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An Introduction to Curricular Analytics: Research and Applications for Curriculum Assessment and Review

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Author Note

"The curricular analytics tools discussed in this article are free and available for public use at https://curricularanalytics.org/home. I have no conflicts of interest to disclose."

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Abstract: With the recent development of curricular analytics tools designed to quantify the structure of a curriculum (Heileman, Abdallah, et al., 2018), some institutions of higher education are examining their curricula to find ways that these pathways to graduation can be improved (McMurtrie, 2021). The tools used to analyze curricula were created to address an issue of importance in the field of undergraduate engineering, that issue being the decreasing enrollment trend over the past two decades. The purpose of this article is to describe curricular analytics in a broad sense to extend its reach to the higher education assessment community. This article discusses why curricular analytics is increasingly important, provides elementary definitions and the theory behind it, summarized prior research, provides an illustrative example, and concludes with a discussion of the potential applications for higher education professionals.

Keywords:: *assessment, learning analytics, curriculum design, curriculum review*

Introduction

According to the curricularanalytics.org homepage, "the curriculum a student must traverse en route to a degree is the most foundational element for student success" (Curricular Analytics, n.d.-a). But how often do assessment or student success professionals examine the curriculum itself? A team of engineering professionals felt strongly about the potential benefits derived from examining the relationships between courses in a curriculum, focusing on the sequences involved in a curriculum, namely the courses and the relationships among them. Using the guiding principle that "student progress towards a degree is the most direct measure of student success" (Curricular Analytics, n.d.-a, 'Pathways'), the developers, led by Dr. Greg Heileman, developed the tools found on the curricularanalytics.org website. These tools focus on quantifying the requisite relationships among courses.

Curricular analytics can be thought of as "the general study of how program curricula impact student academic success" (Heileman et al., 2019, p. 3) and can be used "to quantify the complexity of curricula, simulate student progress under various scenarios, and create degree plans that maximize the chances of students completing their degrees on time" (Curricular Analytics, n.d.-a, 'Pathways'). The purpose of the tools developed for curricular analytics is to quantify a curriculum by providing an overall complexity value, along with several other metrics for use in curriculum analysis and redesign. These tools seek to empower institutions of higher education to simplify the course requisite structure of a curriculum or degree plan. It should also be noted that curriculum redesign in this sense is not a clandestine method of watering down the curriculum, but rather focuses on metrics allowing curriculum committees to design efficient curricula and degrees plans, by eliminating unnecessary or redundant coursework.

The development of these tools can be traced back to an issue faced by engineering programs across the United States, as a decreasing trend in the number of undergraduate engineering graduates in programs across the country led to serious conversations in engineering departments about how to remedy this situation and improve both recruitment and retention (Heileman et al., 2017). Curricular analytics tools were developed in order to increase student success. Two student-focused issues of central importance that curricular analytics addresses in higher education are retention and graduation rates (McMurtrie, 2021).

As a final note before proceeding further, anyone interested in pursuing curricular analytics should consult the curricularanalytics.org website. The developers have created templates (like the one used in Appendix A) for ease of use, as well as a built-in analytics tool that allows users to calculate metrics for their curricula. However, if you desire to use more advanced tools, like the curricular simulations module, the author recommends using the Julia language directly via Visual Studio Code. The necessary code for conducting basic curricular analytics is provided in Appendix B.

Definitions

Several definitions are important to the work and use of curricular analytics tools. These definitions tend to focus on the metrics used to quantify a curriculum. This section will briefly describe the most important terms used in curricular analytics.

- Blocking factor: Each course within a curriculum that acts as either a pre- or corequisite course blocks a student from taking the next course or courses within the curricular sequence. This metric is expressed as either zero or a positive integer and counts “the number of courses students are blocked from taking until they pass a given course” (Heileman et al., 2017, p. 7) within the curriculum.

- Corequisite course: A course “that may be taken either prior to or at the same time as the [next] course” (Heileman, Abdallah, et al., 2018, p. 4) in the sequence of a curriculum.

- Course complexity: A metric expressed as either zero or a positive integer that equals the sum of the delay and blocking factors for each individual course within a curriculum (Heileman, Abdallah, et al., 2018).

- Curricular complexity: A metric represented as a positive integer and calculated by finding the sum of all individual course complexity values for all courses within the curriculum. It “is determined by the interplay between the structural and instructional complexity of a curriculum" (Heileman et al., 2017, p. 11) and "directly relates how the structure of a curriculum impacts a student's ability to progress through that curriculum to graduation" (Heileman et al., 2019, p. 3).

- Curriculum: A sequence of courses that represents "the formal academic experience of a student pursuing a baccalaureate degree" (Lattuca & Stark, 2009, p. 3). For the purposes of curricular analytics, a curriculum is "the set of courses that a student must complete in order to earn the degree associated with that [academic] program" (Curricular Analytics, n.d.-b, para. 1).

- Curriculum graph: A visualization of a curriculum that utilizes "graph-theoretic concepts to quantify the structural complexity of curricula" (Heileman, Abdallah, et al., 2018, p. 7).

- Degree plan: A subset of the overall curriculum for any academic discipline, where one or more degree plans can be offered within a single curriculum (Curricular Analytics, n.d.-b). They are represented by "the term-by-term organization of…[the] curricula…that students are expected to follow" (Heileman, Abdallah, et al., 2018, p. 4).

- Delay factor: For an individual course, it represents "the number of courses on any prerequisite pathway that includes a given course" (Heileman et al., 2017, p. 7). Delay factor is expressed as either zero or a positive integer.

- Longest path: Related to the delay factor, this metric is expressed as a positive integer and "represents the longest chain of prerequisites through a curriculum" (Wigdahl et al., 2014, p. 5). Additionally, "the number of terms spanned by a longest path in a curriculum provides a lower bound on the number of terms required to complete that curriculum" (Heileman et al., 2020, p. 2).

- Prerequisite course: A course "that must be passed prior to taking the [next] course" (Heileman, Abdallah, et al., 2018, p. 4) in the sequence of a program's curriculum.

- Standalone course: A course that "has no prerequisites, and…is not a prerequisite to another course…and can be taken in any term" (Heileman, Abdallah, et al., 2018, p. 11).

- Structural complexity: A metric expressed as a positive integer that equals "the sum of the course crucialities in the [curricular] pattern" (Heileman et al., 2017, p. 8). More broadly, it is "the manner in which the curriculum is structured" (Heileman, Abdallah, et al., 2018, p. 6) and "is determined by the manner in which the courses in a curriculum are organized" (Heileman et al., 2017, p. 2).

It is important to note that although curricular complexity is defined as being the related to both the instructional and structural complexity of a curriculum, the metrics described in this paper do not focus on the instructional complexity. The instructional complexity is "more qualitative in nature, and thus more difficult to characterize mathematically" (Heileman, Abdallah, et al., 2018, p. 7). Thus, when speaking of the curricular complexity in this paper, the term is synonymous with structural complexity.

Theory

The theory behind curricular analytics comes from two disparate fields of study. One theory is Tinto's Dropout Theory, which is a sociological theory providing a framework for persistence and dropout in higher education (Tinto, 1975). Tinto's Dropout Theory, based on Durkheim's Theory of Suicide, examines and attempts to decipher what factors contribute to student dropout. Citing factors such as family background, pre-college education, educational goal commitment, peer and faculty interaction, and overall social integration at the institution, Tinto (1975) theorized that these factors were largely responsible for determining if a student would continue at that institution or make the decision to drop out.

The other field of study used to underpin curricular analytics is from mathematics. Within the field of mathematics, graph theory is used to provide the basis for the structural complexity calculations used to create the previously defined metrics. Curricular analytics uses graph theory terms such as vertices, edges, and paths. A detailed treatise on the mathematical foundations of curricular analytics can be found in Heileman, Abdallah, et al. (2018).

Prior Research

There exists a sizable body of research in the curricular analytics community. One area of prior research has focused on transfer students. Reeping et al. (2020) described the experiences of students transferring from community colleges into a four-year undergraduate engineering program using a curricular complexity framework. The study found that the curricular "complexity of the entire program increased substantially from 324 to 543 (+219) in Electrical Engineering and 612 to 726 (+114) in Computer Engineering" (Reeping et al., 2020, p. 7) for transfer students when compared to non-transfers. This study concluded that the engineering curriculum under study should consider allowing for the acceptance of additional coursework for transfer students in an effort to decrease roadblocks to success for these students.

In a second study related to transfer students, Reeping and Grote (2021) created four additional metrics connecting the work of Heileman et al. (2017) to transfer students. The authors theorized four metrics for transfer students: structural complexity, transfer student delay factor, lost credit hours for transfer students, and a new metric, the inflexibility factor. The inflexibility factor was defined as "a measure that quantifies how inflexible a curriculum is by examining the portion of the curriculum where courses are immovable" (Reeping & Grote, 2021, Table A1, p. 23). The authors sought to create additional metrics that focused specifically on transfer students and the unique curricular challenges faced by this subset of students.

Another study related to transfer students, from Grote et al. (2020), found that curricular complexity values showed great variability across different engineering disciplines. Further, for students in engineering disciplines that began at the same institution they started at (as opposed to transferring into that institution), curricular complexity was negatively correlated to graduation rates. However, there was no significant correlation for transfer students. This finding suggests that the curricular complexity transfer students navigate was lower than for non-transfer students. Yet despite this finding, transfer students were behind their non-transfer peers in four and five-year graduation rates. Another area that has been studied in curricular analytics involves the idea of program quality. A study by Heileman et al. (2019) examined the relationship between program quality of undergraduate electrical engineering programs and their curricular complexity values. The study used the 2018 U.S. News & World Report rankings and compared the curricular complexity values among three tiers of programs. They found "that higher quality electrical engineering programs have lower curricular complexity, and that lower quality electrical engineering programs have higher curricular complexity" (Heileman et al., 2019, p. 11). This finding was supported by another study examining computer science programs.

Heileman et al. (2020) also examined program quality within computer science programs using CSRankings (see csrankings.org) and again compared curricular complexity among three tiers of programs. The authors found "the complexity of the computer science undergraduate curricula at the highest quality programs…is drastically less than the complexity of the curricula at those departments judged to be at the lower end of this quality ranking" (p. 10). The results from both studies suggest that an inverse relationship exists between curricular complexity and the quality of the curriculum for undergraduate computer science programs.

Finally, it is worth mentioning an article that aids in the tedious task of data collection for the curricular analytics process. Reeping et al. (2023) provided an outline of a systematic process researchers can use to collect data for curricular complexity analysis. The article provides a solid foundational approach for any interested reader.

Illustrative Example

Curricular Analytics

Using a fictitious self-building certificate program, this section describes the use of curricular analytics in practice. Following the template in Appendix A, the first step is to record the curricular information in the curriculum template. In this case, the analysis uses the template for the overall curriculum, since students only have one option to choose from when completing the shelf-building certificate. There are no additional sub-plans or degree plans available. Templates for a curriculum or a specific degree plan can be found at curricularanalytics.org.

The template in Appendix A provides basic information about the certificate program, including information about individual courses, such as the number of credit hours, as well as the course prefix, number, and title. The template also captures all requisite relationships. In this curriculum, the course SLV 201 has a prerequisite of SLV 101, which is captured in the prerequisites column, with the course ID (1) for SLV 101 located in the column for SLV 201. No corequisite relationships were noted in the curriculum, while two courses had strict corequisite relationships, these being SLV 301 and SLV 302. It should also be noted that this curriculum has no standalone courses. Standalone courses often occur in curricula where courses such as general education courses are required to meet institution-level requirements, but do not impact the curricular requisites in the required courses for major of study.

After completing this step, the template is run using Julia code (or done through the curricularanalytics.org website). The curricular analytics output is provided in Table 1, and the curriculum graph is provided in Figure 1.

Table 1

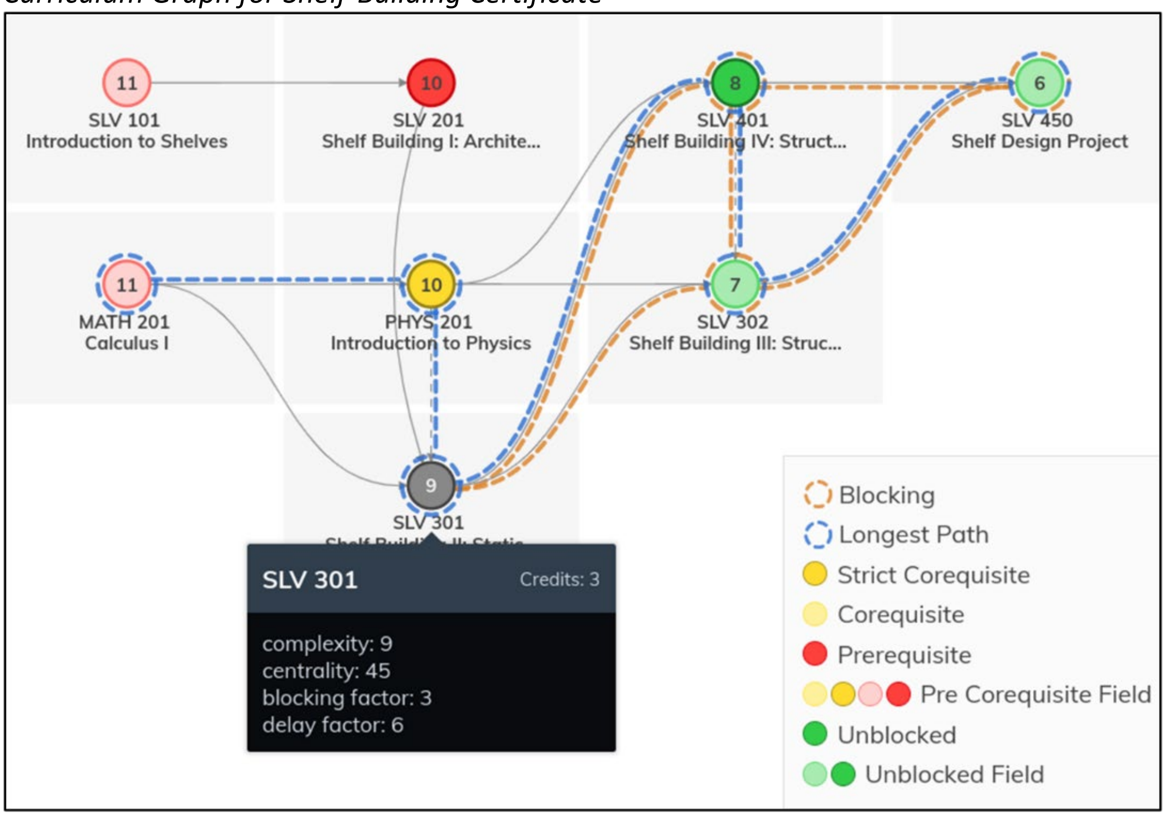
Curricular Complexity Output for Shelf-Building Certificate

Metric	Curriculum	Max. Value	Length	Number of paths
Blocking factor	24	5		
Delay factor	48	6		
Complexity	72	11		
Longest path			6	2

Note. The max. value is the maximum value for an individual course in the curriculum.

Figure 1

Curriculum Graph for Shelf-Building Certificate



The output also tells us that the total credit hours in the curriculum are 25, and the number of courses is eight. From Table 1, we see that the overall complexity of the curriculum is 72, which is the sum of the total blocking factor and total delay factor for the entire curriculum. The overall curricular complexity can also be calculated by summing the individual course complexity values. Information about the longest path is also provided. In this case, the length of the longest path is six, and there are two paths of this length. An example of one of the longest paths is presented in Figure 1 in blue. The interactive nature of the curriculum graph allows the user to visualize the relationships of the requisite structure.

Curricular Simulations

Another useful tool simulates the success of students within the curriculum. The simulation tool considers two inputs, one being the curriculum as described in the previous section. The other input is information about the course pass rates, which are used to determine a variety of simulated outputs. Additional inputs revolve around information about the maximum credit hours per term, the maximum number of times a student can attempt a course, and the number of students to simulate going through the curriculum.

The outputs provide information about the number of students who are predicted to graduate and stop out at each point in the curriculum. More helpful information can be found on the Curricular Analytics *GitHub* page.

Application of Curricular Analytics

There are several applications of curricular analytics for the assessment professional. The first is using these tools for enhanced curriculum mapping. These tools aid in curriculum mapping by considering the requisite relationships and providing an interactive curriculum graph, allowing for enhanced understanding of the curricular structure. Tied to this is the notion of curriculum redesign or enhancement. Although this is often left under the purview of departmental curriculum committees, assessment professionals can provide valuable insight into the process using curricular analytics tools. Questions could be asked, such as: Does a curriculum need all of the courses and credits it has? Can the curriculum be restructured? What does the length of the longest path tell you? The metrics could also be used to benchmark results from similar academic programs at other institutions. After a set period of time, the results could be used for periodic academic program review in order to gain a better understanding of curricular structures for programs.

Other applications in higher education include early alert and tutoring services. By identifying the courses where students are most likely to struggle, students can be identified earlier in the curriculum and receive tutoring services. Although this service has become commonplace on campuses for the last two decades, the tools in curricular analytics can provide new insights, especially when focusing on courses causing a delay, and long paths of courses students must navigate to complete the necessary requisites.

Two additional areas curricular analytics can be applied to are academic advising services and course selection and offering. Academic advisors can use curricular analytics to help students identify courses that fall on a long path and thus are most likely to delay that student from successfully navigating the curriculum. Course selection and offerings, whether done at the departmental level or by the registrar, can also serve as an important use of the curricular analytics tools. If, for example, a course is only offered every spring semester during odd years, it might be helpful to consider offering the course in every spring term. Likewise, if a course is only offered once per year, it might be beneficial to consider offering it annually, once in the fall and again in the spring terms. Both options could assist students who fail a course to reenter the curriculum with minimal delay.

Appendix A Curriculum Template

Curriculum	Shelf Building
Institution	Fictitious Institution
Degree Type	Certificate
System Type	semester
CIP	12.1234
Courses	

Course ID	Course Name	Prefix	Number	Prerequisites	Corequisites	Strict-Corequisites	Credit Hours	Institution	Canonical Name
1	Introduction to Shelves	SLV	101				3		
2	Shelf Building I: Architectural Design	SLV	201	1			3		
3	Calculus I	MATH	201				4		
4	Shelf Building II: Static Forces	SLV	301	2;3		5	3		
5	Introduction to Physics	PHYS	201	3			4		
6	Shelf Building III: Structural Mechanics	SLV	302	4;5		7	3		
7	Shelf Building IV: Structural Stability	SLV	401	4;5			3		
8	Shelf Design Project	SLV	450	6;7			2		

Appendix B Julia Code for Curricular Analytics

```
# Template for Curricular Analytics curriculum, not degree plan.
# 1. Load the packages:
    using CurricularAnalytics
    using CurricularVisualization
# 2. Load (read) the data for the curriculum:
    Program = read_csv("[Insert file path]/[CSV file name].csv")
# 3. Basic metrics:
    metrics = basic_metrics(Program)
    println(String(take!(metrics)))
    basic_metrics(Program)
    Program.metrics
# 4. Check if the curriculum is valid:
    errors = IOBuffer()
    if is_valid(Program, errors)
      println("Curriculum $(Program.name) is *VALID*")
    else
      println("OH NO! Curriculum $(Program.name) is NOT valid")
      print(String(take!(errors)))
    end
# 5. Create analytics output:
    println(" ")
    println("$(Program.institution)")
    println(" ")
    println("System type = $(Program.system_type)")
    println(" ")
    println("Delay factor = $(delay_factor(Program))")
    println("Blocking factor = $(blocking_factor(Program))")
    println("Curricular complexity = $(complexity(Program))")
# 6. Visualize the curriculum, creating a curriculum graph:
    visualize(Program, scale=.95)
```

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