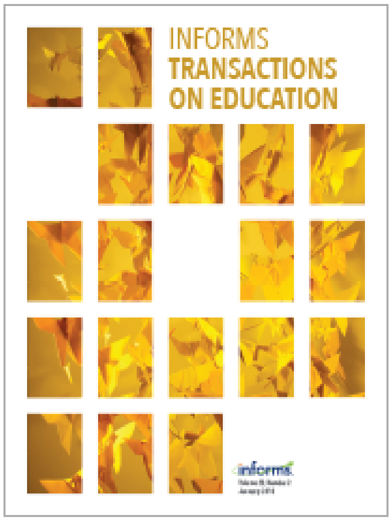

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A Student-Centered Approach to the Business School Management Science Course

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We describe a student-centered approach for the required business school management science course. We articulate three principles for teaching management science to business students: real-world context, spreadsheet-native attitude, and student self-efficacy. We examine the implications of these principles and how they affect course content and delivery. We show how to establish relevance as perceived by business students. We highlight the business analysis lifecycle as a valuable "roadmap" for students and instructors alike. We explain costs, benefits, and techniques for spreadsheet-native modeling. Spreadsheet modeling should be treated as a computer programming process, based on the properties of the spreadsheet programming language. We explain how and why to separate the modeling process from the act of typing into a spreadsheet. Spreadsheets can function as valuable organizational assets. We candidly discuss the challenges faced transitioning from a tools-based teaching approach to a student-centered approach.

Keywords: developing analytical skills; spreadsheet modeling; teaching management science; student-centered; business analysis lifecycle; business student
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1. Introduction

Teaching management science to business students is a fascinating challenge. Students are diverse in terms of prior experience, interests, and prerequisite skills. Management science is inherently mathematical, yet many business students find mathematics a barrier to learning rather than a language for precise communication. Management science is focused on analysis whereas business students are interested in influencing an organization and having an impact on business outcomes. The challenges were articulated in an insightful INFORMS task force report (Jordan et al. 1997, §3.3) which found that for business schools, "the demand is for courses that focus on business situations, include prominent non-mathematical issues, use spreadsheets, and involve model formulation and assessment more than model structuring."

We start with the students and seek to shape management science concepts into a coherent package that fits their worldview and abilities, rather with a traditional mathematical approach to teaching that is adjusted (some would say "dumbed down") for business students. Our approach is less "eat your spinach" and more "have a tasty meal that is good for you." We recognize that there is a tension here, because what business students experience as tasty and nutritious can seem like fast food to faculty with a doctorate in applied mathematics.

This paper describes a student-centered teaching philosophy that addresses the concerns of Jordan et al., that has been successful for us at the University of San Francisco. We have most fully developed this approach in the full-time MBA, but are also using it successfully with part-time MBA, executive MBA, traditional undergraduate, and nontraditional undergraduate students. Whatever the demographic, the task for the instructor is always the same: invest in learning about the students so that we can "meet them where they are" to help them get to where they seek to go.

The Student-Centered Approach

We follow in the footsteps of the broader student-centered learning and activity theory concepts found in the education literature (see Jonassen and Land 2000 for more details and references). In particular, our goals for our students include inculcating skills and practices that enable independent problem solving and lifelong learning, which we believe to be essential to enabling them to apply the ideas and tools from our management science course in their own professional careers.

Our approach to teaching the business school management science course is based on careful and respectful consideration of the interests, skills, and objectives of our business students. This leads us to three key principles of teaching (§3) that have caused us to rethink all aspects of our work. We describe these principles, rigorously explore their implications, explain how this affects what and how we teach, and discuss some of the challenges faced by instructors in adopting this approach.

The student-centered approach led us to articulate a value proposition to our students, which boils down to this: "We will teach you to harness the power of mathematics to influence a business, even if you are bad at math." We deliver on this promise to students first by teaching them the foundation of all quantitative analysis—the ability to create a mathematical model that they can use to perform computations—and second by giving them a "roadmap" to the analytical process that will allow them to use that model to influence an organization.

It is this foundation that enables students to be independent Problem solvers and life-long learners, for it provides the mechanism to engage constructively with quantitative analysis. Only after this foundation is established are business students ready for more sophisticated management science ideas to be delivered, whether later in the core course or in elective courses.

This approach is aligned with the recommendation of Powell (1997) that business students be educated to be "active modelers" and users of quantitative analytical tools, not mere "educated consumers" of the work of management science consultants. Our job is to empower students to function as independent analysts (albeit at a much less sophisticated level than their expert faculty) by insuring they have the ability to create a model and use it in an organizational context. Our students crave this, especially those with poor mathematical skills or who feel a sense of innumeracy.

This student-centered approach has proved highly successful for us. When we started teaching this course at USF in 2004, our required management science course was not particularly popular. After the changes, which were mostly implemented by 2009, students greatly value this course, and the instructors routinely receive a disproportionately large share of the teaching awards from the MBA student society (in the three-year period 2011–14, we taught 8% of the MBA sections and received 33% of the awards). Instructors in the core finance course have asked that their course be taught after our course so they can leverage the students' improved practical quantitative skills. Most importantly, after we adopted this student-centered approach, students began proactively to approach MBA program administrators to ask for management science elective courses as a follow-on to the required course. We now offer 12 semester-units of elective courses (previously there were no elective courses), and many of the courses are over-subscribed, even as overall enrollment shrinks. This has helped us to hire new tenure-track faculty in our department.

Contribution

This paper makes several contributions. We articulate three student-centered principles for teaching management science to business students, based on real-world context, spreadsheet-native attitude, and student self-efficacy. We discuss in detail the teaching implications of these principles and what can be done to bring them to life. We give examples of readings that can be used to place course content into a meaningful business context that establishes relevance as perceived by business students. We highlight the business analysis lifecycle as a valuable "roadmap" for students and instructors alike. We explain how modeling can be done in a spreadsheet-native manner, and explain the time investment necessary. We show the benefits of treating spreadsheet modeling as a computer programming process, and we present key properties of the spreadsheet as a programming language. We use software engineering concepts to explain why modeling should be kept separate from spreadsheeting, and how this can be done. We encourage instructors to educate students on the importance of spreadsheets as valuable organizational assets. We candidly discuss the challenges faced by an instructor who seeks to transition from a more traditional tools-based teaching approach to a more student-centered approach. We believe that many aspects of our experience with student-centered teaching will be valuable to instructors at other institutions.

Overview

We discuss in §2 the characteristics of business students, qualities that we have kept foremost in mind while designing, teaching, and evolving their required management science course. In §3, we articulate three student-centered teaching principles and in §4 rigorously explore their implications. We discuss (§5) the challenges and growth opportunities for instructors seeking to adopt this type of approach. We conclude in §6 with suggestions for further work.

2. Common Characteristics of Business Students

Our journey toward a student-centered teaching approach began with an honest examination of who business students are. These students differ from their management science instructors—that is, us—in significant ways. In this section, we examine some of these differences and explore their implications for how to most effectively support learning by these students.

Intrinsic Interests and Professional Objectives

Business students are typically interested in learning how to improve business outcomes and meaningfully address practical problems of relevance within the context of the business world. Business students are highly motivated to obtain robust, meaningful skills that can help them to contribute, succeed, and be recognized and rewarded in today's unpredictable and complex business world.

Business students are often skeptical or disinterested in classroom content when the relevance of that content is not readily apparent to them. This trait can cause faculty to describe them as "lacking intellectual curiosity." Undoubtedly this is true of some business students.

However, we believe that this characterization is not necessarily fair nor even accurate. We offer a different interpretation. In contrast to many management science instructors, business students are not inspired by mathematical problems; the opportunity to delve into properties or computational efficiency of algorithms is not exciting to them; they are not particularly motivated by the successes of management science professionals who utilize skills they don't have. It is to be expected that they lack curiosity on these topics, even though they are of keen interest to their instructors.

In our view, the burden is upon us as instructors to make our course content relevant to students' interests and objectives, *as perceived by the students*, so that they are intrinsically interested in what we do. We have the right, perhaps even the obligation, to stretch and challenge them and to uphold high standards. But it ought to be done in service to the students' objectives rather than to instructor preferences. The challenges we give to students are ones where they recognize the value of mastering the challenge and therefore engage willingly. We provide specific suggestions later in the paper for establishing and maintaining a sense of relevance.

Relationship with Mathematics

Most business students are not particularly comfortable with mathematics. In our MBA program, fewer than 20% of students have a STEM background, which is a strong signal of mathematical skill. In our BSBA program, administrators tell us that most of the mathematically talented students change programs, usually to do a BA in economics, because that program is a better fit for their skills. INFORMS has flagged poor mathematical preparation as a challenge (Jordan et al. 1997), and other sources are provided by Grossman (2001). Savage (2009) aptly describes an "algebraic curtain that separates management students from management science."

Many of our business students have little to no facility with algebraic notation, which restricts their ability to learn management science through the traditional medium of algebraic representations. In many cases, this relative lack of mathematical preparation can be coupled with significant anxiety about any math-related activities, making learning even more difficult.

In contrast, management science instructors enjoy math and are good at it, normally possessing degree(s) in mathematically rich disciplines such as statistics, operations research, or engineering. We recommend that business school management science instructors cultivate the ability to relate to their students' anxieties and struggles with mathematics and algebraic notation.

One of the most satisfying teaching experiences for an instructor is to find a way to empower business students to achieve a level of competence at quantitative analysis that they never themselves believed possible. We describe below how this can be achieved.

3. Student-Centered Teaching Principles

As instructors teaching a required management science course, our high-level goals are to enable our business students to recognize opportunities for the powerful capabilities of quantitative analysis in general, and management science in particular, and to appropriately utilize those capabilities in the business world after completing the course.

After teaching this type of course for both undergraduate business majors and MBA students on a regular basis for several years, we found ourselves challenged to re-design our course to take into account the mathematical mindset, intrinsic interests, and professional objectives of our students.

Over time, we have identified three important student-centered principles:

1. Embed instruction in real-world context
2. Create a spreadsheet-native teaching environment
3. Develop a classroom culture of self-efficacy

In this section, we briefly discuss each of these principles and how they are directly connected to the student characteristics described above. In turn, these tightly integrated principles have several important implications for instructional design and delivery, which we explore in the following section.

Principle 1: Embed Instruction in a Real-World Context

As discussed above, business students are in general motivated by opportunities to influence the actions of their company. As instructors, we work hard to establish in their minds that the skills we ask them to master will be relevant to them.

In particular, at the start of every class session, and when we introduce a new topic (e.g., modeling, spreadsheet design, spreadsheet engineering, selecting base case values, basic sensitivity analysis, optimization, etc.), we are rigorous in discussing how that topic serves a business purpose that is relevant to the kind of work business graduates do. We are careful to frame analytical activities not in terms of a technical context ("what is the right answer"; "what is the most efficient solution approach") but instead in a business context ("how can you use that right answer to persuade your boss to change"; "how can you hand this off to the next person").

We believe that this is key to motivating students, particularly students with weaker quantitative or programming backgrounds who find the course inherently challenging.

Principle 2: Create a Spreadsheet-Native Teaching Environment

We teach a course that is spreadsheet-native from start to finish. With very rare exceptions, all data and calculations are discussed and presented in the context of spreadsheet cells.

There are several reasons for this. First of all, regardless of their backgrounds, virtually all of our students are aware that spreadsheets are a ubiquitous tool in nearly every business environment, and that developing solid spreadsheet skills is inherently valuable in its own right. Secondly, the interactive nature of spreadsheets helps keep business students engaged. Finally, by avoiding algebraic notation, we reduce math anxiety, which in turn improves the students' capacity to learn and master the course topics.

Principle 3: Develop a Class Culture of Self-Efficacy

Business students often come into our required management science course with serious doubts about their ability to be successful, and hoping merely to "get through" the class. This is a consequence of their concerns about their mathematical aptitude and/or preparation. In addition, students who do not come into class with a strong background with spreadsheets are often concerned about their ability to do what the course requires of them. It is to their benefit (and ours!) for them to take "ownership" (self-efficacy) of their learning.

We take steps to establish a sense of self-efficacy through guided mastery (Bandura 1993). Recent neuroscience research shows that providing exercises that help students focus their attention is very effective in reducing math anxiety and improving performance (Lyons and Beilock 2012). We start this prior to the first class session.

A few days before the start of the class, students participate in an initial 2–5 hour "boot camp" on Excel basics. This insures that students can navigate Excel, save files, write a simple cell formula, and do basic formatting. However, the main value of the boot camp is less about skills and more about establishing a culture of self-efficacy. Boot camp is led by student instructors who have successfully completed our course, and provides the new students with role models, many of whom had the same doubts prior to taking the class themselves. A theme of boot camp is personal ownership of skills. The boot camp provides demonstrations accompanied by written reference material. The message from the student instructors is "here is what you need to master, and if you don't master it now you need to do so on your time, right away." This sets the tone early, and helps create a culture that each individual student knows they can succeed, and that each individual student understands that they need to take responsibility for their own learning.

In our experience, self-efficacy results in the best learning when expectations are clear, students can self-identify gaps in their knowledge, and external support is immediately available. We routinely discuss and use email to remind students of the things they need to master before next class. We regularly assign ungraded in-class and out-of-class exercises which allow students to evaluate their own abilities, as well as to learn. (These also allow us to monitor student performance, answer student questions in real time, and "take the pulse" of the class.) Students have on-demand access to resources such as teaching assistants (who routinely make themselves available in the commons), videos on YouTube and Lynda.com, and above all the assistance of their fellow students who are often seen in the commons helping each other.

In addition, our decision to eschew the use of algebraic notation supports a culture of self-efficacy, because we ask students only to learn things that are within their reach. Facility with algebra and algebraic notation is similar to facility with a foreign language; a student who lacks basic language (or algebra) skills simply can't fix that during our course, and that contradicts the goal of self-efficacy.

4. Teaching Implications of the Student-Centered Principles

Taken together, these student-centered principles have had a substantial impact on the design and delivery of our core management science course for business students. In this section, we discuss some of the major teaching implications.

Establish Business Context and Relevance Up Front, and Don't Stop

We begin to embed instruction in a real-world context from the very outset of the course. Strange as it may sound, the relevance and importance of analytical work in general, and management science in particular, is not necessarily obvious to business students. Their background has not made this visible to them. They need to be educated, or even "sold" on this idea. At the start of the course we take time to present evidence of relevance, and throughout the course we connect what we teach to that evidence.

We provide readings that help students understand the role of analytical models and spreadsheets in business. There are many such readings. We typically assign a few for discussion, and encourage students to peruse the rest. We regularly mention findings from these readings during class and in informal discussions with students outside of class.

The readings we find valuable fall into two categories. First are empirical investigations of how spreadsheets are used in practice. Croll (2005) discusses the critically important role of spreadsheets in financial services. Grossman et al. (2007) provide a rich empirical examination of how important spreadsheets are used in practice across many industries, including examples of spreadsheet application software (software written by developers and distributed to users), and accidental legacy spreadsheets (spreadsheet models inherited by a person when they step into an existing role). Schrage (1990) discusses how spreadsheets are essential tools for evaluating many possible business possibilities, and includes a glorious description of how bankers "out-spreadsheeted" their counterparty in a billion-dollar negotiation.

The second category is case studies of analytical spreadsheet models in individual firms. We find Olavson and Fry (2008) to be a compelling read for business students. It discusses how spreadsheet models are used at Hewlett-Packard, including the role of spreadsheet applications suitable for handoff to internal customers, and providing a valuable flowchart indicating whether analysis is even appropriate and what type of analytical engagement to undertake. Farasyn et al. (2008) describe how Procter and Gamble uses spreadsheet models to manage inventory worldwide. Oggier et al. (2005) describe how Nestlé used spreadsheets to improve modeling across a global corporation. Additional readings of this nature are summarized in Leblanc and Grossman (2008).

Students do not have unlimited time, but we find it valuable to ask them to do these readings, and to invest some class time to discuss the key findings. We have learned that this is time well spent, because when students believe a topic is relevant to them, they will be far more motivated to work hard to master concepts they find challenging, and we can push them harder without creating problems with teaching ratings.

As a final note, we eschew readings, including most papers in *Interfaces*, that describe the success of management science specialists using skills and tools that are out of reach of a typical business student. Such successes, although inspiring to us as management science specialists, are not relevant to our students.

Provide a Roadmap to Connect Technical Work to Business Context

When students are wrestling with challenging technical work, it is helpful to provide them with a roadmap of how their efforts are in service to the larger goal of influencing business outcomes. This does not make the students' struggle any easier, but it does make it more rewarding and we believe that it increases student morale and satisfaction.

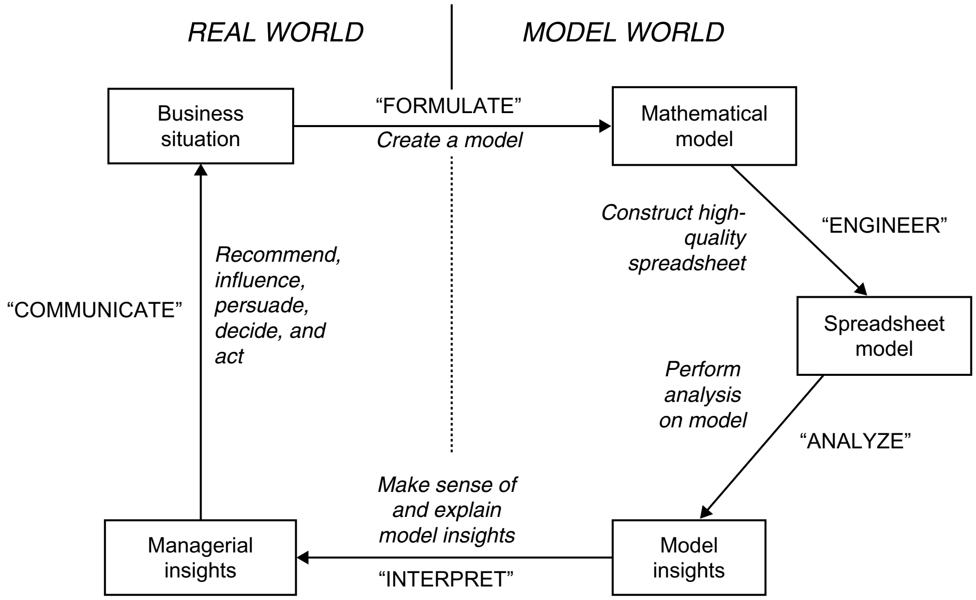
The roadmap takes the form of a conceptual framework called the Business Analysis Lifecycle (Figure 1). This lifecycle model was originally developed by Powell and Baker (2007), and extended and discussed in detail by Grossman et al. (2008).

The need for such a roadmap was underscored by Jordan et al. (1997, §3.3) which highlighted the need to address "business situations,…use spreadsheets, and involve model formulation." Figure 1 integrates these important recommendations, and identifies specific activities that students need to learn.

The roadmap distinguishes between a "Model World" and a "Real World." Model World is the realm of the *technician*. In Model World, we are concerned with the details of a model, its computer implementation, how to analyze that model, the exact numeric values that emerge from the analysis, and we seek to discover the optimal decision. In contrast, Real World is the realm of the *manager*. In Real World we are concerned with the (messy) business situation and the practical, social, and political issues that affect business decision making, and we seek to influence how an organization ultimately takes action. To be effective, the analyst needs be able to work in both the Model World and the Real World, and needs to fluidly cross the boundary between them.

The business analysis lifecycle is the five-phase loop in Figure 1. It begins with a *business situation*—something important to the organization. The analyst

Figure 1 The Analysis Roadmap (Business Analysis Lifecycle)



uses his understanding of the business situation to *formulate* a *mathematical model* that captures the quantitative relationships inherent in the business situation. The act of formulation is the bridge between the Real World and the Model World. It is here that the analyst makes assumptions about what to include and exclude from the model and which data will be necessary.

The analyst must then *engineer* a *spreadsheet model* to implement the mathematical model as a computer program. Because the only programming language available to business students is the spreadsheet, all models are implemented in spreadsheets. As discussed later in the paper, careful attention needs to be paid to the nuances of spreadsheet design and programming.

The analyst next will *analyze* the spreadsheet model using one or more structured techniques or algorithms to generate *model insights* that summarize the analytical results. Model insights are framed in the Model World and therefore are numeric, exact, and use technical terminology.

Next, the analyst needs to *interpret* the model insights and articulate them as *business insights* that summarize the meaning of the analytical results. Business insights are framed in the Real World and therefore are verbal, approximate (the model is only an approximation to reality), and use business terminology. Interpretation is the bridge between the Model World back into the Real World. The analyst must revisit any elements of the business situation that were assumed away during formulation.

Finally the analyst *communicates* the business insights to influence real-world decisions and actions that ultimately affect the business situation. This requires leadership and managerial skills to craft a message that can be understood and will be acted upon by people in the organization.

This roadmap establishes several key ideas immediately, including:

- The time and effort we ask students to expend is for the ultimate purpose of improved business understanding, insight, and action
- Any analytical shortcuts (or cool technical tricks) exist in service to the business outcome, and are not valuable in and of themselves. (It is important for research-active management science instructors to remember this!)
- The importance of separating formulation of a model from engineering a spreadsheet. For small problems, especially illustrative textbook examples, one can write a spreadsheet model directly without a separate formulation step. For larger problems, this approach breaks down and one must consider the conceptual representation of the business situation (formulation) separate from the programming (spreadsheet engineering).
- The importance of having in hand a well-engineered spreadsheet model as a prerequisite to conducting analysis.

We keep a copy of the roadmap in a separate file and routinely display it throughout the course, especially before embarking on a technical topic that students find challenging. In our experience, this is a very helpful mechanism for helping students to understand when it is appropriate to raise a business question, which resides in "real world," and when it is appropriate to raise a technical question, which resides in "model world" (Powell 2008). It is also central to giving students a sense of purpose when they are struggling.

Address All Phases of the Roadmap

For students to be effective in the workforce, they need to be able to complete the entire loop of the lifecycle. For example, if a student is very strong on, say, "analyze" but can't "engineer" a spreadsheet model that is suitable for analysis, that student will not be able to perform analytical work on the job; and we will have failed to prepare them to have an impact in business. Thus, It is essential for the instructor to insure that students have reasonable ability in all five phases of the lifecycle.

Typically, business school management science courses are strong on the "Analyze" phase of Figure 1. We have reflected upon student awareness and course content on the other phases. We address all five phases in our required business school course. Part of our approach to the "Interpret" and "Communicate" phases are addressed in Grossman et al. (2008). In our experience, the primary barriers to student application of analytical techniques reside in the "Formulate" and "Engineer" arrows of Figure 1, which is considered in Grossman et al. (2015).

Be Concrete Rather Than Abstract

The decision to be spreadsheet-native requires that a model be represented and manipulated using a spreadsheet. A spreadsheet uses "concrete" numbers rather than "abstract" mathematical equations to represent a model. Any spreadsheet model can be directly converted to a set of algebraic equations and any set of algebraic equations can be programmed in a spreadsheet. Although the two model representations are equivalent, the choice of representation affects how one understands, communicates, and interacts with a model.

A model represented using algebraic equations uses variables to represent numeric values. An algebraic model can be seen and discussed independent of any specific numeric values. Mathematical formulas can be written but are not actually computed. Algebraic models are inherently abstract.

A model represented as a spreadsheet uses cells to contain specific numeric values. Models can be seen and discussed only when specific numeric values are entered into cells. Mathematical formulas are automatically computed as soon as they are written. Spreadsheet models are inherently concrete.

These are fundamental differences that profoundly affect teaching and learning. When working with algebraic models, the unit of manipulation is the equation, and the intellectual work is performed using mathematical abstractions. When working with spreadsheet models, the unit of manipulation is the cell, and the intellectual work is performed using concrete numbers.

For instructors, this means that any discussion of a model must be done in concrete terms, using numbers. Any equation that is presented should be worked out using numbers. This requires that even simple model examples be computed. The instructor must allow time for the use of a hand calculator (or spreadsheet) for students to compute numeric results.

This is more time-consuming than using the more powerful algebraic abstraction. For students with strong mathematical preparation it quickly becomes redundant. However, our experience has taught us that taking the time to do this is essential for students with limited or no facility using the abstract representation. This is the foundation for all future learning by these students, and we have found that this choice opens the door for many of them by decreasing math anxiety levels, lowering barriers to understanding technical ideas, and enabling them to genuinely learn the course content.

Teach Spreadsheet Modeling as a Computer Programming Process

Students are eager to learn to build spreadsheet models because they know this will help them advance their careers. We give our students a simple spreadsheet modeling problem at the start of each course and have discovered that most of our students are not very good at building spreadsheet models. Some are unable to build even small-scale models. Some do hand calculations that they enter into a spreadsheet (this is not from lack of basic spreadsheet skills, as all students attend a multi-hour spreadsheet boot camp prior to the first day of class). Some students who are able to build small models find it difficult to build larger models. Even those students with solid spreadsheet skills sometimes struggle to articulate what they do and why.

This is not because these students are foolish. Rather, it has to do with the challenge of computer programming. When you write a spreadsheet model, you are writing a computer program. Some of our students lack even the most basic concepts of programming. They need to be taught. To do this well requires we understand the properties of the spreadsheet as a programming language, teach our students to separate the task of modeling from the task of creating a spreadsheet (called "Formulate" and "Engineer" in Figure 1), and teach our students the basics of software engineering for spreadsheets so they can create quality spreadsheets.

The Spreadsheet as a Programming Language. Spreadsheet programming can seem easy. But this ease can be misleading, because the informal approach that people commonly use to build a small spreadsheet model will not in general "scale" to create a larger spreadsheet model. This can lead to dire consequences.

As discussed in a classic software engineering text (McConnell 1996, p. 518) the spreadsheet is a programming language with much to recommend it, and "spreadsheets boost productivity through the roof." The spreadsheet language belongs to the class of rapid development languages (RDL). RDLs have natural-language type features, are easy to learn, and provide very high productivity. However, RDLs encourage programmers to use sloppy design and coding practices, and such practices cause difficulties on larger projects. McConnell argues that programmers using RDLs should employ careful design and coding standards. And so it is for spreadsheet programmers.

Some of our students have sufficient prior experience with spreadsheets that they have discovered coding practices that are effective. Very few have received advanced training from prior employers. But the large majority have never been taught nor seriously considered how to go about constructing a spreadsheet. They utilize what might be called a naïve programming approach, or what McConnell calls "sloppy practices." The naïve approach can be effective for small models, especially for ones that will not be maintained or extended over time. However, as McConnell warns, the naïve approach does not work for larger models, and the breakdown can come suddenly as model size increases.

This issue is often not appreciated by people, including instructors, who have not programmed sizable spreadsheet models. It is qualitatively different to build a sizable spreadsheet model, and the task is best approached as a software engineering exercise and must not be treated as a casual, trivial activity. If we do not teach students practices that will work for larger spreadsheet models, they will stumble into these issues on the job and it will limit their effectiveness. Most important to instructors, this will reduce or eliminate the possibility that they can utilize management science techniques in the workforce.

Based on our experience, we strongly believe that management science instructors should teach business students effective practices to design and build spreadsheet models. This is a natural consequence of spreadsheet-native instruction.

Separate Modeling from Creating a Spreadsheet. A fundamental insight from the field of software engineering is that one should determine what shall be programmed prior to programming it. In the language of management science, this means separating the task of modeling from the task of creating software to implement the model. However, spreadsheets have the attractive property that, for small models, modeling and spreadsheet development can be conflated. This is a great boon and is a primary reason that spreadsheets are so popular.

Following Powell and Baker (2013), we define modeling as the process of determining the relationships between the inputs, calculations, and outputs. Based on the findings of Powell and Willemain (2007) and Willemain and Powell (2007), we also believe that modeling needs to be done in some fashion prior to touching the spreadsheet, and that this practice is particularly important for novices as well as for others who lack extensive experience with conceptualizing and implementing mathematical representations of business situations. Students resists this, until they encounter a model that is large enough that their naïve approach fails; then they become converts.

Teach Students How to Construct a Quality Spreadsheet. After the model has been completed, it is time to create the spreadsheet. However, creating a good piece of software requires good software engineering practices. Issues of structure, design, usage, maintenance, reusability, transferability others, and the best way to actually write formulas all enter into the discussion.

It is important to understand that this is not mere "spreadsheet tips and tricks" but is in fact software engineering for spreadsheets, a topic worthy of study and mastery. Leong and Cheong (2008) make important contributions in this regard. Powell and Baker (2013, Chapter 2) provide much practical wisdom. Grossman (2006) provides guidance on spreadsheet engineering, including modularity, separation of calculations from data, row-and-column structure, visual formatting and labels, clear logical flow, and also on the task of programming by actually writing cell formulas. There is much opportunity for further research on guidelines and process.

Teach Students to View Quality Spreadsheet Models as Valuable Organizational Assets

Readers of *Interfaces*, the OR Practice column in *Operations Research*, and many research articles will notice that some successful management science models are employed repeatedly over time or even integrated into daily business processes. Such models are valuable organizational assets and are carefully managed by their owners.

The same is true of successful spreadsheet models. The empirical literature on spreadsheets (discussed above) shows clearly that important spreadsheet models often serve as valued organizational assets. These assets are utilized repeatedly over time as a vehicle for model calculations, for relatively simple and sensitivity analysis (highly valued in practice), and for utilization of management science techniques.

Spreadsheet model assets can be transferred (formally or informally) from an analyst to the analyst's successor, sometimes for several generations of analysts. Spreadsheet model assets can be transferred from consultant to client, and some consulting firms have rigorous standards for such models. Spreadsheet model assets can even be made into spreadsheet application software that is purposefully deployed to multiple users around the globe.

This concept provides a rich organizational and career context for spreadsheet modeling work. It makes business students excited about the possibility of leaving a lasting legacy in their job, and that helps excite them about our course. It also piques student interest in learning how to create quality spreadsheet models that are suitable for long-term use.

5. The Instructor's Journey: Challenges in Adopting a Student-Centered Approach

As graduate students who studied analytical algorithms and techniques, and young instructors who inherited a tools-based course, we conceptualized the business school management science course as a big box of tools. Our job was to introduce tools to students as fast as we could. Office hours were spent mostly with the top students who were fun to work with, and whose high levels of engagement made us feel that we were doing a good job. There was no real consideration of whether students, especially the median student, were genuinely being prepared to utilize the tools in a messy business world, and there was no culture of seeking feedback from alumni on the impact of our teaching. We simply carried on.

We now conceptualize our job as giving the majority of our students the genuine ability, confidence, and understanding to influence an organization's performance by appropriately building and using mathematical models. This change in mindset is the key. Note that the "organization" comes before the "mathematics." This is in marked contrast to our graduate training, where issues of organizational impact were ignored or treated blithely in a few sentences in a report, as if getting an organization to do something different was somehow easy, uninteresting, or unimportant.

This new conceptualization required us as instructors to be aware of our own tacit assumptions and biases, to teach not as we were taught, but instead to "meet our students where they are" by teaching to their strengths. This led us to the hard work required to understand and address foundational skills. It forced us to engage more richly with the problem of the algebraic curtain, which led to the decision to become spreadsheet-native, to recognize the importance of self-efficacy, and above all to frame the course in terms of business impact rather than tool-study (a wag might say "tool fetish").

Learning about students has become a distinct "task" for us. We make a point of attending orientation events to ask incoming students about their backgrounds, skills, aspirations, fears, strengths, and so forth. We do a web-based survey on student background and worries just as the course begins. As the semester goes on we continue to dialog with students at breaks and outside of class, and we ask our teaching assistants for their thoughts. In addition, a key source of information is professional staff. We regularly reach out to student-facing staff in roles like advising, career services, and alumni relations. They think differently than we professors do. We find that nonacademic staff have many valuable insights to share. Students will tell them things they won't tell us. We wonder whether the academic side of the house systematically under-utilizes the resource of student-facing staff.

One important point: This is a lot of change. It takes time. There is much to be learned, and to be unlearned. It can't all be done at once.

Using the Roadmap to Stay "Business Focused" Not "Tool Focused"

One of the challenges we faced was to bring our own attention to the business and reduce our focus on the tools. We discovered that the roadmap (Figure 1) is very helpful to us as instructors. It is a regular reminder to stay grounded in the larger student-centered context of influencing a business outcome. The discipline of referring to the roadmap at the start of each class session helped us to see areas where there were missing pieces, or where the content was excessively technical. In particular, the roadmap makes it easier for us to release our desire for students to find the "best," "most efficient," or "most elegant" technical approach, and instead to help each of them develop the ability to get through every phase of the loop in some reasonable way.

Struggles, Frustrations, and Hard Decisions

As we adopted this approach, we found at first that it was inefficient and frustrating to present even a simple model without using the power of algebraic variables and subscripts. However, the benefit to students—especially the median student and the weaker students with poor mathematical skills and/or high levels of math anxiety—convinced us it is worth the effort to be fully spreadsheet-native. This led us to learn the students' language for models, which is concrete and spreadsheet-based, and refers to model elements using cell references rather than algebraic variables. By explaining the structure of the model in these terms, rather than as mathematical entities, our business students can get a far clearer conceptual understanding of model calculations and outputs. But the cost in efficiency still sometimes grates.

One might argue that instructors should insist upon using the algebraic model representation because of its precision, scalability, and efficiency. This argument is not without merit. We tried this for years. However, we came to realize that it is not in our power to remediate students with weak algebraic preparation. And if students don't "speak the language" of algebra, we are not actually communicating with them if we persist in using a model representation they cannot fully understand.

So we had to choose. Either continue to speak primarily to the minority of students with strong preparation, or speak to the class as a whole. In our view, in an elective course one has the privilege and pleasure of choosing the former, but in a required course one has an obligation to choose the latter. Once we realized that it was in a very real sense our job to find a way to teach quantitative skills without algebra, our attitude shifted from frustration and resistance to curiosity and experimentation.

Similarly, we were at first uncomfortable with having to explain the business relevance of management science methods and spreadsheet models to our students. Not only did this seem self-evident, but we also wondered about whether we might be wasting valuable class time. We now understand the importance of educating students on the context in which they will apply our tools in the working world, and it is essential for motivating our students to engage fully with the course.

Handling the Challenge of Syllabus Pressure

A difficult challenge for us was to release "syllabus pressure." In a traditional tools-based course, there might be a week or two each on optimization (perhaps with separate explorations of linear programming, nonlinear programming, and metaheuristics), decision analysis (or at least decision trees), simulation, Bayes rule, t-tests, z-tests, forecasting (with a multitude of possible models), and so on. We used to teach such a course. Some syllabus pressure can come from the need of a "service" course to deliver tools to be used in later courses. We explored this intensively with colleagues in other departments and found that there are only very few of them who genuinely utilize the tools in their courses. For us, most of the syllabus pressure was self-inflicted.

We sought feedback from students and alumni on the utility of the course. (Because our school has only recently invested in alumni relations, our feedback from alumni is not as systematic or complete as we would like; however the conversations are compelling and eye-opening.) We realized that many of our alumni were not providing positive feedback on the value of what we had taught them. Current students expressed no interest in elective courses. Most important, we came to understand that almost all our students lacked essential foundational skills in algebra, modeling, and/or spreadsheet engineering, which rendered their knowledge of our course content moot. In a very real sense, we were failing. This was a distressing discovery, but it was instrumental in setting us upon the student-centered journey. We now have reduced the number of tools in the core course, replacing them with essential foundational topics. As discussed in the next section, some of those tools removed from the core course found their way into new elective courses.

The Joy of Teaching Student-Centered Business School Management Science

Because of the success of the student-centered required course, students clamored for electives. Once the noise got loud enough that administrators starting also clamoring for electives, we began to offer them. And, good news: many of the tools we pulled out of the core course are taught in elective courses! (Note: We make a point of doing a dog-and-pony show to "sell" the electives just prior to registration time.) In electives, students self-select and we can tell them in advance that skill in, say, algebra is required to succeed in a particular course. We can then do what many instructors most enjoy, which is to take prepared students on an in-depth journey into a topic and bring them along quickly. This is a nice bonus that accrued from the painful transition in the core course.

A delightful prize for us is having students who are eager to come to class. Not just the top students, but the median students and also many of the weaker students start to acquire and strengthen real ability in modeling, spreadsheet, and analysis, and become hungry for more. Many of the weaker students bloom in gratitude and excitement. Whereas we used to frequently feel that we were "pulling teeth" to get students to learn something, now students are pulling on us to teach them more. We used to find classroom teaching to be tiring, even exhausting. We now find it to be energizing, because the students are richly engaged. These are delights that all instructors should enjoy.

Most importantly, the act of being "student-centered" required us to become students ourselves. We had to learn new ways of doing things, and learn new skills such as how to create high-quality analytical spreadsheet models, and read the literature on how spreadsheets are used to help businesses succeed.

We encourage instructors to approach this learning with the same curiosity and interest that they approach learning a new technique in our discipline. The instructor's journey should be a pleasure, not a chore!

6. Conclusions and Future Work

The required business school management science course should be among the best-respected, most enjoyed courses in the business school core. A successful, popular core course opens the door to elective courses where students can be filtered based on technical skill and innate interest, allowing for more advanced topics to be covered at high efficiency.

One way of achieving this happy outcome is by adopting a student-centric approach as described in this paper. For us, this was a decade-long journey, and we are still learning and changing course content as we deepen our understanding of our students' needs and abilities. It requires a change in mindset from "I teach tools" to "I prepare every student to make a difference using models and analysis." Once the mindset shifts, the journey becomes easier. Our hope is that this paper speeds the journey of other instructors.

It is important to understand that we are not compromising rigor and challenge. We have created a challenging and at times extremely demanding course. However, the rigor and challenge is grounded in what students need to be successful in their careers as business generalists, as opposed to analytical specialists. We have done this without alienating students nor harming teaching ratings. The key is that difficult tasks must be, in the students' minds, connected to outcomes they value.

Every school is different. Every program is different. Every student body is different. Although it is unlikely that other instructors would want to duplicate our approach exactly, we believe that elements of it can be valuable to students and instructors at almost every school. Teaching management science to business students should be a pleasure and if it is not, we encourage you to make it so.

There are several areas where further research is needed. First, we need to know more about how to teach modeling to business students who are spreadsheet-native. Second, we need more research on how to construct high quality analytical spreadsheet models. This is a software engineering question rather than a management science question. For each of these, it would be very helpful to have a well-established formal methodology that can be taught to students. Finally, we need empirical research on the use of quantitative analysis by business school graduates, both at individual schools and across the profession. What are they actually doing out there, and what can business schools do to give them the best possible preparation? A particularly interesting question is, what is the usage frequency of analysis techniques, including basic sensitivity analysis, in the careers of our alumni?

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