadmap illustrated in Figure 7.

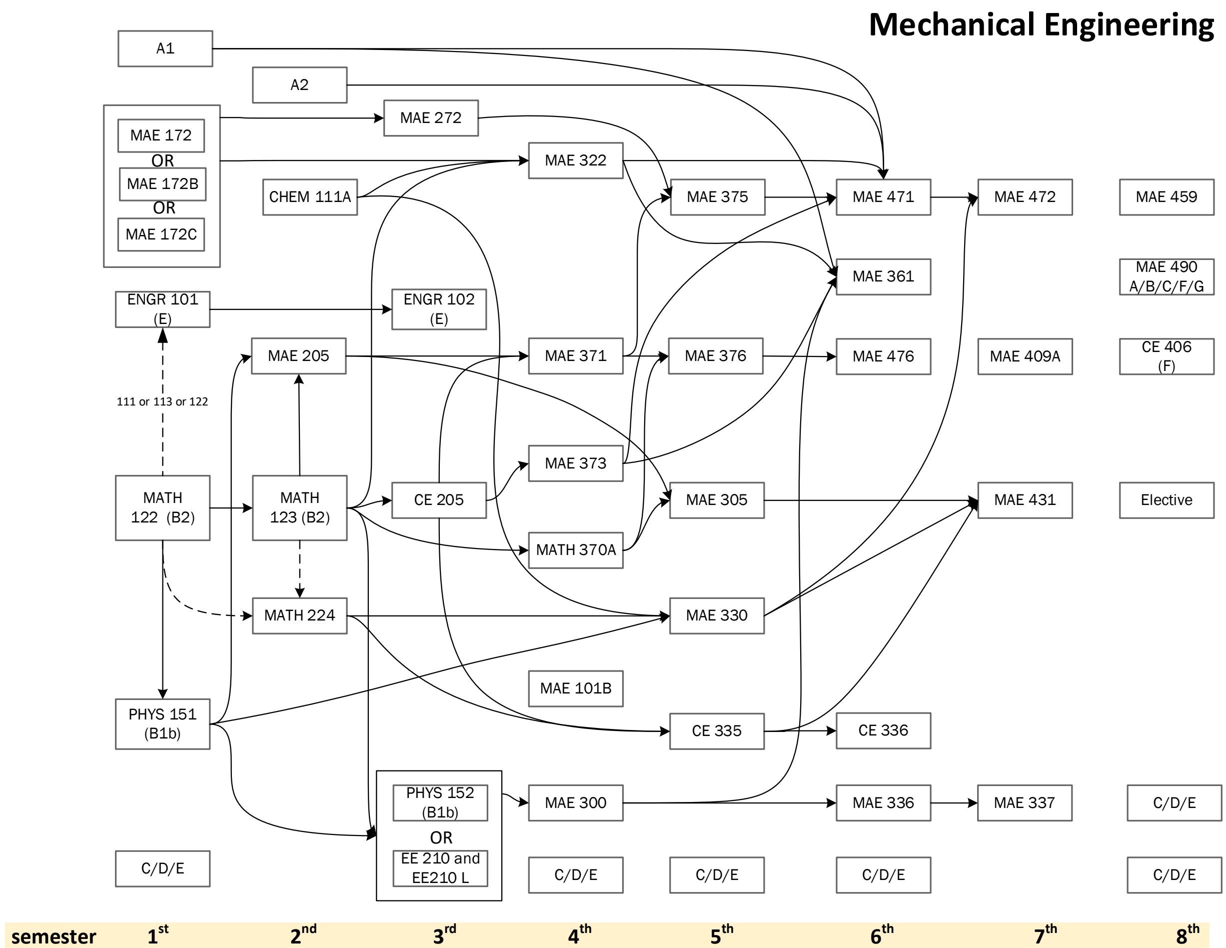


Figure 7: Improved Degree Roadmap for Mechanical Engineering Major in College of Engineering

The key is to schedule critical courses, i.e., those on long paths as early as possible so that in case disruptions happens, long paths still stand a chance of completion within eight semesters. In the MAE case, we ended up having all three 7-semester-long paths scheduled for completion by semester #7. We created a buffer for MAE 205. In case students fail MAE 205, which students do all the time, they have this buffer to catch up and not delay their degree progress on this path. We also study the impact of each course completion on the timely graduation by studying the traffic leading into the course (the number of immediate pre-requisites) and traffic leading out of the course (the number of immediate followers). For example, if a course has multiple immediate followers, the completion of this course is critical for student to complete subsequent courses (paths). If a course has multiple immediate pre-requisites, it is a good idea to schedule a buffer semester before this course to reduce disruption and increase the robustness of the roadmap. For instance, we could have scheduled MAE 431 in semester #6 and pushing back one GE (C/D/E) course, but inserting an idle buffer before MAE 431 is necessary. In case a student cannot take any of the three prerequisites on time or fail any of them, the student have semester #5 to correct the issue and still progress to take MAE 431 in semester #6 as planned. This reduces disruption to course scheduling.

Although the task of crafting a 4-year degree map for every major seemed simple in scope, at the University of Hawaiʻi at Mānoa, it was three years before the information was integrated into the university catalog along with the other information that was shared with students by advisers, faculty advisers, and departmental handouts. We recommend the appointment of the University Catalog Committee to oversee this work and maintain dependable and accurate roadmaps for students. It is also imperative to make the 4-year roadmap an integral part of students' mandatory advising and their registration meetings with advisers.

4. Graduation Rate Model and Simulation

Given a roadmap, there are two factors that determine students' timely graduation. The first factor is the probability of successful course enrollment. It correlates with course accessibility, and can be estimated based on factors such as number of seats available, diversity of time slots during which those seats are offered, as well as the frequency at which the course is offered, i.e., every semester, once a year, every other year, etc. The second factor is the probability of successful course completion, i.e., getting a passing grade instead of D, F or W. Note that W stands for withdrawal. We aim to find out, given the current degree roadmap, what is the theoretical upper bound of 4-year graduation rate.

4.1 The Model

Define

$p_1^i =$ the probability of successful course enrollment in course i

$1 - p_2^i(DFW) =$ the probability of successful completing course i where $p_2^i(DFW)$ represents the probability that a student gets a grade D or F, or withdraw from a course/class i

$P(l) =$ the probability of successfully completing path l in the 4-year window

Suppose there are k paths in a degree roadmap: $l_1, l_2 \cdots l_k$

Further define

$P(l_2|l_1)$: the probability of successfully completing path l_2 given successfully completing path l_1, and

$P(l_3|l_2 \cap l_1)$: the probability of successfully completing path l_3 given successfully completing path l_1 and l_2.

$P =$ the probability of completing degree in the 4-year window, then

$$P = P(l_1 \cap l_2 \cdots l_k)$$
$$= P(l_1) * (l_2|l_1) * P(l_3|l_2 \cap l_1) *\cdots* P(l_k|l_1 \cap l_2 \cdots l_{k-1})$$

Taking "Mechanical Engineering BS" degree as an example, it has 37 paths including one 7-semester long paths and seven 6-semester long paths among others. Student need to complete all 37 paths before completing the degree. For the 7-semester long path MATH 122 -> MATH 123 -> CE 205-> MAE 374 -> MAE 375 -> MAE 471 -> MAE 472, the probability of completing this path in four years (eight semesters) can be approximated as follows:

$$P(l) = z + \sum_{i=1}^{7} z \cdot \left(\frac{p_1^i}{1 - p_1^i} + \frac{1 - p_2^i(DFW)}{p_2^i(DFW)} \right)$$

$$where\ Z = p_1^1(1 - p_2^1(DFW)) \cdot p_1^2(1 - p_2^2(DFW)) \cdots p_1^7(1 - p_2^7(DFW))$$

4.2 Impact of Roadmap Improvement on Graduation Rate - Simulation Study

We develop a Monte Carlo simulation model that allows us to determine the graduation rate given a particular roadmap. Monte Carlo simulation is a computerized mathematical technique that allows people to see all possible outcomes for a particular course of action. It is a powerful tool commonly used in risk analysis of a system where some parameters are inherently uncertain. In our problem, whether or not a student can successfully enroll in a particular class as planned in the degree roadmap and whether or not the student can successfully earn a passing grade (A, B or C) are uncertain. Failure to enroll in a class or failing a class would disqualify the student for enrolling courses that have this class as the prerequisite, and hence affect his/her graduation time. In a Monte Carlo simulation, each replication represents a possible combination of realized values of all uncertain parameters involved in the system, for instance, a student passed classes X and Y, but failed class Z. We can also view one replication as what happens to a particular single student. Given these realized values, we can estimate the time it takes for this particular student to complete all the courses. By running the simulation for a large number of replications, we can then calculate the percentage of students who are able to successfully complete all the courses in a certain time frame. In our study, we run simulation for four, five and six years respectively, which corresponds to the four-year, five-year and six-year graduation rates. The simulation model was coded in C++. We use the model to assess various degree roadmaps described in the previous sections. Particularly, we want to demonstrate the improvement in four-/five-/six-year graduation rates after applying the roadmap optimization technique illustrated in section 3.2.

In the following, we use ***Mechanical Engineering (MAE)*** as an example to illustrate our analysis. In the simulation, we use the actual DFW rates and class fill rates in different courses, which were obtained from the dataset described in Section 2. The DFW rates and class fill rates for all associated courses in MAE degree roadmap are presented in Table A-2 in the appendix. Note that success rate is the probability that students successfully earn a passing grade (A, B or C) in a particular class, which is equal to 100% - DFW rate. We further assume that students can always get enrolled in a class with fill rates under 95%. For classes with fill rates between 95% and 100%, students can successfully get enrolled in those classes with probability 98% (due to possible schedule conflict with other classes). For classes with fill rates above 100%, students can successfully get enrolled in those classes with probability 95% (subject to the outcome of petition and/or instructor permission).

Based on the actual DFW rates and class fill rates, as well as the estimated probability of successful course enrollment, the simulated graduation rates for the current roadmap and optimized roadmap are shown in Table 2 below. The results show significant improvement in graduation rates from 7.93% to 22.03% by simply changing the timing of courses on the degree roadmap. For comparison purpose, we also present the historical four-year graduation rates for the same major.

Table 2: Historical and simulated graduation rates for MAE major

Historical four-year graduation rate	
Fall 2008	6.34%
Fall 2009	8.49%
Fall 2010	4.24%
Fall 2011	5.98%
Fall 2012	9.13%

Simulated four-year graduation rate	
Current Roadmap	7.93%
Optimized Roadmap	22.03%

5. Sensitivity Analysis and Recommended Solutions

The Monte Carlo simulation model proposed above also allows us to perform what-if analyses by evaluating the impact of various factors that affect graduation rate, hence shedding lights on the effectiveness of various initiatives administration may choose to undertake. For example, administration can change registration policy to increase the likelihood that students can access certain critical courses in a timely manner. Likewise, administration can allocate more resources to enhance tutoring services for certain critical-path courses to improve successful course completion rate. We can also analyze the graduation rates under various "hypothetical circumstances", for example, removing the prerequisite requirements for a particular course, moving a course to an earlier/later semester on a degree roadmap. Such technique will allow us to see the "immediate outcome" if a particular action is taken. By comparing the outcome associated with different possible actions, we can identify the most effective action, say, improving the success rates in class X will lead to a 10% increase on graduation rates while improving the success rates in class Y only leads to a 3% increase on graduation rates. This will greatly help the university administrators determine where the limited resources should be allocated to accomplish the best results.

We test the following scenarios in the simulation study, where the starting letter "C" indicates the current degree roadmap while the starting letter "I" indicates the improved degree roadmap by applying the approach discussed in Section 3.2. For both the "C" and "I" scenarios, we test the impact of course accessibility (indicated by "Access") and course success rates (indicated by "Success") on the graduation rates. In addition, we test the case where a student can only take no more than five courses per semester (indicated by "Load") due to other commitments such as part-time or full-time jobs, which is fairly common at an institution like CSULB. In other scenarios, students can take up to six courses if needed (e.g., to catch up if they fail one course). Finally, we also test the impact of prerequisite requirements for different courses (indicated by "prerequisite"). Note scenario C is the base scenario that resembles the current situation, i.e., the current degree roadmap and the actual DFW rates and class fill rates for all the associated courses.

- ***Scenario C***: This is the base scenario where students will follow the current degree map. We use the actual DFW rates and class fill rates in the simulation for all the associated courses, as shown in Table A-2.
- ***Scenario C_Access_1***: In this scenario, all class fill rates are brought down to under 100%.
- ***Scenario C_Access_2***: In this scenario, all class fill rates are brought down to under 95%. In other words, students are guaranteed a seat in any class they plan to take following the degree roadmap.
- ***Scenario C_Success_1***: In this scenario, we reduce the DFW rates for all courses by 50%.
- ***Scenario C_Success_2***: In this scenario, we bring up the success rates for all courses taken in the first year to at least 90%.
- ***Scenario C_Success_3***: In this scenario, we bring up the success rates for all the courses to at least 90%.
- ***Scenario C_Load***: In this scenario, we allow each student to take five courses at most in each semester.
- ***Scenario I***: In this scenario, we improve the course sequences by applying the approach discussed in Section 3.2. We use the actual DFW rates and class fill rates in the simulation for all the associated courses.
- ***Scenario I_Access_1***: In this scenario, all class fill rates are brought down to under 100%.
- ***Scenario I_Access_2***: In this scenario, all class fill rates are brought down to under 95%. In other words, students are guaranteed a seat in any class they plan to take following the degree roadmap.
- ***Scenario I_Success_1***: In this scenario, we reduce the DFW rates for all courses by 50%.
- ***Scenario I_Success_2***: In this scenario, we bring up the success rates for all courses taken in the first year to at least 90%.

- ***Scenario I_Success_3***: In this scenario, we bring up the success rates for all the courses to at least 90%.
- ***Scenario I_Success_4***: In this scenario, we bring up the success rates of two critical courses, MATH 122 and MATH 123 to 85%.
- ***Scenario I_Prerequisite_1***: In this scenario, we simply remove CE 205 as a prerequisite for MAE 371.
- ***Scenario I_Prerequisite_2***: In this scenario, we remove the prerequisite requirements for all the courses. This is not a realistic scenario. However, it allows us to understand the pure impact of course prerequisite requirements.
- ***Scenario I_Load***: In this scenario, we allow each student to take five courses at most in each semester.

Table 3: Summary of simulation results

Scenario	Four-year graduation rate	Five-year graduation rate	Six-year graduation rate
C	**7.93%**	**65.33%**	**81.82%**
C_Access_1	12.59%	72.09%	83.15%
C_Access_2	16.76%	75.86%	83.50%
C_Success_1	28.48%	93.24%	99.16%
C_Success_2	8.86%	69.28%	84.88%
C_Success_3	21.52%	89.44%	97.18%
C_Load	0.00%	58.10%	81.53%
I	**22.03%**	**72.35%**	**82.65%**
I_Access_1	30.46%	77.23%	83.54%
I_Access_2	37.29%	79.64%	83.54%
I_Success_1	54.59%	96.74%	99.30%
I_Success_2	27.03%	78.39%	85.75%
I_Success_3	45.35%	94.09%	97.38%
I_Success_4	29.80%	81.44%	87.67%
I_Prerequisite_1	30.23%	78.28%	83.33%
I_Prerequisite_2	56.34%	83.61%	83.94%
I_Load	6.41%	67.28%	82.55%

The simulation results are presented in Table 3. The four-year graduation rates from the simulation model for the base case C closely matches the actual numbers we reported in Table 2. We also present the simulated five-year and six-year graduation rates just for informational purpose. Note that the simulated graduation rate is based on the assumption that students are willing and able to closely follow the degree roadmap and take five or even six courses per semester as suggested and the willingness is independent of the course accessibility issue.

Many insights can be drawn from these results. For instance, the results for scenario C_Access_1 and C_Access_2 clearly indicate that course accessibility can significantly affect the graduation rates. If we can ensure class accessibility for all students, we can bring the four-year graduation rates from the current 7.93% to 16.76%. The results for scenarios C_Success_1, C_Success_2 and C_Success_3 show the pure impact of class success rates on the graduation rates. While this shows another possible way to increase the graduation rates, it typically requires more effort and financial resources campus-wide. The results for scenario I imply that improved degree roadmap can dramatically improve the graduation rate without improving course accessibility and course success rates, i.e., from the current 7.93% to 22.03%. It is worth mentioning that this improvement requires minimum campus-wide resources. The results for scenarios I_Access_2 and I_Success_4 show a very promising direction. If additional resource is available which allows us to either ensure course accessibility or improve the success rates for a couple of critical courses, it is possible that we can bring up the four-year graduation rate to around 30%. This requires reasonable campus resources. The results for scenario C_Load and I_Load clearly demonstrate a challenge to CSULB and many other institutions. Due to the fact that many of our students have off-campus commitment, the university may need to offer more summer and winter courses for students to catch up, which may require more financial support from the government.

6. Conclusion and Future Research

Statistics show that less than half of America's college students ever graduate. Poor retention rate and extremely low graduation rate at US's large public schools have been draining state budget and causing concerns about the ever shrinking availability of affordable education to average Americans. Viewing the higher education institution as an operations system, our research applies operational research techniques to analyze and improve the processes on which students proceed to degree. We examine both demand and capacity of this system. On the capacity side, we find CSULB has a much tighter long-term aggregate capacity than its peers, as indicated by the significantly higher average class fill rates and the skewed distribution of fill rate toward overloaded courses. The tightness of aggregate capacity means that students cannot enroll in the courses they need due to insufficient seats. On the demand side, students have great difficulty navigating college without a clearly charted degree roadmap. On the flip side of the coin, due to the lack of patterns in students' course enrollments, the institution has no means to predict time-phased demand for courses, hence cannot proactively plan structural capacity to make the right seats available at the right time. All these three factors lead to the low probability of success course enrollment, and hence low timely graduation rate.

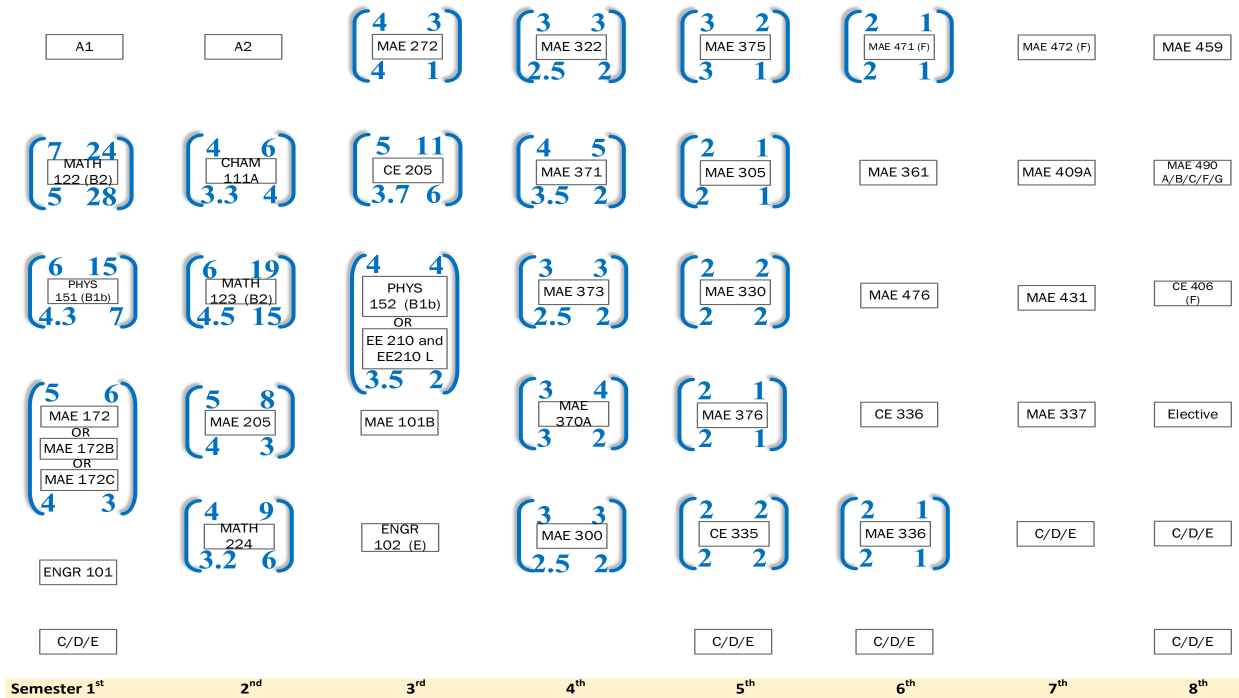
This study contributes to higher education timely graduation literature by proposing a probabilistic model-based method to improve degree roadmap. Given a particular curricular structure, our study applies line-balancing technique to find the optimized course sequence that can improve the timely graduation rate, while also taking into consideration of the robustness of the roadmap in terms of less susceptible to disruptions. The optimized degree roadmap points out a clearly charted course of actions for students. Through intrusive advising based upon the optimized degree roadmap, the institution can effectively guide the timing of students' demand for specific course seats. The institution can also better forecast time-phased demand and better plan structural capacity, making seats available for the right students, at the right time. While long-term capacity issue can only be solved by faculty hires and facility addition, an optimized degree roadmap design directly guides structural demand and facilitates structural capacity planning without adding additional cost.

Another major contribution of our research is to quantitatively assess timely graduation rate using probabilistic model and Monte Carlo simulation. Given a degree roadmap, the estimated probability of successful course enrollment, and the actual course successful completion rate, we can simulate the expected 4-year, 5-year, and 6-year graduation rates, respectively. The simulation results further prove that the optimization of roadmap design can significantly improve timely graduation rate. In addition, we run sensitivity analysis of the timely graduation rate in response to various initiatives and policy options. The sensitivity analysis identified most effective actionable options for administration. Our findings would stimulate a mindful conversation between state legislators, administrators, academic advisors and students to confront the essential timely graduation challenge at higher education. Some improvement recommendations are relatively easy to implement. Given the dismal budget situation that most public universities face, the insights derived from our research are essential for administration to direct limited resources to the most effective initiatives and policy adjustments.

We acknowledge that students' choices and behaviors would bear effects on the timely graduation rate. Our study on the structure of the degree roadmap focuses on full-time students only. Timely graduation for part-time students remains a challenge and the design of degree roadmaps for part-time students warrants a separate study. In addition, at this stage of our research, we haven't factored in variables such as student behaviors. For instance, some students may prefer exploring various fields of study before settling for one pre-determined degree roadmap right from beginning. For future research, we will use student survey as well as data mining in the current database to understand students' behavior, and prescribe more comprehensive solutions accordingly. We also will go beyond addressing the timely graduation rate problem for a specific degree to tackle course scheduling problem in a bigger environment, for example, a college that offers ten different major options that share certain common courses. The probabilistic model needs to be extended to handle the bigger environment accordingly.

Appendix

A-1: Importance Metrics for all Courses Required for Mechanical Engineering Degree



A-2: Average DFW rates and fill rates for all associated classes involved in MAE degree roadmap

Course	DFW Rates	Class Fill Rates	Course	DFW Rates	Class Fill Rates
MAE 172	12%	87%	MAE 375	13%	105%
ENGR 101	4%	98%	MAE 305	14%	97%
MATH 122	30%	103%	MAE 330	16%	106%
PHYS 151	16%	88%	CE 335	24%	102%
GE A1	11%	90%	MAE 300	3%	102%
GE A2	8%	90%	MAE 471	1%	114%
CHEM 111A	23%	96%	MAE 361	3%	97%
ENGR 102	5%	95%	MAE 376	13%	108%
MATH 123	31%	103%	CE 336	2%	105%
MAE 101B	3%	83%	MAE 336	7%	105%
MAE 272	22%	89%	MAE 472	0%	101%
MAE 205	21%	101%	MAE 409A	10%	106%
CE 205	16%	105%	MAE 476	12%	104%
MATH 224	27%	103%	MAE 431	5%	106%
PHYS 152	15%	88%	MAE 337	2%	108%
MAE 322	11%	96%	MAE 459	4%	94%
MAE 371	16%	107%	MAE 490	6%	110%
MAE 373	17%	98%	CE 406	10%	108%
MATH 370A	23%	105%			

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