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# Developing a Methodology for Analyzing Educational Offerings Using Competency Descriptors

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THESIS

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## Abstract

The United States Air Force needs to ensure its Airmen are receiving the best possible education so that they can perform their jobs as effectively as possible. One way to improve the evaluation and development of its Airmen is to incorporate the use of competencies to develop standards for performance and use competency-based education principles to improve the quality of education delivered to the Airmen. One of the educational centers of the United States Air Force is The Civil Engineer School. However, The Civil Engineer School needs a way to evaluate its current coursework on how well it develops competencies in Airmen and a way to create curriculums for future educational programs that focus on development of a particular competency profile.

This research accomplishes both of those tasks by using the building block of competency models, descriptors. By deriving from the principles of competencies and competency-based education evaluation criteria, a methodology for determining competency development from a course is created by relating the coursework to the competency model's descriptors. Once the descriptors have been related to coursework, an optimization tool can be used to develop curriculums based on a given competency The Civil Engineer School desires to develop. This research provides one such tool, using Microsoft Excel to determine the curriculum that meets the desired competency development in the shortest time using existing coursework or to build a new course that accomplishes the desired competency development in the shortest time using existing coursework.

*This thesis is dedicated to all the Airmen in the Civil Engineer career field.*

*Can Do - Will Do*

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I would like to thank and acknowledge all my classmates in the GEM program for their support and encouragement throughout my entire time at AFIT. Having them by my side made all I have achieved possible.

Andrew Lowe

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# DEVELOPING A METHODOLOGY FOR ANALYZING EDUCATIONAL OFFERINGS USING COMPETENCY DESCRIPTORS

## I. Introduction

### 1.1 Importance of Education for the USAF

While the United States Air Force (USAF) has historically enjoyed a technological advantage over its adversaries, the key to its strength and superiority in the air space has always laid with its people ("U.S. Air Force Science and Technology Strategy" 2019). This fact will become increasingly important in the future as continually improving technology emerges and the battlespace evolves. According to United States Army research and reports, the way modern society produces rapid science and technology advancements will close the gap of technological superiority held by the USAF because every military force will develop its technical capabilities the way America has (Johnson 2017). As the technological playing field becomes level, the skill of the people that operate the technology and a fighting force's people will become the difference maker in future combat. In addition to the rapid development of technology on both sides of conflict, the asymmetrical properties of modern warfare create complex environments that demand a high level of critical thinking and problem-solving ability from its participants (Smith et al. 2019). However, as the world around the USAF changes, so does its personnel. The new personnel that enter the USAF today grew up in a world of dynamic technological capabilities, meaning the new members of the USAF can access and apply a greater range of information and skills than previous generations (Roberson and Stafford 2017). The capabilities of today's Airmen are radically different

from the skills that are emphasized in the education models currently used by the USAF, which leads to underdeveloped Airman (Guerin 2020). The combination of these three factors (rigorous demands from the battlespace, the influence of personnel on combat results, and improved capabilities of today's airman) require that the USAF's education and training strategy and systems need to be working as optimally as possible to maximize the development and readiness of Airmen warfighters.

In addition to the rising demands as a military force, the USAF has innate motivations for wanting to ensure its airmen receive the best training and education possible. Civilian organizations understand the costs of having employees with shortcomings in their capabilities; over $50 billion is cumulatively spent annually by corporations to educate and train their personnel (Walston and Khaliq 2010). While continuing education and training are valuable to organizations, literature shows that individual employees are unmotivated to seek out continuing education opportunities on their own unless there is a direct career or personal advancement opportunity associated with it (Walston and Khaliq 2010). This lack of personal effort to obtain continuing education means the burden of upkeeping employees' competencies falls on the organization. Because of the large number of personnel in the USAF and the unique skills demanded from their Airmen, the USAF would benefit greatly from investing in their own developmental infrastructure rather than rely on third party organizations and institutions. This "internal" development of its airmen will allow for the USAF to better

create the learning environment and content, which can make the development more tailored to the skills and competencies the Airmen need.

As outlined in the Continuum of Learning, competency is built on a three-legged stool of education, training, and experience (Roberson and Stafford 2017). One way an organization can ensure proper development of its employees is that all of them are fully educated by initially receiving academic education and continuing their growth through continuing professional education. This continuing education helps personnel develop and hone new skills while demonstrating existing capabilities (Flynn et al. 2017). Additionally, personnel who have limited experience in their role can use continuing professional education to overcome some of their shortcomings in their skills directly needed in their job. In this way, continuing professional education can supplement a university-based academic degree (whether or not the profession requires a degree) that does not provide an employee with the tools and skills needed for every challenge that will arise while performing employment-related duties (Mizell 2010). The USAF utilizes a number of education models to provide professional continuing education to its airmen (Department of the Air Force 2013); one way of improving these education models is to incorporate competency-based education (Roberson and Stafford 2017).

### 1.2 Current Use of Competencies in the USAF

The USAF has already begun incorporating competencies and competency-based education into its training and professional education plans for its personnel. Air Force Handbook 36-2647 sets out the guidelines and procedures for developing competency

models; these guidelines create new opportunities to develop competencies for each job in the USAF (Department of the Air Force 2019). Additionally, the USAF already uses competencies to evaluate its Airmen with The Air Force Institutional Competencies, a list of competencies that is expected from all Airman in the USAF (Roberson and Stafford 2017). Additionally, a recent update to the Civil Engineer career field's Career Field Education and Training Plan (CFETP) includes specification of the career field's occupational competencies for its officers. These occupational competencies were developed by eliciting knowledge from the expert practitioners in the career field and synthesized into a competency model (Department of the Air Force 2019; Guerin 2020).

**1.3 Purpose and Significance of this Research**

Through research, The Civil Engineer School (TCES) have developed competency-based education models based on those Civil Engineer competencies identified by the expert practitioners. However, there are three additional areas that require further research: a way to validate the development of the competencies based on TCES education models, a way to track an Airman's competency development progress, and a way to identify an Airman's education pathway to continue in their development.

This research aims to address some of those needs of TCES by developing a methodology to identify competency development from existing coursework and a tool to determine optimal educational pathway ensures development of competencies. This research will accomplish this by answering the following research question:

*"How can a competency-based educational curriculum be developed from existing processes and structures within the Civil Engineer career field, including the existing processes and structures within TCES?"*

This research question is in part derived from the results of the Air Force 4-star panel CORONA in February of 2017. From that panel, it was decided the Air Force would adopt the Continuum of Learning for its educational institutions and introduce the use of competencies and competency-based education (Stafford 2017). Part of the lines of effort that were decided to implement this adoption was chunking, which is "the process of taking individual units of information and grouping them into larger units" (Baker 2010). In the context of education, this is the grouping of courses or lessons together to teach a specific topic. This research sets out to develop a methodology that allows TCES to perform this chunking with their current educational offerings.

The research question posed will be answered by this research by producing a tool that takes TCES's coursework and the Civil Engineer career field's competency model as inputs and return an optimized curriculum as its output. In this research, the "optimal solution" returned by the tool will be defined as the curriculum that achieves the desired competency development in the least amount of time.

The significance of this research is that it provides TCES a methodology to evaluate its educational offerings and ensure it is fulfilling its vision and mission to educate Civil Engineer Airmen to execute mission objectives ("AFIT / The Civil Engineer School / Vision & Mission Statements."). Additionally, this research will allow

TCES to enhance its educational offerings by allowing it to identify curricula pathways that will lead to targeted development of specific Airmen competencies. Beyond the scope of the TCES and its operations, this research will help fill a gap in the literature about competency-based curriculum development.

**1.4 Assumptions and Limitations of the Research**

While conducting this research, several assumptions were to help scope the research. The major assumptions made during this research are listed and briefly discussed below:

1. *The educational infrastructure already exists.*

This research utilizes existing educational infrastructure (i.e., current courses and lessons). Development of new coursework for specific competencies are not considered in the development of the tool.

2. *Existing coursework is not going to be modified or changed.*

This assumption precludes the notion that TCES should overhaul their coursework to adapt to the introduction of a new competency model. For this research it is assumed the existing coursework is not going to be modified in any way.

3. *A competency model for the given profession already exists and is valid.*

This research assumes the competencies developed are valid and seeks to determine the best way to develop competencies through education. Developing new competencies or evaluating the validity of existing competencies for their profession is beyond the scope of this research.

4. The competency model tool focuses only on educational requirements. Competency development occurs by combining the three aspects of the Continuum of Learning: education, training, and experience. This assumption was made to accommodate the desired end user- TCES. TCES has control over the educational aspect of a Civil Engineer officer's development, where as training and experience are controlled by other entities.

### 1.5 Organization

This thesis has 5 chapters, each of which contributes a separate component of the research. The current chapter provides an overview of the research, which includes an introduction to the topic, the intent of the research, and the scope of the work. The second chapter provides a literature review of relevant topics to this research, which helps establish the vocabulary and fundamental concepts to be used throughout the research. The third chapter details the proposed methodology to identify educational pathways to competency development by the tool that was created in this research. The fourth chapter presents the results of the competency mapping tool on a synthetic data set of course. The final chapter summarizes the uses and limitations of the developed tool and outlines related future research endeavors.

# II. Literature Review

## 2.1 Introduction

This chapter summarizes the existing literature on related topics and introduces the concepts needed to conduct this research. The first topic introduced is competencies and their structure. The next topic discussed is competency-based education and the development of a competency-based education curriculum. Then competency-based education is compared to traditional education models, which leads into a discussion of the limitations of competency-based education. The final topic is the structure of an educational curriculum.

## 2.2 Competencies and Their Structure

The concept of competencies is a recent development in the educational field (Ford 2014) and can be defined as "the quality or state of having sufficient knowledge, judgment, skill, or strength" (Miriam Webster Dictionary 2021). In the context of a professional field, competencies are closely related with job performance, where a person combines knowledge with behaviors and thinking processes to demonstrate a set of abilities (Dedovic and Music 2017). These abilities are referred to as "competencies" are a tangible way to evaluate the capabilities of a professional against a standard (Maicher and Frank 2015). An important characteristic of competencies is that they are unique to each field and are not generalized. The competencies needed to practice law are going to be different than the competencies needed to practice medicine because those professions have different roles, objectives, and skills required to be successful (Clear et al. 2020).

Professional fields have always known and understood the concept of competencies; many professions require a period of apprenticeship under a practicing professional as a supplement to a student's education. This apprenticeship can be viewed as a rudimentary version of a competency-based education model (Ford 2014). These apprenticeship periods are necessary to developing competencies because it adds an evaluation of the technical skills in a profession, because perfect scores on tests in education programs do not always translate to a successful professional in the field (Clear et al. 2020).

Competencies need to be derived from the expected requirements of the field the student will be entering (Torres et al. 2015). Ideally, the competencies would be developed using an existing job with a current employee providing a benchmark for the competencies. In the absence of existing data from professionals on the job, competencies can be developed from a conceptual standard of desired abilities; however, it becomes more difficult to validate the competency model (Williams 2012).

The first step in developing competencies for a given profession is to develop a competency model – a description of the expected skills required for a job and what defines successful performance in that role (Dedovic and Music 2017). Existing professionals who demonstrate the desired skills at appropriate performance levels need to be identified and used as a benchmark. Data should be collected on those professionals and their behaviors that lead to their superior performance. After these behaviors have been identified, they need to be analyzed to understand how the behaviors interact with each other and lead to the success of the professional (Williams 2012). This profile of

successful behaviors becomes the list of competencies that the educational curriculum should develop in its students (Torres et al. 2015).

The next step is to determine the degree or level of attainment. Some guiding questions can be- “do these behaviors have multiple degrees of demonstrability?” or “is there a singular level of capability?” Competencies can have varying levels of capabilities that could be demonstrated and are referred to as “tiered” competency models, whereas competencies that are either demonstrated or not are referred to as “binary” competency models (Jones and Voorhees 2002).

### 2.2.1 Competency Structure

Competencies are complex and it can be very difficult to summarize every skill needed for a profession into a handful of competencies (Clear et al. 2020). It is expected that a competency model for a profession will contain competencies that are vague and not very specific. For clarity purposes, competency models often include subcompetencies under each competency to better organize and explain that competency (Markowitsch and Plaimauer 2008). While not intended to act in hierarchical manner, subcompetencies can be thought of as building blocks for competencies. For example, completing development in all the associated subcompitencies will result in development in the competency (Patel Gunaldo et al. 2017).

Competencies and subcompetencies ae further defined by using “descriptors”, which are “statements that describe observable behaviors which indicate that the person concerned has achieved a certain level of proficiency with regard to a competence”

("Descriptors - Their uses and purposes."). As the lowest level of the competency structure, these descriptors are the most specific description of what skills and behaviors a professional should exhibit and are the best way to objectively evaluate performance of an individual because the descriptors are supposed to be clear, actionable, and behavioral (Maicher and Frank 2015).

Finally, some competencies can be similar or related to each other; these competences can be lumped together into "groups" or "categories". These groups are just another level in which the abilities demanded from a given profession can be organized and prioritized. Groups of competencies are common in professions where there are different sectors that have different priorities that an individual can be expected to perform (Bird 2017). This approach of having groups of competencies that are broken up into subcompetencies that have descriptors to describe the specific skills of each subcompetency is used in the Air Force's competency models, including the one of the Civil Engineer career field (Department of the Air Force 2020).

### 2.2.2 Further Detail on Descriptors

At the bottom of the competency structure, descriptors are the most specific descriptions of observable skills that a professional will need to exhibit in their field (Maicher and Frank 2015). In a competency model, "these descriptors help to operationalize the competences and provide important and useful tools for curriculum planning, teaching and learning, and assessment" ("Descriptors - Their uses and purposes.") by outlining what exactly students in a field need to learn by describing what

skills they will need to possess ("Descriptors - Their uses and purposes."). These descriptors need to be free from ambiguous language and use a commonly defined vocabulary across a profession (Shippman et al. 2000); this clarity allows the professional, educational institutions, and employers to have a common ground when discussing the needs of profession and properly evaluate the development of a given individual (Torres et al 2015). Descriptors also outline not only specific skills expected of a professional but behaviors that define the successful demonstration of the necessary skills in a field ("Descriptors - Their uses and purposes.").

### 2.3 Competency-Based Education and Curriculum Development

Competency-based education (also referred to as proficiency-based, mastery-based, outcome-based, performance-based, and standards-based education) is defined as "systems of instruction, assessment, grading, and academic reporting that are based on students demonstrating that they have learned the knowledge and skills they are expected to learn as they progress through their education" (Glossary of Education Reform 2014). This teaching model has gained traction in the last few decades, as American higher education institutions have begun incorporating competency-based education methods and programs as an alternative to the traditional model for students (Smith et al. 2018). The implementation of competency-based education has not been limited to just academia; many companies are starting to use competency-based education models for training new employees and using competency-based education concepts for evaluating current employees for promotion (Voorhees 2001). Competency-based education models

are predicated on the idea that an education curriculum teaches knowledge on a topic and teach students how to take that knowledge and “put it to work” by applying it to situations and attempting to gain successful outcomes (Klein-Collins 2013). Because of this, competency-based education models are more than just a “wish list” of competencies that the curriculum hopes that students achieve; the competencies are a set of outcomes that the curriculum needs to teach and build up (Adelman 2013). When developing a competency-based education model, the competencies need to be the focal point of the curriculum and be the requirement for program completion. This focus on the competencies is what makes competency-based education models unique and differentiates them from other methods of instruction. The emphasis on competencies in the coursework and curriculum means that the competencies need to be identified and developed before developing a curriculum for a competency-based education model (Klein-Collins 2013).

Once the competency model has been generated, the curriculum can be developed. There is very little literature that explains how to develop a generic competency-based education curriculum because of the competencies (and the education for them) are specific to each field. However, there are some generalities; the first is that the curriculum should have a clear mapping of coursework leading to the outcome competencies. This is important for students in the educational program because ambiguity in coursework represents unnecessary excess. If it is unclear how a component of the curriculum develops a competency, then there is no point in engaging with it

because it does not help the student progress as a professional in their field (Johnstone and Soares 2014). If a particular skill was not important enough to be included in the competency model, then it is a low priority for students to learn (Williams 2012).

Another generality of competency-based education curriculum is that they need to bundle related skills together. Competencies can be important to multiple different professions but require different skills to execute; "for example, measuring distances is important to both professional golfers and surveyors. Of course, different measuring skills may be involved in carrying out these two tasks, but the skill involved in performing measurement, irrespective of technique or method, should produce the same result" (Voorhees 2001). Similar competencies across different professions require different bundles of skills, each defined by the context of the profession. It is the role of the educational institution offering the program to identify the bundles and provide coursework that instructs the students on these bundles of skill and teaches them the knowledge they need to apply the skills (Voorhees 2001).

An additional generality of developing competency-based education curriculums is that the learning resources developed for the program need to be made openly accessible for students. Because of the variable pacing in competency-based education models, students cannot be limited to accessing learning material at a specific time or for a limited duration. Limiting access to learning content reduces the opportunities for students to master the content, which can lead to students being unable to develop proficiencies before the resources become inaccessible (Johnstone and Soares 2014).

Furthermore, there should be multiple, high-quality resources available to students. Educational institutions cannot provide a long list of learning resources with no guidance; the students will then struggle to determine which resources to use to develop their competencies. Instead, it is ideal if the educational institution provides a few, high quality resources to instruct the students as well as a suggested path through the resources to give the students guidance on how to navigate their learning. Additionally, providing multiple types of resources will and address the needs of different types of learners (McIntyre-Hite 2016).

The final generality of competency-based education curriculums is that the assessments need to be valid, secure, and reliable. Since the assessments are the primary tool used to evaluate competency proficiency in competency-based education, the assessments need to be developed with input from industry and academic experts alike (Johnstone and Soares 2014). On top of that, the assessments should be aligned directly with the competency; each "final" assessment should directly measure proficiency in the taught competencies and the score a student receives should show exactly where that student is in their development (McIntyre-Hite 2016). Assessments can take multiple forms, ranging from a demonstration of a skill to an objective test. For any assessment that takes the form of the test, the test needs to be conducted with proctoring and student verification. Because of the role these assessments have in the certification of the student's proficiency in competencies, these assessments need to be protected and prevent any student from doing well on the assessments without mastering the content

(Johnstone and Soares 2014). Once assessments have been developed, they need to be tested with an iterative process. Assessments should be fair and be true evaluation of the student's proficiency of the competency, not their ability to understand unclear instructions or complete work unrelated to the competencies of their profession. Additionally, the grading systems and rubrics should be consistent and tested; the assessments should be as objective as possible and educational institutions should do their part to remove as much instructor bias as possible. Part of this is to openly provide evaluating rubrics to the students, so that they know exactly what is considered mastery of the competencies (McIntyre-Hite 2016).

Once the educational curriculum has been developed, it needs to be validated. The validation of the competency-based education model, starting from the educational curriculum and ending with the competencies themselves, is crucial. Both the students and the educational institution need to know if the designed program develops students to be professionals in their field; if not, it should be redeveloped in an iterative process (Johnstone and Soares 2014). Validation ideally should take multiple educational cycles to complete. The best way to validate the competency model is to collect student graduation data and follow the students as they enter/return to their professional field. By tracking competency assessment scores before the student completes the course and evaluating their performance, the institution offering the educational course can determine if its curriculum is adequately developing the competencies in its students (Dedovic and Music 2017).

A competency-based education curriculum does not have to be developed from scratch; many higher education institutions in America are developing their competency-based education curriculum from their existing traditional education curriculums (Klein-Collins 2013). When doing this, the educational institution needs to make sure that it is making the new curriculum in accordance with the previously mentioned generalities. In addition to that, educational institutions need to be sure that they are including resources for students to learn to adjust to the new style of education, particularly if their only experience was with traditional education methods. Medical students in a medical school program were studied when the program began transitioning from a traditional education model to a competency-based education model. The study found that the students initially struggled with self-regulated learning skills because their existing learning strategies were ineffective, which researchers attributed to the lack of classroom-orientated teaching methods found in traditional education. However, the researchers did assert that the educational institution can support students in the transition by helping provide resources to develop these skills and to integrate them into their coursework (Binbin et al. 2020).

## 2.4 Comparing Competency-Based Education and Traditional Education

Because of the two educational models have different approaches, competency-based education has some defining traits that differentiate it from traditional education. One of these traits is the measurement of completion by learning as opposed to time. In traditional education models, students complete their program by completing a set

duration of time on subjects and concepts with little flexibility to adapt based on how quickly they master the concepts. Because competency-based education focuses on the student's mastery of the concepts, competency-based education curriculum needs to be able to adapt to the student and their pace of learning (Jenkins et al. 2020). If a student can demonstrate mastery of a particular concept or subject, they should not be forced to keep practicing the same concept; likewise, if a student is struggling with a particular topic, they should remain on it until they have mastered it and can demonstrate proficiency instead of being forced to move on and begin learning to the next topic (Frank et al. 2010). In addition to being flexible enough to adapt to how a student learns, competency-based learning can reward students who have proficiency in a subject before they begin training. If a student has been working in the profession before they begin their education program, successful demonstration of their skills in a module pre-test can allow them to "test out" and receive the credit for the module, since the student has already mastered the competency (Stafford 2017).

There is evidence that a more personalized schedule should apply the coursework itself, not just the pacing of the educational program. In an experiment conducted on students in a psychiatry residency program, the students were taught two modules, one using a more traditional education model and curriculum and the second incorporating competency-based learning techniques. The results of the experiment found that the modules that incorporated competency-based learning techniques, including the use of online tools to deliver instruction and the ability to complete the module at their own

pace and on their own time, returned slightly higher scores and a higher level of satisfaction with the learning (Hickey et al. 2015). These findings are by a similar study conducted on dentistry students. This second study found that there were some benefits of competency-based education for not just students but instructors; some of these additional benefits include a reduced dependence on instructors for learning. Reducing the dependence on instructors to instruct all students all of the course material allows them to adapt their time, attention, and effort to the students and areas that need it most (Yip and Smales 2000). There is also evidence that the more personalized pace of learning that competency-based learning utilizes can improve student engagement and help deficient students catch up to their peers (Jenkins et al. 2020). The existing literature on competency-based learning indicates that allowing a more flexible learning schedule for students results in a more optimal learning experience for them, which leads to better learning and better development of skills and competencies.

The difference in the pacing of the courses between competency-based education models and traditional education models leads to a difference in the learning outputs. In traditional learning models, the time and pacing of courses is fixed, so the amount of learning each student achieves is going to be variable. However, in competency-based education models, the pacing is more flexible and allows adaptability for the students. The adaptability of the coursework allows the student to gain proficiency, which makes the learning achieved by the student a fixed amount when completing the educational program (Klein-Collins 2013). Because of the more consistent learning output,

competency-based education models produce a more uniform level of learning from the program than traditional education models. Competency-based education models produce a more consistent learning result because students need to demonstrate proficiency in the skills and competencies outlined by the professional field, unlike traditional education models where students can easily pass through without developing proficiency or demonstrating any mastery of the subject (Torres et al 2015).

Having a more consistent learning output provides competency-based educational models a few advantages over traditional education models. The first is that it is easier to adapt the coursework to the changing demands of the profession. When an educational program is utilizing 10 a competency-based education model, it becomes apparent when it is not working; its graduates will be unable to complete work in the field because the graduates will not be successful in their profession. Whether the lack of success is due to poor instruction of competencies or the competency model is invalid, the educational institution can adapt its coursework to address the changing needs of the students. Traditional education models are unable to do this, as they are unable to adapt until after a widescale disaster reveals systemic issues in the education model (Smith et al. 2019). Furthermore, the reduced variability in what a student gains from the educational program means that it is easier to use competency-based education models for the education programs to develop certification and credentialing systems. With less variability in the students' learning, the educational program can be certified with greater confidence and be more meaningful (Torres et al. 2015).

Another trait that differentiates competency-based learning models from traditional learning models is how assessments are used in the curriculum. In traditional learning methods, assessments are used as the output of learning: a student takes a course, learns from it, and takes an assessment which returns a grade that summarizes how well the student developed a mastery of the subject (Torres et al. 2015). Additionally, most traditional education methods use poorly designed testing methods; a multiple-choice standardized test is a bad way to evaluate a student's ability to complete a certain task because it is completely unrepresentative of how most professions operate (Klein-Collins 2013). However, competency-based learning uses assessments as a tool used to measure the level of learning a student has achieved. By using assessments before, during, and after the course, the curriculum can gauge student mastery of a given topic and show areas where the student may be deficient in. As deficiencies in the student's learning are identified, the coursework and instruction can be adapted or increased to provide the student the means to succeed (Johnstone and Soares 2014). Additionally, since competency-based education focuses on getting the students to be proficient in the various competencies, students can retake assessments multiple times until they have demonstrated proficiency. Allowing retakes removes the pressure of test taking away from the students and allows them to learn for development instead of competition for grades (Torres et al. 2015).

## 2.5 Limitations of Competency-Based Education

Competency-based education does have its limitations as an educational model. The most apparent limitation is that it is a more resource-demanding educational model than traditional education models. Because the competency-based education models prioritize a more individual learning pace and personalized instruction, it costs more to instruct the same number of students than a traditional education model. This additional cost includes the additional instructional staff needed to provide adequate instruction through additional learning resources and to develop the assessments required to gauge the student's proficiency of the competencies (McIntyre-Hite 2016) as well as any technological upgrades needed by the educational institution to be able to deliver the new coursework (Frank et al. 2010). In an era when the costs of higher and advanced education are already growing exponentially, these additional costs will be hard to justify to educational institution leaders (Clear et al. 2020).

An additional limitation to competency-based education is that there are issues with the recognition of competency proficiency. Each employer within a professional field may have different standards for what constitutes proficiency in the different competencies from their peers and the educational institutions providing the educational courses. This difference in how every organization evaluates the competencies makes it difficult to have a uniform standard for evaluating a person's skills and abilities (Ford 2014). Additionally, if different organizations use different scales for their measurements of proficiency (a binary scale vs. three-tier scale, for example), it can be difficult to

translate the levels of proficiency demonstrated at one organization to another organization (Guerin 2020). Furthermore, these different organizations may have differing views on what competencies are important to the field; some companies may want certain skill sets out of their employees that the educational institutions deemed excess or unnecessary (Frank et al. 2010). Since the competency-based education models are predicated on building up and teaching to those competencies, nonuniformity of desired competencies in a professional field will render the competency-based education models no better than the traditional education models.

The biggest limitation to competency-based education models is that there is not a consensus that this education model is better than traditional education models. The medical profession was one of the first to start implementing competency-based education models as a part of its education and training programs; within that field there is still a debate among the profession's educators and employers if the future of medical education is going to be competency-based (Frank et al. 2010). On top of that, there is some stakeholders in the medical field that believe competency-based education glosses over fundamental skills required for the profession. The belief is that it is difficult to define exact competencies and to teach them prioritizes general abilities over specific medical skills (Pijl-Zieber et al. 2013).

Skepticism of the benefits of competency-based education extends beyond just the medical field; critics of competency-based education models are found in every profession. One of the biggest arguments against competency-based education is that the

assessments, which are a critical component of competency-based education, are too difficult to execute and are no different from traditional education model assessments (Voorhees 2001). Additionally, there is much concern on how the logistics of managing different students and their own pace of learning, particularly when the number of students is scaled up (Frank et al. 2010). These criticisms would normally not cause such a problem for the implementation of competency-based education programs, except that the biggest skeptics are the senior leaders and executives. Without any belief or support from the senior leadership of organizations, competency-based education will not take hold or be effective. Even if there is senior leadership support for a competency-based education model within an organization, any level of leadership change can cause this support to disappear as new leaders repeal and undo previous leaders' policy and developments (Hollenback and McCall 2003). On top of senior leader's skepticism of competency-based education, there is skepticism over the concept of competencies, particularly in the business and management fields. This skepticism exists because there is a belief that the development of executives is driven by experience and is something that happens on its own- it is not something that can be forced. There is also a belief that executives' competencies cannot be defined, particularly for the more senior executives. This belief is rooted in the notion that growth is attributed to getting results, not specific behaviors (Hollenback and McCall 2003). If traits cannot be attributed to success in a professional field, then competency-based education will not be any more effective than the traditional education models.

## 2.6 Structure of an Educational Curriculum

An educational curriculum is a "standards-based sequence of planned experiences where students practice and achieve proficiency in content and applied learning skills" (Hege and Fischer 2012). The curriculum is the guide for students and faculty alike to understand what the expected outcome of the educational program is, such as the knowledge gained and skills demonstrated. Educational curriculums have two main components: a course sequence and overall student outcomes; the course sequence shows what courses a student is supposed to take and the outcomes explain what the student will be able to do after completion of the program (McEneaney and Meyer 2000).

The courses that make up a curriculum will have varying durations and will cover a variety of topics; some courses will directly lead to the completion of the curriculum's student outcomes and others may not, serving as a prerequisite for other courses or helping build the knowledge base for the student to learn more advanced concepts (Hege and Fischer 2012). Courses themselves are built as a collection of lessons, which are plans to instruct students on a specific subtopic within the topic of the course. The topics that lessons cover are narrower in scope than that of the course and are more tangibly understood. For example, the course topic will be something broad like "Calculus" and the lessons will be something more specific such as "Taking Derivatives of Polynomials" or Integration by Parts" (Gallagher and Smith 2019).

Like the overall curriculum, lessons have associated outcomes that students are supposed to exhibit by their completion. These are called lesson objectives and like the

curriculum's student outcomes they are specific statements of demonstratable behaviors that a student can be evaluated on (McEneaney and Meyer 2000). What makes these lesson objectives important is that they were the learning a student is supposed to achieve from a curriculum. Because lesson objectives are specific, actionable, and measurable in some way, they represent the knowledge and skills a student should learn from the educational program (Chatterjee and Corral 2017). The culmination of successfully achieved lesson objectives should result in the meeting of the student outcomes set forth by the curriculum (Hege and Fischer 2012).

# III. Methodology

## 3.1 Introduction

The result of this research is the Competency Portfolio Analysis Tool (CPAT), which addresses the needs of TCES. This CPAT has two functions; the first is to create a curriculum by determining which combination of the courses offered by TCES provides the desired competency development in the shortest time. To complete this task, the CPAT will be provided two inputs: the details of the courses offered by TCES and the competency model of the Civil Engineer career field. The user of the CPAT will decide on a set of competencies that they desire a curriculum for and running the tool will return a list of courses, which is the optimal curriculum for the particular competency development profile chosen by the user.

The second function of the CPAT is to determine which combination of lessons that TCES has in their catalog could be combined to create an optimal new course that provides a desired competency development. This task is completed using the same inputs as the first and is used in a similar manner; the user of the CPAT selects the desired competency development that the new course will complete and running the tool will return a list of lessons, which is the optimal course for the particular competency development profile chosen by the user

This chapter discusses the mechanics of the CPAT itself and how it was constructed. First in this chapter is a discussion of the fundamental approach of the CPAT and why the tool acts the way it does, as well as justifying the approach with academic

literature. This is followed by a discussion of the specific assumptions made during the construction of the CPAT, which is immediately followed by a detailed description of the how the CPAT works. This chapter ends by discussing how the CPAT will be validated using a synthetic case study.

**3.2 CPAT Approach**

In order to develop a complete curriculum to achieve the desired competency development, the CPAT needs to define what a successful curriculum is. As explained by published literature, a curriculum defines what skills students should be able to learn and demonstrate proficiency in at the end of the learning experiences (Hege and Fischer 2012). In the context of competencies, these skills that a curriculum develops are the descriptors of a competency model, as descriptors are defined as being objective and evaluable skills needed in a profession (Maicher and Frank 2015). The CPAT uses the descriptors as the building blocks for creating a curriculum or new course by evaluating possible solutions against the desired competency development as input by the user of the tool. By attributing descriptors to lesson objectives that develop them, competency development in a curriculum or new course could be tracked by tallying which lesson objectives get delivered to the student via lessons and courses.

Since developing these descriptors through included coursework are the goal of the curriculum, the CPAT needs to define what constitutes as a complete curriculum in terms of descriptors. If the curriculum includes coursework that develops all of the descriptors that make up a desired competency, then the curriculum develops that

competency because it develops student's proficiency in the actionable skills that exhibit the competency. Determining which descriptors build to a competency is simple; because competencies are divided into subcompetencies, which are divided into descriptors, the competency is built from all of the descriptors that make up each of the subcompetencies since the relationships between these levels of the competency structure are transitive. Figures 1 and 2 show examples of competency structures and how each level can be equated to a set of descriptors. When the user of the CPAT selects which competencies they want a curriculum build for, the tool converts them into the long list of descriptors; a selection of courses that develop the descriptors on this descriptor list is the output from the CPAT.

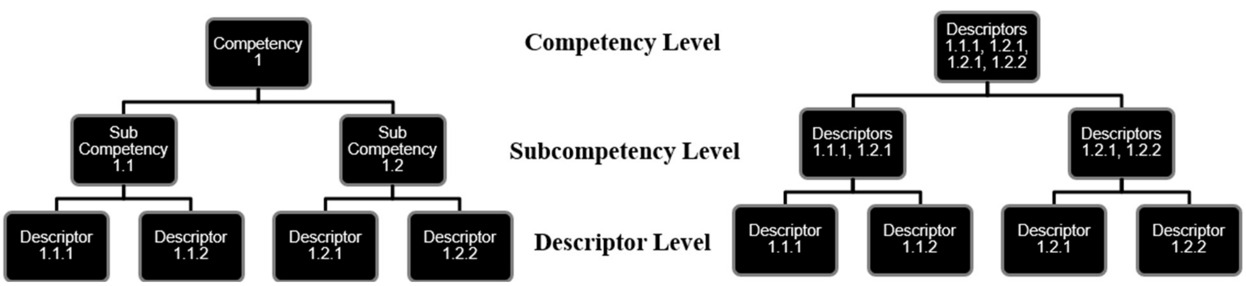


**Figure 1: A Sample Competency Model and its Equivalent Collection of Descriptors**

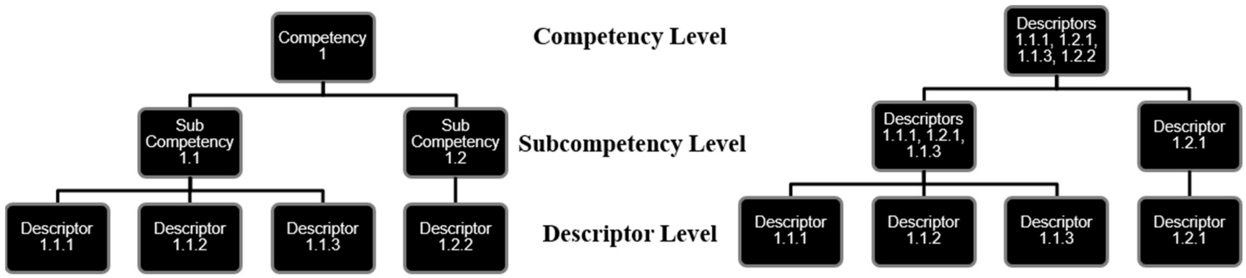


**Figure 2: A Sample Competency Model and its Equivalent Collection of Descriptors**

As demonstrated in Figures 1 and 2, it doesn't matter how many descriptors make up a subcompetency or how many subcompetencies make up a competency. The idea that each level of a competency model can be equated into a set of descriptors holds true no matter how the competency model is structured.

### 3.3 Validation of Descriptor Association

One way to conceptualize the relationship between lesson objectives and descriptors is as a network. Each lesson objective and descriptor can be thought of a node in this network and can be related to each other with edges of the network. Each lesson objective can have a one-to-one, many-to-one, or one-to-many relationship with any descriptors that the lesson objectives develop. Additionally, lesson objectives can be related to other lesson objectives using directed edges, denoting that some lesson objectives may need to be completed before other ones can be completed. While this research does not look into mapping out this relationship network between lesson objectives at TCES and the Civil Engineer career field's competency model, it is

important to recognize the network exists in order to be able to justify the association of descriptors to lesson objectives.

As discussed in the previous section, the CPAT works by tracking how many descriptors from the competency model a curriculum or course is developing. The CPAT does this by dissolving courses into the lessons that make up the course and then dissolving those lessons into their lesson objections. The CPAT works with lesson objectives because those lesson objectives can be used to identify competency development through the descriptors. Lesson objectives and competency descriptors can be related due to their similarity in structure and purpose; lesson objectives are used to describe the specific skills students will be able to demonstrate after they undergo the educational material (McEneaney and Meyer 2000), where competency descriptors are used to describe specific skills a professional will need to be able to demonstrate and utilize to be successful (Maicher and Frank 2015). If the skills described in a lesson objective is the same as those in a particular competency descriptor, then educators can consider that descriptor's development a part of the result of a student completing that lesson objective because the objective is describing a student learn and demonstrate the skills a profession demands from its professionals.

Further justification of this relationship between lesson objectives completion and competency descriptor development is that both have similar structures and wording. Lesson objectives "include the following 5 elements: who, will do, how much or how well, of what, by when" and utilize observable action verbs to describe those five

elements (Chatterjee and Corral 2017). This level of detail is also demanded from competency descriptors, as they need to be specific, concise, definite, and observable actions (Mirabile 1997). Lesson objectives and competency descriptors are so similar in their structure that guidance for creating descriptors for a competency model should be "be formulated using the language of learning outcomes" ("Descriptors - Their uses and purposes."). Given that lesson objectives and competency descriptors are so similarly worded and developed, it is easy to relate one to another and use this relation to evaluate competency development from coursework.

To provide guidance and help educational faculty determine if a lesson objective and competency descriptor can be related and consider the former to develop the later, a series of criteria have been determined to evaluate the relationship. These criteria are derived from the definitions of competencies and competency-based education; if all of them are met, the lesson objective can be considered to develop the competency descriptor. The criteria are listed below and discussed:

1. The lesson objective covers the same skills as the descriptor

Given that competency-based education is built around the idea that students are able to apply knowledge to complete tasks, the lesson objective must have the student demonstrate the same skills as the descriptor details.

2. The lesson objective can only be met with demonstrated proficiency

One of the fundamental principles of competency-based education is that students have fully developed their skills before completion of their educational program, even if this

means that a student retakes parts of the curriculum multiple times to practice a skill until it is adequately learned. If a lesson objective can be met without complete demonstration of proficiency, then it cannot be considered for competency development because it is not ensuring development of the desired abilities needed in a profession.

3. The lesson objective is assessed in a similar way to how the competency will be demonstrated in the professional field

The intent of competencies and competency-based education is to better evaluate the skills of a professional in a manner more similar to what will be expected of them as they operate as a professional in their field. This means that in their learning environment has to contextualize their learning in this manner; a student has not demonstrated their proficiency in a desired competency if they were not assessed in a way that the competency would be utilized in their field, even if the skill is the same. This means a lesson objective that teaches a skill that is desired in multiple professions may only relate to one of those profession's competency model depending on how that skill is assessed in students.

**3.4 Assumptions Made**

While creating the Competency Portfolio Analysis Tool, several assumptions were made in order to simplify the task at hand and improve the applicability of the tool. The major assumptions made during construction of the tool are listed and briefly discussed below:

1. Competency development is binary

Even though the current competency model utilized by the Civil Engineer career field utilized a three-tier proficiency scale, the CPAT only considers the development to be binary. This assumption was made to reduce the complexity of the input data needed.

2. Descriptor development occurs entirely in a single lesson objective

It is possible that development of a descriptor may take multiple lesson objectives or have prerequisite lesson objectives that build to the development of the descriptor. However, the CPAT assumes that a descriptor can be developed in a singular lesson objective to reduce the complexity of the input data needed.

3. Descriptor development from different lesson objectives is considered equivalent

It is possible that multiple lesson objectives develop the same descriptor in students, even if the lesson objectives have no relation to each other or are a part of different lessons. The CPAT considers each of these developments equivalent to reduce the complexity of the input data needed as well as to reinforce the assumption that competency development is binary.

4. Only in-class time was considered for the optimization

In the CPAT, the optimal solution is defined as the solution that takes the least time. This "least time" is calculated only as classroom time and does not include additional time to account for part time courses, time in between courses, any breaks that interrupt a course, etc. that would increase the real-life experienced time. For example, the CPAT could return a curriculum that includes two courses that are offered each offered only once a year at the same time; the CPAT is only accounting for the how many classroom hours in

each course and is disregarding the year the student would have to wait to take the second course before completing the curriculum. This assumption was made to reduce the number of variables involved and simplify the input data demand.

5. Only one competency model is used for analysis at a time

Even though the skills developed in courses offered by TCES can be applicable to multiple professions/career fields and their competency models, the CPAT only works with the Civil Engineer career field's competency model and its descriptors. This assumption was made to reduce the number of variables involved and simplify the input data demand.

### 3.5 CPAT Methodology

The CPAT was developed using the spreadsheet software program Microsoft Excel and is composed of 17 different spreadsheets within a single file. Table 1 shows a list of each spreadsheet's title and purpose in the CPAT. Each spreadsheet then has a brief subsection dedicated to it, going into fuller detail about the role that spreadsheet plays in the CPAT and how it was built.

**Table 1: List of Spreadsheets in the CPAT**

| Spreadsheet Name | Primary Purpose |
|---|---|
| Imported Courses | Inputting course data<br>Serves as master list of all courses for the rest of the CPAT |
| Imported Lessons | Inputting lesson data<br>Serves as master list of all lessons for the rest of the CPAT |
| Imported Lesson Objectives | Inputting lesson objective data<br>Serves as master list of all lesson objectives for the rest of the CPAT |
| Import Prerequisites | Inputting course data |
| Import Competencies | Inputting the competency model<br>Serves as the master list for competencies, sub competencies, and descriptors for the rest of the CPAT |
| Import Completed Courses | Inputting course data |
| Choose Competencies | User selects desired competency development |
| Solving Page | Executes the curriculum development optimization<br>Returns the tool's final solution |
| Solving Courses | Converts courses included in the curriculum into lessons |
| Solving Lessons | Converts lessons included in the curriculum into lesson objectives |
| Solving Lesson Objectives | Converts lesson objectives included in the curriculum into descriptors |
| Solving Descriptors | Converting desired competency development into descriptors |
| Solving Prerequisites | Ensures curriculum meets competency development constraints |
| Build Page | Executes the course development optimization<br>Returns the tool's final solution |
| Build Lessons | Converts lessons included in the course into lesson objectives |
| Build Lesson Objectives | Converts lesson objectives included in the course into descriptors |
| Build Descriptors | Ensures course meets competency development constraints |

A number of programs were considered to develop the CPAT, including RStudio and Matlab. However, Excel was chosen for two primary reasons. The first is that Excel has a robust database of built-in functions and data management tools that come with it. These existing functions expedited the creation of the CPAT since they did not need to be made from scratch and could be easily replicated by other research efforts. Additionally, the expansive support Microsoft provides for these built-in tools made it easier to understand their capabilities and troubleshoot any issues with the CPAT. The second reason Excel was used is that it is a very common program that most people have access to and familiarity with. Since this research is designed to address needs of TCES, the result of the research needs to be usable by the faculty of TCES. It's far more likely that whichever faculty use the CPAT has access to Microsoft Excel rather than some of the other program options considered.

The CPAT was built across the 17 separate sheets instead of one or two sheets in order to compartmentalize each action in the portfolio analysis. Each sheet conducts a different step of the analysis, which is how it the work was divided among sheets and the total number of sheets in the CPAT was determined. If future research on the subject adds on to the methodology to expand the capabilities of the CPAT, then additional sheets should be added to incorporate any developed additional steps to the methodology.

### 3.5.1 Import Courses

The first sheet of the CPAT is where course data is imported into the tool as a large table. Each of the courses that are available for inclusion into a curriculum are populated in column A, starting in Row 2 (Row 1 is reserved for column titles). Column B contains the duration of the course listed in the adjacent course, measured by the number classroom hours in the course. Columns C through AA are titled “Lesson 1” through “Lesson 25”, which is where the lessons within each course are input. Many courses may not be made up of 25 lessons; any extra lesson columns are just left blank.

### 3.5.2 Import Lessons

The second sheet of the CPAT is where lesson data is imported into the tool as a large table, similarly to the previous sheet. Each of the courses listed on the Import Courses sheet are reentered in column A and their duration is entered in column B. Columns C through L are titled “Objective 1” through “Objective 10”, which is where each of the lesson objectives for each lesson are input. Many lessons may not have 10 lessons; any extra objective columns are just left blank.

### 3.5.3 Import Lesson Objectives

The third sheet of the CPAT is where lesson objective data is imported into the tool as a large table, similarly to the previous sheets. Each of the objectives listed on the Import Lessons sheet are reentered in column A and columns B through D are titled “Descriptor 1” through “Descriptor 3”. Columns B through D are where each of the

associated descriptors for the objective are input. Many objectives may not have 3 associated descriptors; any extra descriptors columns are just left blank.

### 3.5.4 Import Prerequisites

The fourth sheet of the CPAT is where prerequisite data is imported into the tool as a large table, similarly to the previous sheets. Each of the courses listed on the Import Courses sheet are reentered in column A and columns B through D are titled "Prerequisite 1" through "Prerequisite 3". Columns B through D are where each prerequisite for a given course are input. Many courses may not have 3 prerequisites for them; any extra prerequisite columns are just left blank.

### 3.5.5 Import Competencies

The fifth sheet in the CPAT is where the Civil Engineer career field competencies were imported into the CPAT and codified for the rest of the tool. As published, the competency profile only numerically labels the competencies and their subcompetencies; this sheet assigns numbers to both the subcompetencies and the individual descriptors. Columns A through H are titled, in order, "Group", "Competency", "Subcompetency", "Descriptor", "Group Name", "Competency Name", "Subcompetency Name", and "Descriptor Name". Each row represents a unique descriptor from the Civil Engineer competency model each column is appropriate filled out for each descriptor: columns A through D are filled out with the associated numerical value and columns E through H are the related names of each level of the competency model. Column I is labeled as "Descriptor Number" and cells I2 through I110 are the generated descriptor number for

each descriptor. The descriptor number takes the form X.Y.Z, where X is the competency number, Y is the subcompetency number, and Z is the descriptor number and is generated in Excel using the “CONCATENATE” function. For example, descriptor number 4.2.3 is the third descriptor of the second subcompetency of the fourth competency, which from the competency model is “Establish and cultivate relationships with community and host nation partners to maximize installation readiness capabilities and host nation stability” descriptor from the “Build-Up” subcompetency from the “Beddown” competency from the “Contingency Operations” group.

### 3.5.6 Choosing Competencies

The sixth sheet of the CPAT is where the user can choose which competencies they desire a curriculum developed for. Each of the possible values from the Civil Engineer competency model for each level of structure of competency was populated into a column as an option choice; cells A2 through A4 are filled with groups 1 through 3, cells D2 through D8 are filled with competencies 1 through 7, cells G2 through G22 are filled with the 21 subcompetencies, and cells J2 through J77. The cell to the right of each unit of each level of the competency model is populated with a “0” as a baseline value. The user of the CPAT changes the associated cell of any unit of any level of the competency model they want developed to a “1”; this is how the CPAT knows what the resulting competency development should be by the curriculum or course it develops.

### 3.5.7 Import Completed

The seventh sheet of the CPAT is where the user can further customize the resulting curriculum or course built by the CPAT by inputting any completed coursework by the student that the curriculum or course is being developed for. In column A, the list of courses is imported from the "Import Courses" sheet and in column F the list of lessons is imported from the "Import Lessons" sheet. The cell to the right of each unit of coursework is populated with a "0" as a baseline value. The user of the CPAT changes the associated cell of any unit of educational that they want to be considered as completed when the CPAT develops a curriculum or new course to a "1".

### 3.5.8 Solving Page

The eighth sheet of the CPAT is where the user of the runs the CPAT to develop a curriculum from existing course at TCES by utilizing Excel's Solver tool. This page is set up to mirror a basic optimization problem: establish the decision variables, define the objective function, and incorporate any constraints. For this particular problem, the courses offered by TCES are the decision variables, the objective function is the total time of the new curriculum, and the constraints are the descriptors that need to be developed during the curriculum.

Starting in cell B5, the available courses that could be added to the new curriculum were imported into column A from the "Import Courses" sheet. The cell to the right of each course is populated with a "0" as a baseline value. When the CPAT is ran, the Excel Solver tool changes these 0s to 1s to evaluate the impact of each course's

inclusion on the curriculum’s competency development; when the optimal curriculum is determined, the courses that make it up are left as a 1 to indicate their inclusion and the rest of the courses are returned to the baseline value of 0 to indicate their omission from the optimum curriculum.

Cell H4 acts as the objective function for this sheet. The cell finds the total duration of the developed curriculum by adding up the duration of each individual courses included in the curriculum. The cell calculates this by using the SUM function and adding up the durations of each course as listed in column C of the “Solving Courses” sheet.

Starting in cell M5, the descriptor numbers for each of the descriptors from the Civil Engineer career field competency model were imported into column M from the “Import Competencies” sheet. In the cell to the right of each descriptor, a binary variable indicates whether or not that descriptor is needed to meet the desired competency development as inducted by the user on the “Choosing Competencies” sheet. These variables are imported in from column D of the “Solving Descriptors” sheet; a 0 means the descriptor is not needed from the developed curriculum and a 1 means the descriptor is needed. In the cell to the right of this first binary variable is a second binary variable, which is imported in from column B of the “Solving Descriptors” sheet. In this second variable, a 0 means that descriptor is not developed by the curriculum modeled in column C and a 1 means it is. These binary variables act as the constraints for optimization problem ran by the Excel Solver program.

The final component of the “Solving Page” is the Excel Solver tool and how its set up. In the Solver tool window, the objective is set to Cell H4 and the “min” option is selected and the binary course inclusion variables in column B are imported as the variable cells to be changed by the Solver tool. Four constraints were imported into the Solver window; the first three ensure the course inclusion variables are either a 0 or 1. Those three constraints are that the variable sin column B are greater than or equal to 0, the variables were less than or equal to 1, and the variables were an integer. The fourth constraint added to the Solver window was that the binary variable in column O is greater than or equal to their equivalent variable in column N. This constraint ensures that the developed curriculum includes the necessary descriptors to meet the competency development needs. Figure 3 shows what this Solver tool window looks like. The last input into the Solver tool window is which optimization algorithm is to be used when the CPAT is ran; the built-in Evolutionary algorithm is selected and used.

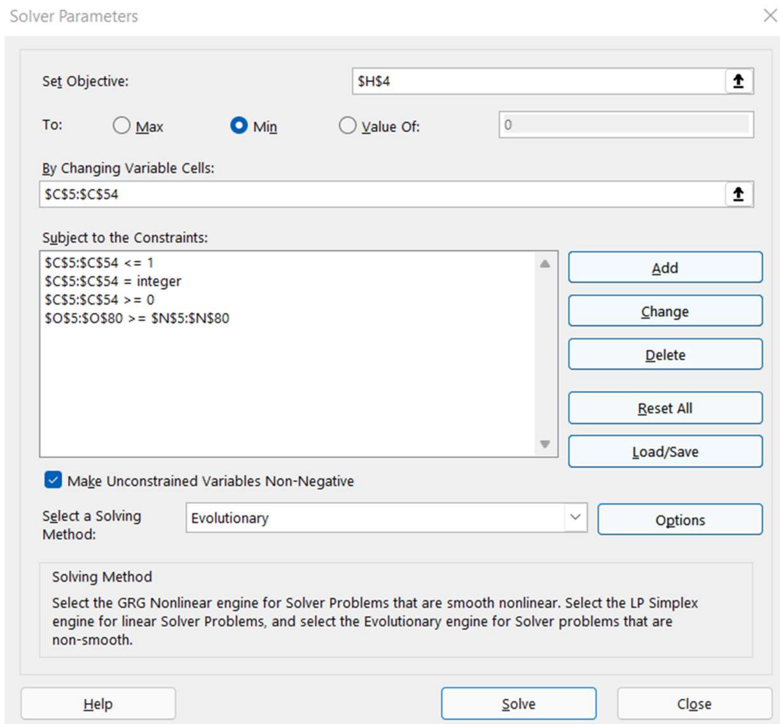


**Figure 3: Excel Solver Tool Window for "Solving Page" Sheet**

### 3.5.9 Solving Courses

The ninth sheet of the CPAT is where the tool determines the impact of previously completed courses and prerequisites for other courses on the curriculum developed by Solver on the sheet "Solving Page", as well as determine the length of the created curriculum. The list of courses is imported from the "Import Courses" into column A and using the Excel functions "MATCH" and "INDEX" the binary inclusion variable from the "Solving Page" sheet into column E. In column F, a binary variable is imported in from the sheet "Solving Prerequisites" using the "MATCH" and "INDEX" functions; this variable indicates whether that course is needed as a prerequisite to a

course that is included in the determined curriculum that Solver returns. In column G, another binary variable is imported from the sheet “Import Completed” using the “MATCH” and “INDEX” functions; this variable indicates whether this course has already been completed by the student, as input by the user of the CPAT.

If a course contributes to the curriculum’s development of descriptors through any means (as a part of the curriculum, as a prerequisite, or by having already been completed), that course’s lessons are imported into columns I through AG. The CPAT determines if this occurs by using the “IF” function; if the course is not included at all, then its lessons are left blank. The CPAT also determines the course’s contribution to the duration of the curriculum using a series of nested “IF” functions in column C; if the course is included in the curriculum or a prerequisite, then the duration of the course is imported from the sheet “Import Courses”. If a course is included as already been completed or not included at all, a 0 is entered into that course’s associated cell in column C.

**3.5.10 Solving Lessons**

The tenth sheet of the CPAT is where the tool converts courses included in the curriculum into their associated lessons, as well as determining impact of previously completed lessons. The list of lessons is imported from the sheet “Import Lessons” into column A and using the Excel function “COUNTIF” the tool determines if a lesson is included in the curriculum and creates a binary inclusion variable in column D. The tool does this by checking the matrix of lessons that were converted from included courses on

the sheet “Solving Courses”. In column E, another binary variable is imported from the sheet “Import Completed” using the “MATCH” and “INDEX” functions; this variable indicates whether this course has already been completed by the student, as input by the user of the CPAT. A binary variable is created in column B using the “IF” function that determines if each lesson is included either as previously completed by the student or through an included course. For any lesson that is included, its lesson objectives are imported into columns G through P; if the lesson is not included at all, then its lesson objectives are left blank.

### 3.5.11 Solving Lesson Objectives

The eleventh sheet of the CPAT is where the tool converts lesson objectives included in the curriculum into the descriptors they develop. The list of lesson objectives is imported from the sheet “Import Lesson Objectives” into column A and using the Excel function “COUNTIF” the tool determines if an objective is included in the curriculum and creates a binary inclusion variable in column B. The tool does this by checking the matrix of lesson objectives that were converted from included lessons on the sheet “Solving Lessons”. For any lesson objective that is included, its associated descriptors are imported into columns D through F; if the lesson objective is not included at all, then its associate descriptors are left blank.

### 3.5.12 Solving Descriptors

The twelfth sheet of the CPAT is where the tool determines which descriptors the curriculum develops. The list of descriptors is imported into column A from the sheet

"Import Competencies" and using the Excel function "COUNTIF" the tool determines if a descriptor is developed by the curriculum and creates a binary inclusion variable in column B. This sheet also creates four binary variables in columns E through H using the "MATCH" and "INDEX" functions; these variables indicate whether or not the descriptor is a part of the desired competency profile developed by the curriculum. Column E represents if it's needed because its group was selected by the user, column F represents if it's needed because its competency was selected by the user, column G represents if it's needed because its subcompetency was selected by the user, and column H represents if it's needed because the descriptor itself was selected by the user. A binary variable is created in column D using the "IF" function; this variable represents if the descriptor is needed at all, no matter the level it was selected at. In column J, a binary variable is created using the "IF" function to determine if the descriptors needed to be developed by the curriculum (as indicated in column D) are met by the descriptors developed by the curriculum (as indicated in column B).

### 3.5.13 Solving Prerequisites

The thirteenth sheet of the CPAT is where the tool determines which courses need to be included in the curriculum as a prerequisite for a selected course. In column A, the list of courses were imported in from the sheet "Import Courses". Using the functions "MATCH" and "INDEX", column B imports the binary inclusion variable from the sheet "Solving Page" to indicate if a course has been selected by the Solver tool. If a course is included, its prerequisites are imported from the sheet "Import Prerequisites" into

columns F through H. In column D, a binary variable is created using the “COUNTIF” function; this variable determines if a course is needed as a prerequisite by checking the matrix of prerequisite courses in columns F through H.

### 3.5.14 Build Page

The fourteenth sheet of the CPAT is where the user of the runs the CPAT to develop a new course from existing lessons at TCES by utilizing Excel’s Solver tool. This page is set up to mirror a basic optimization problem: establish the decision variables, define the objective function, and incorporate any constraints. For this particular problem, the existing lessons at TCES are the decision variables, the objective function is the total time of the new course, and the constraints are the descriptors that need to be developed during the curriculum.

Starting in cell B5, the available lessons that could be added to the new course were imported into column A from the “Import Lessons” sheet. The cell to the right of each course is populated with a “0” as a baseline value. When the CPAT is ran, the Excel Solver tool changes these 0s to 1s to evaluate the impact of each lesson’s inclusion on the course’s competency development; when the optimal curriculum is determined, the courses that make it up are left as a 1 to indicate their inclusion and the rest of the courses are returned to the baseline value of 0 to indicate their omission from the optimum curriculum.

Cell H4 acts as the objective function for this sheet. The cell finds the total duration of the developed course by adding up the duration of each individual lesson

included in the curriculum. The cell calculates this by using the SUM function and adding up the durations of each course as listed in column C of the “Build Lessons” sheet.

Starting in cell M5, the descriptor numbers for each of the descriptors from the Civil Engineer career field competency model were imported into column M from the “Import Competencies” sheet. In the cell to the right of each descriptor, a binary variable indicates whether or not that descriptor is needed to meet the desired competency development as inducted by the user on the “Choosing Competencies” sheet. These variables are imported in from column D of the “Build Descriptors” sheet; a 0 means the descriptor is not needed from the developed curriculum and a 1 means the descriptor is needed. In the cell to the right of this first binary variable is a second binary variable, which is imported in from column B of the “Solving Descriptors” sheet. In this second variable, a 0 means that descriptor is not developed by the curriculum modeled in column C and a 1 means it is. These binary variables act as the constraints for optimization problem ran by the Excel Solver program.

The final component of the “Build Page” is the Excel Solver tool and how its set up. In the Solver tool window, the objective is set to Cell H4 and the “min” option is selected and the binary course inclusion variables in column B are imported as the variable cells to be changed by the Solver tool. Four constraints were imported into the Solver window; the first three ensure the course inclusion variables are either a 0 or 1. Those three constraints are that the variable sin column B are greater than or equal to 0,

the variables were less than or equal to 1, and the variables were an integer. The fourth constraint added to the Solver window was that the binary variable in column O is greater than or equal to their equivalent variable in column N. This constraint ensures that the developed curriculum includes the necessary descriptors to meet the competency development needs. Figure 4 shows what this Solver tool window looks like. The last input into the Solver tool window is which optimization algorithm is to be used when the CPAT is ran; the built-in Evolutionary algorithm is selected and used.

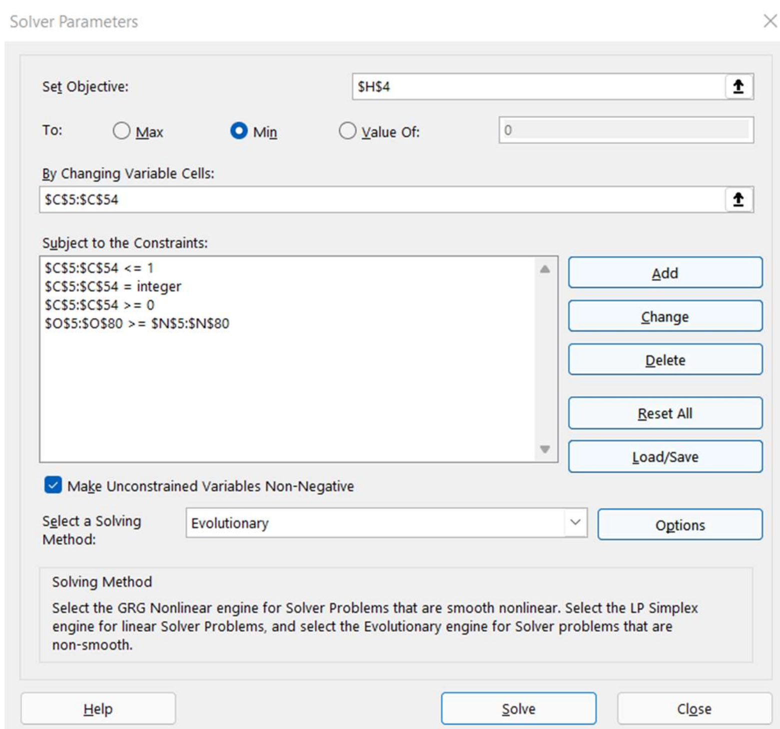


**Figure 4: Excel Solver Tool Window for “Build Page” Sheet**

### 3.5.15 Build Lessons

The fifteenth sheet of the CPAT is where the tool determines the impact of previously completed lessons on the course developed by Solver on the sheet “Build Page”, as well as determine the length of the created course. The list of lessons is imported from the “Import Lessons” into column A and using the Excel functions “MATCH” and “INDEX” the binary inclusion variable from the “Build Page” sheet into column E. In column F, another binary variable is imported from the sheet “Import Completed” using the “MATCH” and “INDEX” functions; this variable indicates whether this course has already been completed by the student, as input by the user of the CPAT.

If a lesson contributes to the new course’s development of descriptors through any means (as a part of the curriculum or by having already been completed), that lessons’ lesson objectives are imported into columns H through Q. The CPAT determines if this occurs by using the “IF” function; if the course is not included at all, then its lessons are left blank. The CPAT also determines the lesson’s contribution to the duration of the curriculum using a series of nested “IF” functions in column C; if the lessons is included in the course, then the duration of the course is imported from the sheet “Import Courses”. If a course is included as already have been completed or is not included at all, a 0 is entered into that course’s associated cell in column C.

### 3.5.16 Build Lesson Objectives

The sixteenth sheet of the CPAT is where the tool converts lesson objectives included in the new course into the descriptors they develop. The list of lesson objectives is imported from the sheet "Import Lesson Objectives" into column A and using the Excel function "COUNTIF" the tool determines if an objective is included in the course and creates a binary inclusion variable in column B. The tool does this by checking the matrix of lesson objectives that were converted from included lessons on the sheet "Solving Lessons". For any lesson objective that is included, its associated descriptors are imported into columns D through F; if the lesson objective is not included at all, then its associate descriptors are left blank.

### 3.5.17 Build Descriptors

The seventeenth sheet of the CPAT is where the tool determines which descriptors the new course develops. The list of descriptors is imported into column A from the sheet "Import Competencies" and using the Excel function "COUNTIF" the tool determines if a descriptor is developed by the course and creates a binary inclusion variable in column B. This sheet also creates four binary variables in columns E through H using the "MATCH" and "INDEX" functions; these variables indicate whether or not the descriptor is a part of the desired competency profile developed by the course. Column E represents if it's needed because its group was selected by the user, column F represents if it's needed because its competency was selected by the user, column G represents if it's needed because its subcompetency was selected by the user, and column

H represents if it's needed because the descriptor itself was selected by the user. A binary variable is created in column D using the "IF" function; this variable represents if the descriptor is needed at all, no matter the level it was selected at. In column J, a binary variable is created using the "IF" function to determine if the descriptors needed to be developed by the curriculum (as indicated in column D) are met by the descriptors developed by the curriculum (as indicated in column B).

### 3.6 Evolutionary Algorithm

The Evolutionary algorithm is a genetic algorithm ("Excel Solver - Evolutionary Solving Method Stopping Conditions."), which means it approaches problems by altering candidate solutions through evolution and determining if the evolutions improve the solution (Forrest 1996). When the Evolutionary algorithm is executed, a random selection of samples is created. The algorithm then evaluates these initial solutions, choosing the best one to be the original solution and assigning the rest of the created solutions to be "role model". The algorithm then begins makes a new solution to compare against the original solution by evolving the original solution through mutation (random changes to the original solution) and crossover (exchanging components of the original solution with the corresponding parts of one of the role model solutions); when the new solution candidate is completed, it is compared against the original solution and the better of the two options is retained (Forrest 1996). This retained population becomes the current solution, which the algorithm repeats the evolution process with repeatedly until the algorithm declares the solution has converged, which means the best solution has been

determined (Němec et al. 2021). A flowchart of how this algorithm works can be seen in Figure 5, originally published in “A comparison of continuous genetic algorithm and particle swarm optimization in parameter estimation of Gompertz growth model” by Windarto et al.

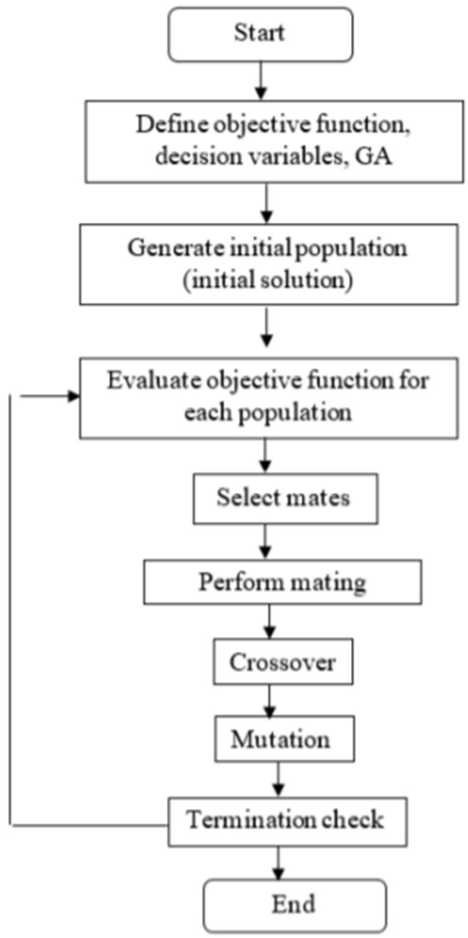


**Figure 5: Genetic Algorithm Diagram (Windarto et al. 2019)**

Excel Solver determines that the algorithm converged when it takes too long to find an improvement over the current solution; the duration that constitutes as too long is predetermined by Solver with its “Maximum Time since improvement” parameter (“Excel Solver - Evolutionary Solving Method Stopping Conditions.”). The CPAT uses the default values for all the Evolutionary algorithm parameters, which are shown in Figure 6 (which can be found under the “Options” tab of the Excel Solver window).

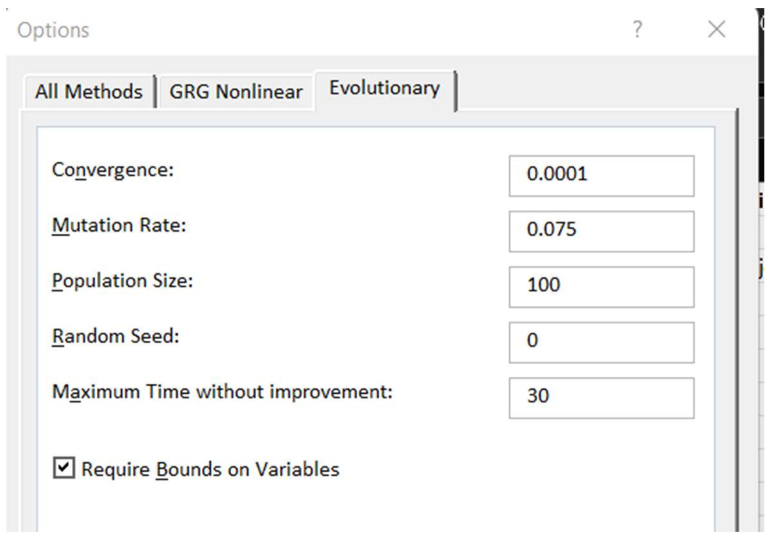


**Figure 6: Excel Solver Evolutionary Algorithm Default Parameters**

In Figure 6, four additional parameters for the Evolutionary algorithm are shown. The first is “Convergence”, which is dictates the threshold the algorithm uses to determine when it has determined the optimal solution. The convergence value represents the “maximum percentage difference in objective values for the top 99% of the population” that Solver allows before ending the algorithm (“Excel Solver - Evolutionary Solving Method Stopping Conditions.”). A smaller threshold will give the algorithm a higher

probability of reaching the globally optimal solution, but it will take a longer time to run and require more computational power (Eiben and Smit 2012). The second parameter of the Evolutionary algorithm is “Mutation Rate”, which is a probability that determines how often a part of the solution being evolved will randomly change without influence of another possible solution from the generated population. A higher mutation rate will cause more mutations during the execution of the algorithm, which lowers the chance that the algorithm will converges on a local solution instead of seeking the global solution. However, a high mutation rate will require more computational power and will cause the algorithm to run for a longer time (Hassanat et al. 2019). The third parameter is “Population Size”, which determines how many initial solutions are randomly generated at the start of the algorithm. A smaller population size will reduce the computational power required and the time the algorithm will run but reducing the number of solutions in the initial population set reduces the effectiveness of crossover mutations and makes convergence on a locally optimal solution instead of a globally optimal solution more likely (Hassanat et al. 2019). In the Solver tool, this value is capped at 200 (“Excel Solver - Evolutionary Solving Method Stopping Conditions.”). The final parameter of the Evolutionary algorithm is “Random Seed”; this parameter allows the user to determine the outcome of the random population generation and the random adaption of the initial population of the solutions. By inputting an integer, the user tells the Solver which choices to make at each point it needs to make a random decision; this allows the user to get the same solution for every time the algorithm is executed, even if that solution is not

the globally optimal solution ("Excel Solver - Evolutionary Solving Method Stopping Conditions.").

The Evolutionary algorithm is appropriate for the type of problem presented in the CPAT, which is a non-smooth nonlinear problem that has many variables to consider. This kind of optimization problem requires a lot of solution sets to be tested to converge upon the optimal solution, which is exactly what the Evolutionary algorithm does. Furthermore, neither of the other algorithm options in the Solver tool applied to the problem; the other options are the SimplexLP algorithm, which works best for linear problems, and the GRG Nonlinear algorithm, which works best for nonlinear problems that are smooth curves.

However, even though the Evolutionary algorithm is an appropriate and the best option provided by the Excel Solver tool, it does have some limitations to it. The biggest of which is that, like other genetic algorithms, the Evolutionary algorithm has no mechanism for determining if its converged solution is the globally optimal solution ("Excel Solver - Evolutionary Solving Method Stopping Conditions."). Since genetic algorithms do not use gradient information while it solves problems, it can only be sure of that it has kept the most optimal solution of all the tested solutions. Unless the algorithm evaluates every possible solution, there is no way to tell if the retained solution is the globally optimal. Additionally, since the initial solution that gets created and evolved is determined at random, the Evolutionary algorithm is nondeterministic and could return different solutions to the problem when ran multiple times (Němec et al.

2021). Because of these two limitations, its common for genetic algorithms to be ran many times in succession to address the limitations and help the algorithm converge on the globally optimal solution (Windarto 2014), as rerunning the genetic algorithm using the previous iteration's result to be considered an incumbent solution and allows the algorithm to generate a new population set of possible solutions to try to improve the solution without losing the progress it previously made ("Excel Solver - Evolutionary Solving Method Stopping Conditions.").

### 3.7 Using the CPAT

After importing all the course data, the user of the tool selects which function of the CPAT they want use by going to their respective page: the optimization tool for the course function is located on the Solve Page and the optimization tool for the lesson function is located on the Build Page. After ensuring the Solver add-in is installed, the user opens the Solver tool window, which is already filled out. The user only needs to adjust the Variable Cells and the first three constraints to match the number of courses or lessons that are being considered. The user then runs the Solver tool and allows the CPAT to execute. Even though the two functions of the CPAT are act independently from each other, the two cannot be ran simultaneously due to Excel's Solver tool only being able to run one problem at a time. However, the two functions can be run consecutively without any consequences; the user does not need to reset one function before using the other.

Because of the use of the Evolutionary algorithm in the CPAT, it's suggested the user runs the Solver tool multiple times in succession. Doing so will increase the probability that the final solution provided by the CPAT will be the globally optimal solution. There is no set number of iterations that the user should use, as there are a number of variables to consider such as the complexity of the imported data, how many descriptors the user wants to develop, how much uncertainty the user is willing to risk, and how much time the user is willing to invest in using the CPAT. If the user is familiar and comfortable with the CPAT and the Evolutionary algorithm, they may want to edit the algorithm parameters to better tailor the CPAT to their needs.

### 3.8 Validation of the CPAT

To validate the CPAT and its methodology, a synthetic case study was conducted. Sample courses offered by TCES were created and input into the CPAT, which was then executed over multiple scenarios using the Civil Engineer career field's competency model. These results were then analyzed to determine if the CPAT was working correctly. Both the course function and lesson function were tested. In the following sections, the methods for creating the data and the scenarios for the synthetic case study are discussed.

#### 3.8.1 Test Model Creation

For the case study, data needed to be generated to be input into the CPAT. For this case study, 25 courses, 100 lessons, and 150 lesson objectives were used to generate the data; these courses, lessons, and lesson objectives would be combined to create a

model that would be used to simulate the educational infrastructure at TCES. Descriptors from the Civil Engineer career field's competency model were then assigned to each of the lesson objectives to simulate the execution of the methodology developed in this research to complete the inputs needed for the CPAT to be ran.

Using an RStudio script, the courses were generated by randomly assigning lessons to each of the 10 courses. Course length in terms of number of lessons was also randomized; each course was assigned a random number between 1 and 25, which became the number of lessons that course. Each course's duration was calculated by summing the durations of the lessons in that course.

The same RStudio script developed the lessons by assigning random lesson objectives to each lesson. Like the courses, each lesson was assigned a random length by randomly choosing a number between 1 and 10, which became the number of objectives in that lesson. Each lesson's duration was calculated by the number of objectives in the lesson; for this case study, it is assumed that each lesson objective would take a comparable amount of class time to accomplish.

The same RStudio script assigned descriptors to the lesson objectives at random. Each lesson objective was assigned a random number between 1 and 3, which became the number of descriptors that lesson objective developed.

Tables with the generated data for this case study can be found in Appendix A.

### 3.8.2 Scenario Determination

To test the capabilities of the CPAT, 10 different scenarios were created. Each scenario had a different desired competency profile that the new curriculum or course was to develop. The scenarios were created to test the CPAT's ability to develop varying levels of complexity in a competency profile, as there are four different levels of the competency model that the user of the CPAT can choose desired competency development. Each scenario was executed a variable number of iterations to best determine the globally optimal solution for that scenario; each scenario was run until the CPAT returned the same solution five times in a row, which is an indicator that the CPAT has settled on what it thinks is the globally optimal solution. This value of five was arbitrarily chosen for the number of repeated solutions and is supposed to represent a balance between the desire to reduce uncertainty and look for the global optimal solution and the acknowledgement that each iteration adds more time to the total analysis. After each scenario was completed, the CPAT was returned to its original state of having all zeros in the decision variable cells to prevent influence on future scenarios.

Three of the generated scenarios had their desired developed competency profile made up entirely of descriptors, three of the scenarios were made up from only subcompetencies, three of the scenarios were built entirely from competencies, and the final scenario was made from just a single group. Within each trio of scenarios that had their desired developed competency profiles made from the same level of the competency model, each had a different number of units and did not repeat any of the same unit.

Additionally, it was ensured that every descriptor from the Civil Engineer career field's competency model was desired in at least one of the scenarios to test the CPAT's ability to return different solutions. Each scenario can be seen in Table 2.

**Table 2: Synthetic Case Study Scenarios**

| Scenario | Desired Competency Profile |
|---|---|
| 1 | Descriptors: 1.1.1, 1.1.2, 4.1.4, 5.3.1 |
| 2 | Descriptors: 3.2.1, 4.2.3, 7.3.1, 7.3.2, 7.3.3 |
| 3 | Descriptors: 2.2.2, 2.2.5, 6.3.4 |
| 4 | Subcompetencies: 1.4, 2.1 |
| 5 | Subcompetencies: 4.1, 6.3, 7.1 |
| 6 | Sub competencies: 5.2 |
| 7 | Competencies: 1 |
| 8 | Competencies: 2, 3 |
| 9 | Competencies: 6,7 |
| 10 | Groups: 2 |

# IV. Results

## 4.1 Overview

With the creation of the CPAT, TCES now has a tool to help them evaluate their course catalog and develop new educational material to address any shortcomings of the existing curriculum. However, this tool and its methodology needs to be validated in order to be used with confidence. The results from the synthetic case study outlined in Chapter 3 are presented in this chapter, which are followed by a brief discussion and analysis of the results.

## 4.2 Synthetic Case Study Results: Course Solution

Tables 3 through 12 show the course solution results from each of the scenarios ran. Each table represents a separate scenario and show the results from each iteration of the CPAT. Included in the table are both the duration of the courses set, the reduction of time in the solution from the previous iteration (both as the number of time units and as a percentage of the previous iteration's duration), and what course(s) make up that solution. At the bottom of each table shows the total reduction in time from the initial solution created in the first iteration to the converged solution in the final iteration; this total reduction is expressed both as the number of time units and the percentage of the first iteration's duration.

**Table 3: Synthetic Case Study Scenario 1 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 38 | - | EGN4, EGN5 |
| 2 | 38 | 0 (0%) | EGN4, EGN5 |
| 3 | 38 | 0 (0%) | EGN4, EGN5 |
| 4 | 38 | 0 (0%) | EGN4, EGN5 |
| 5 | 38 | 0 (0%) | EGN4, EGN5 |
| Total Reduction: 0 (0%) | | | |

**Table 4: Synthetic Case Study Scenario 2 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 66 | - | EGN19, EGN21 |
| 2 | 66 | 0 (0%) | EGN19, EGN21 |
| 3 | 66 | 0 (0%) | EGN19, EGN21 |
| 4 | 66 | 0 (0%) | EGN19, EGN21 |
| 5 | 66 | 0 (0%) | EGN19, EGN21 |
| Total Reduction: 0 (0%) | | | |

**Table 5: Synthetic Case Study Scenario 3 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 109 | - | EGN5 |
| 2 | 109 | 0 (0%) | EGN5 |
| 3 | 109 | 0 (0%) | EGN5 |
| 4 | 109 | 0 (0%) | EGN5 |
| 5 | 109 | 0 (0%) | EGN5 |
| Total Reduction: 0 (0%) | | | |

**Table 6: Synthetic Case Study Scenario 4 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 146 | - | EGN14, EGN22 |
| 2 | 146 | 0 (0%) | EGN14, EGN22 |
| 3 | 143 | 3 (2.05%) | EGN11, EGN22 |
| 4 | 143 | 0 (0%) | EGN11, EGN22 |
| 5 | 143 | 0 (0%) | EGN11, EGN22 |
| 6 | 143 | 0 (0%) | EGN11, EGN22 |
| 7 | 143 | 0 (0%) | EGN11, EGN22 |
| Total Reduction: 3 (2.05%) | | | |

**Table 7: Synthetic Case Study Scenario 5 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 238 | - | EGN11, EGN13, EGN18 |
| 2 | 238 | 0 (0%) | EGN11, EGN13, EGN18 |
| 3 | 238 | 0 (0%) | EGN11, EGN13, EGN18 |
| 4 | 238 | 0 (0%) | EGN11, EGN13, EGN18 |
| 5 | 238 | 0 (0%) | EGN11, EGN13, EGN18 |
| Total Reduction: 0 (0%) | | | |

**Table 8: Synthetic Case Study Scenario 6 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 85 | - | EGN11, EGN23 |
| 2 | 85 | 0 (0%) | EGN11, EGN23 |
| 3 | 85 | 0 (0%) | EGN11, EGN23 |
| 4 | 85 | 0 (0%) | EGN11, EGN23 |
| 5 | 85 | 0 (0%) | EGN11, EGN23 |
| Total Reduction: 0 (0%) | | | |

**Table 9: Synthetic Case Study Scenario 7 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 123 | - | EGN10, EGN13 |
| 2 | 123 | 0 (0%) | EGN10, EGN13 |
| 3 | 123 | 0 (0%) | EGN10, EGN13 |
| 4 | 123 | 0 (0%) | EGN10, EGN13 |
| 5 | 123 | 0 (0%) | EGN10, EGN13 |
| Total Reduction: 0 (0%) | | | |

**Table 10: Synthetic Case Study Scenario 8 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 203 | - | EGN3, EGN18 |
| 2 | 203 | 0 (0%) | EGN3, EGN18 |
| 3 | 203 | 0 (0%) | EGN3, EGN18 |
| 4 | 203 | 0 (0%) | EGN3, EGN18 |
| 5 | 203 | 0 (0%) | EGN3, EGN18 |
| Total Reduction: 0 (0%) | | | |

**Table 11: Synthetic Case Study Scenario 9 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 157 | - | EGN13, EGN21 |
| 2 | 157 | 0 (0%) | EGN13, EGN21 |
| 3 | 157 | 0 (0%) | EGN13, EGN21 |
| 4 | 157 | 0 (0%) | EGN13, EGN21 |
| 5 | 157 | 0 (0%) | EGN13, EGN21 |
| Total Reduction: 0 (0%) | | | |

**Table 12: Synthetic Case Study Scenario 10 Results (Course Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 109 | - | EGN5 |
| 2 | 109 | 0 (0%) | EGN5 |
| 3 | 109 | 0 (0%) | EGN5 |
| 4 | 109 | 0 (0%) | EGN5 |
| 5 | 109 | 0 (0%) | EGN5 |
| Total Reduction: 0 (0%) | | | |

### 4.2.1 Analysis of Course Solution Results

As seen in Tables 3 through 12, the CPAT returned a variety of results when ran under different scenarios with different desired competency profile development. This was an expected result; because each scenario has a different desired result, each set of courses should be different and vary from each other. From the 10 different scenarios, 9 different unique solutions were returned. The one solution that was repeated, EGN5 for scenarios 3 and 10, is one of the largest courses in the synthetic data set and it is unsurprising that it itself would develop enough descriptors to be the solution for multiple solutions. Furthermore, even though there was a couple of courses that appeared in multiple solutions, there was no consistent theme throughout each of the solutions. This would indicate that the CPAT is not creating one solution and attempting to fit it in no matter the inputs, which helps validate the CPAT as an optimization tool that creates the best solution for the given inputs.

Only one of the 10 scenarios, scenario 4, had the initial solution presented by the CPAT changed in a later iteration. This is likely due to the fact that the synthetic data is

not very complex at the course level; there are only 25 courses that are being considered by the course function, which means there are a limited number of combinations for the CPAT to consider. One conclusion from this observation is that if future users of the CPAT are able to filter the input data and reduce the number of combinations the CPAT needs to consider, the CPAT is more likely to deliver them the globally optimal solution they seek in less times and the user will not need to run as many iterations to be confident they have achieved the globally optimal solution.

**4.3 Synthetic Case Study Results: Lesson Solution**

Tables 13 through 22 show the lesson solution results from each of the scenarios ran. Each table represents a separate scenario and show the results from each iteration of the CPAT. Included in the table are both the duration of the lesson set, the reduction of time in the solution from the previous iteration (both as the number of time units and as a percentage of the previous iteration's duration), and what lesson(s) make up that solution. At the bottom of each table shows the total reduction in time from the initial solution created in the first iteration to the converged solution in the final iteration; this total reduction is expressed both as the number of time units and the percentage of the first iteration's duration.

**Table 13: Synthetic Case Study Scenario 1 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 9 | - | L10, L21, L42 |
| 2 | 9 | 0 (0%) | L10, L21, L42 |
| 3 | 8 | 1 (11%) | L42, L44 |
| 4 | 8 | 0 (0%) | L42, L44 |
| 5 | 8 | 0 (0%) | L42, L44 |
| 6 | 8 | 0 (0%) | L42, L44 |
| 7 | 8 | 0 (0%) | L42, L44 |
| 8 | 8 | 0 (0%) | L42, L44 |
| Total Reduction: 1 (11%) | | | |

**Table 14: Synthetic Case Study Scenario 2 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 17 | - | L3, L29, L32, L41 |
| 2 | 12 | 5 (29.41%) | L3. L27, L32, L37 |
| 3 | 12 | 0 (0%) | L3. L27, L32, L37 |
| 4 | 12 | 0 (0%) | L3. L27, L32, L37 |
| 5 | 12 | 0 (0%) | L3. L27, L32, L37 |
| 6 | 12 | 0 (0%) | L3. L27, L32, L37 |
| Total Reduction: 5 (29.41%) | | | |

**Table 15: Synthetic Case Study Scenario 3 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 11 | - | L4, L16, L34 |
| 2 | 11 | 0 (0%) | L4, L16, L34 |
| 3 | 9 | 2 (18.18%) | L13, L16, L34 |
| 4 | 9 | 0 (0%) | L13, L16, L34 |
| 5 | 9 | 0 (0%) | L13, L16, L34 |
| 6 | 9 | 0 (0%) | L13, L16, L34 |
| 7 | 9 | 0 (0%) | L13, L16, L34 |
| Total Reduction: 2 (18.18%) | | | |

**Table 16: Synthetic Case Study Scenario 4 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 39 | - | L3, L9, L17, L31, L41, L49, L94, L96 |
| 2 | 39 | 0 (0%) | L3, L9, L17, L31, L41, L49, L94, L96 |
| 3 | 37 | 2 (5.13%) | L3, L9, L17, L26, L31, L41, L49, L94 |
| 4 | 36 | 1 (2.70%) | L3, L9, L17, L26, L31, L41, L49 |
| 5 | 34 | 0 (0%) | L3, L9, L17, L26, L31, L41, L49 |
| 6 | 34 | 0 (0%) | L3, L9, L17, L26, L31, L41, L49 |
| 7 | 34 | 0 (0%) | L3, L9, L17, L26, L31, L41, L49 |
| 8 | 32 | 2 (5.88%) | L3, L9, L26, L31, L41, L49 |
| 9 | 32 | 0 (0%) | L3, L9, L26, L31, L41, L49 |
| 10 | 32 | 0 (0%) | L3, L9, L26, L31, L41, L49 |
| 11 | 32 | 0 (0%) | L3, L9, L26, L31, L41, L49 |
| 12 | 32 | 0 (0%) | L3, L9, L26, L31, L41, L49 |
| Total Reduction: 7 (17.95%) | | | |

**Table 17: Synthetic Case Study Scenario 5 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 33 | - | L4, L8, L9, L10, L17, L20, L35, L36, L42, L64, L69 |
| 2 | 31 | 2 (6.06%) | L4, L8, L9, L10, L20, L35, L36, L42, L48 |
| 3 | 29 | 2 (6.45%) | L4, L8, L9, L20, L35, L36, L42, L52 |
| 4 | 29 | 0 (0%) | L4, L8, L9, L20, L35, L36, L42, L52 |
| 5 | 29 | 0 (0%) | L4, L8, L9, L20, L35, L36, L42, L52 |
| 6 | 29 | 0 (0%) | L4, L8, L9, L20, L35, L36, L42, L52 |
| 7 | 29 | 0 (0%) | L4, L8, L9, L20, L35, L36, L42, L52 |
| Total Reduction: 4 (12.12%) | | | |

**Table 18: Synthetic Case Study Scenario 6 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 10 | - | L25, L32 |
| 2 | 10 | 0 (0%) | L25, L32 |
| 3 | 10 | 0 (0%) | L25, L32 |
| 4 | 10 | 0 (0%) | L25, L32 |
| 5 | 10 | 0 (0%) | L25, L32 |
| Total Reduction: 0 (0%) | | | |

**Table 19: Synthetic Case Study Scenario 7 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 41 | - | L2, L7, L9, L18, L19, L21, L39, L42 |
| 2 | 41 | 0 (0%) | L2, L7, L9, L18, L19, L21, L39, L42 |
| 3 | 36 | 5 (12.20%) | L2, L7, L9, L19, L21, L39, L42 |
| 4 | 36 | 0 (0%) | L2, L7, L9, L19, L21, L39, L42 |
| 5 | 36 | 0 (0%) | L2, L7, L9, L19, L21, L39, L42 |
| 6 | 36 | 0 (0%) | L2, L7, L9, L19, L21, L39, L42 |
| 7 | 36 | 0 (0%) | L2, L7, L9, L19, L21, L39, L42 |
| Total Reduction: 5 (12.20%) | | | |

**Table 20: Synthetic Case Study Scenario 8 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 136 | - | L3, L5, L7, L9, L10, L11, L12, L13, L17, L18, L19, L20, L28, L29, L31, L32, L40, L44, L55, L65, L69, L83, L88, L94, L99 |
| 2 | 98 | 38 (27.94%) | L3, L5, L9, L10, L12, L13, L17, L18, L19, L29, L31, L32, L33, L40, L44, L47, L65, L88, L94 |
| 3 | 87 | 11 (11.22%) | L3, L5, L9, L10, L12, L17, L19, L27, L29, L31, L32, L33, L40, L44, L65, L88, L94 |
| 4 | 83 | 4 (4.60%) | L3, L5, L9, L10, L12, L17, L19, L27, L29, L31, L32, L33, L36, L40, L64, L69, L79, L87, L88 |
| 5 | 69 | 14 (16.87%) | L5, L9, L12, L17, L27, L29, L31, L32, L33, L37, L40, L41, L69, L79 |
| 6 | 68 | 1 (1.45%) | L5, L9, L12, L17, L27, L29, L31, L32, L33, L37, L40, L41, L79 |
| 7 | 68 | 0 (0%) | L5, L9, L12, L17, L27, L29, L31, L32, L33, L37, L40, L41, L79 |
| 8 | 63 | 5 (7.35%) | L5, L9, L12, L17, L27, L29, L31, L32, L33, L37, L40 |
| 9 | 57 | 6 (9.52%) | L5, L9, L12, L17, L27, L29, L32, L33, L37, L40 |
| 10 | 57 | 0 (0%) | L5, L9, L12, L17, L27, L29, L32, L33, L37, L40, |
| 11 | 57 | 0 (0%) | L5, L9, L12, L17, L27, L29, L32, L33, L37, L40 |
| 12 | 53 | 4 (7.02%) | L3, L5, L9, L12, L17, L27, L29, L32, L33, L40 |
| 13 | 53 | 0 (0%) | L3, L5, L9, L12, L17, L27, L29, L32, L33, L40 |
| 14 | 53 | 0 (0%) | L3, L5, L9, L12, L17, L27, L29, L32, L33, L40 |
| 15 | 51 | 2 (3.77%) | L5, L9, L12, L17, L27, L29, L32, L33, L40 |
| 16 | 51 | 0 (0%) | L5, L9, L12, L17, L27, L29, L32, L33, L40 |
| 17 | 51 | 0 (0%) | L5, L9, L12, L17, L27, L29, L32, L33, L40 |
| 18 | 48 | 3 (5.88%) | L5, L9, L17, L27, L29, L32, L33, L40 |
| 19 | 48 | 0 (0%) | L5, L9, L17, L27, L29, L32, L33, L40 |
| 20 | 48 | 0 (0%) | L5, L9, L17, L27, L29, L32, L33, L40 |
| 21 | 48 | 0 (0%) | L5, L9, L17, L27, L29, L32, L33, L40 |
| 22 | 48 | 0 (0%) | L5, L9, L17, L27, L29, L32, L33, L40 |
| Total Reduction: 88 (64.71%) | | | |

**Table 21: Synthetic Case Study Scenario 8 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 137 | - | L6, L7, L9, L10, L11, L16, L19, L21, L23, L28, L30, L33, L34, L44, L46, L54, L64, L67, L68, L69, L70, L71, L73, L77, L84 |
| 2 | 108 | 29 (21.17%) | L4, L9, L10, L11, L17, L21, L23, L30, L33, L34, L42, L46, L48, L54, L60, L64, L68, L69, L78, L84, L94, L99 |
| 3 | 69 | 39 (36.11%) | L10, L21, L23, L30, L33, L34, L42, L46, L54, L64, L73, L88, L99 |
| 4 | 57 | 12 (17.39%) | L21, L23, L30, L33, L34, L42, L46, L64, L68, L73, L94, L99 |
| 5 | 57 | 0 (0%) | L21, L23, L30, L33, L34, L42, L46, L64, L68, L73, L94, L99 |
| 6 | 55 | 2 (3.51%) | L21, L23, L30, L33, L34, L46, L64, L68, L73, L94, L99 |
| 7 | 53 | 2 (3.64%) | L21, L23, L33, L34, L46, L64, L68, L73 |
| 8 | 53 | 0 (0%) | L21, L23, L33, L34, L46, L64, L68, L73 |
| 9 | 53 | 0 (0%) | L3, L21, L23, L30, L33, L34, L46, L64, L68, L73 |
| 10 | 52 | 1 (1.89%) | L3, L21, L23, L30, L33, L34, L46, L50, L64 |
| 11 | 52 | 0 (0%) | L3, L21, L23, L30, L33, L34, L46, L50, L64 |
| 12 | 52 | 0 (0%) | L3, L21, L23, L30, L33, L34, L46, L50, L64 |
| 13 | 46 | 6 (11.54%) | L21, L23, L33, L34, L36, L46, L64 |
| 14 | 46 | 0 (0%) | L21, L23, L33, L34, L36, L46, L64 |
| 15 | 46 | 0 (0%) | L21, L23, L33, L34, L36, L46, L64 |
| 16 | 45 | 1 (2.17%) | L21, L23, L30, L33, L34, L36, L46 |
| 17 | 45 | 0 (0%) | L21, L23, L30, L33, L34, L36, L46 |
| 18 | 45 | 0 (0%) | L21, L23, L30, L33, L34, L36, L46 |
| 19 | 45 | 0 (0%) | L21, L23, L30, L33, L34, L36, L46 |
| 20 | 45 | 0 (0%) | L21, L23, L30, L33, L34, L36, L46 |
| Total Reduction: 92 (67.15%) | | | |

**Table 22: Synthetic Case Study Scenario 10 Results (Lesson Solution)**

| Iteration | Duration | Reduction | Solution |
|---|---|---|---|
| 1 | 45 | - | L4, L7, L13, L23, L27, L32, L36, L41, L43, L68, L77, L94, L96 |
| 2 | 43 | 2 (4.44%) | L4, L13, L17, L23, L27, L32, L36, L41, L43, L77, L94, L96 |
| 3 | 43 | 0 (0%) | L4, L13, L17, L23, L27, L32, L36, L41, L43, L77, L94, L96 |
| 4 | 36 | 7 (16.30%) | L4, L7, L23, L32, L36, L41, L43, L77, L78 |
| 5 | 36 | 0 (0%) | L4, L7, L23, L32, L36, L41, L43, L77, L78 |
| 6 | 36 | 0 (0%) | L4, L7, L23, L32, L36, L41, L43, L77, L78 |
| 7 | 36 | 0 (0%) | L4, L7, L23, L32, L36, L41, L43, L77, L78 |
| 8 | 36 | 0 (0%) | L4, L7, L23, L32, L36, L41, L43, L77, L78 |
| Total Reduction: 9 (20.00%) | | | |

### 4.3.1 Analysis of Lesson Solution Results

As seen in Tables 13 through 22, the CPAT returned a variety of results when ran under different scenarios with different desired competency profile development. This was an expected result; because each scenario has a different desired result, each set of lesson should be different and vary from each other. From the 10 different scenarios, 10 different unique solutions were returned. Furthermore, even though there was a couple of lessons that appeared in multiple solutions, there was no consistent theme throughout each of the solutions. This would indicate that the CPAT is not creating one solution and

attempting to fit it in no matter the inputs, which helps validate the CPAT as an optimization tool that creates the best solution for the given inputs.

Nine of the 10 initial solutions were changed in by a later iteration. This supports the conclusions drawn from the course solution analysis; because the synthetic data set had 100 lessons in it, the lesson solution function had a lot more variables to consider and combinations to evaluate. This means it is harder for the Evolutionary algorithm to determine the globally optimal solution from the start and it needed the extra iterations to find the right mutations to converge at the globally optimal solution. It can also be observed that the scenarios with the larger desired competency profiles required more iterations to converge compared to the scenarios that only sought after the development of a few descriptors. For example, scenarios 8 and 9 needed 20 or more iterations before converging on the final solution, reducing from the initial solution by over 60%. That is a much longer process and much bigger reduction than observed in scenarios 1 and 2, which converged in 8 and 6 iterations respectively but only reduced the initial solution by 10%-20%. However, scenarios 1 and 2 are only a few descriptors each, which is a lot smaller than scenarios 8 and 9 which are entire competencies.

# V. Conclusions

## 5.1 Introduction

The research conducted in this thesis addressed the research objectives through the creation of the CPAT. This chapter of the thesis summarizes the research conducted and provides insights for future research. First, this chapter discusses the uses and applications of the CPAT, which is followed by a discussion on the limitations of the CPAT. The chapter then presents different optimization methods that could be used to approach the problem this thesis addressed. Finally, this chapter suggests research topics for future work to build off the research conducted.

## 5.2 Applications of the CPAT

The creation of the of CPAT provides TCES a new methodology for them to analyze existing educational offerings and prepare new educational offerings to better serve the Civil Engineer community. The first capability provided by the CPAT is its first function, the curriculum analyzer. This function allows faculty at TCES to develop the most optimal curriculum for a given competency profile. TCES can use this function at its face value; if the Civil Engineer community wants to prioritize the development of a particular competency (or competencies), TCES can easily provide an optimal pathway by utilizing the CPAT and inputting that desired competency development. TCES faculty can also use the curriculum building function of the CPAT to analyze if the coursework offered by the TCES is adequate; by developing curriculum for each competency or subcompetency on its own, faculty can compare the durations of each curriculum to

determine which competencies are being developed slower than the others. Those that are being developed slower can be identified as needed additional coursework for them or revamping the existing coursework to be more efficient.

The second capability of TCES provided by the CPAT is its second function, the course creator. This allows TCES to create new courses from existing lessons to develop a desired competency profile from the course, which has a lot of applications for TCES. One such use is to create new courses to address a short coming of any curriculum developed by the CPAT. If a curriculum needs a specific set of competencies, subcompetencies, or descriptors to be complete but there is no efficient way of adding them, a new course can be created to address that need. An additional use of this capability is to create role specific courses; if the Civil Engineer community determines a particular job or role demands specific descriptors to be developed in the individual filling that role, TCES can create a specific course to develop those descriptors for any prospective individual who will be filling that role.

Beyond the applications of the tool itself, this research also provides TCES a methodology to identify competency development from educational coursework. This methodology is valuable to TCES, as it allows TCES to better understand what its coursework is teaching to its students. Since competencies are so dependent on the context in which they will be evaluated and demonstrated in the field, TCES needs a way contextualize the learning its students do in its courses. The methodology developed in

this thesis allows TCES to do that, both for the current competency model for the Civil Engineer career field and any future competency models.

### 5.3 Limitations of the CPAT

The CPAT, in its current form, does have some limitations to use in executing the previously discussed functions. Some of these limitations are technological due to limitations in the software used; the biggest limitation to the CPAT in a technological context is that there is a level of uncertainty regarding the solution returned by the CPAT because of the use of a genetic algorithm, Solver's Evolutionary algorithm. The use of this optimization method means that the CPAT is not guaranteed to always return the globally optimal solution for the given inputs, nor is it even guaranteed to return the same solution every time it is ran with the same inputs due to the nondeterministic nature of genetic algorithms. A more obvious technological limitation is that only 200 courses or lessons can be considered for inclusion in building a curriculum or course. This limit is introduced due to the use of Excel Solver, which limits the number of decision variables it works with to 200. Additionally, the CPAT returns a singular, optimal solution, as opposed to returning multiple additional solutions that may be close to optimal. Those additional solutions may prove to be useful in analysis by providing options for TCES faculty to consider; this limitation exists because Excel's Solver program only returns one solution after executing optimization. Additionally, if there are multiple solutions that arrive to the same optimal duration, Excel only returns one of them.

Some of the other limitations of the CPAT are by design. The first is that the CPAT only works with a binary competency model, since the CPAT was designed under the assumption that completion of a lesson objective complete developed any related descriptors. This means the CPAT will not work well for any competency model that utilizes a tiered competency model, such as the current Civil Engineer career field's. Another limitation of the CPAT is that it only considers the development of one competency model at a time; many different professions and career fields are educated by the courses offered by TCES, but only the Civil Engineer career's field's officer competency model is considered when creating curriculums or new courses, despite that those same courses may develop descriptors for other competencies models that would need to be considered for those professions.

**5.3. Analysis of the Assumptions and Limitations of the CPAT**

Of the assumptions made during the development of the CPAT, the most impactful one was the assumption that competency development is binary. This assumption was made to simplify the problem; addressing the research objective to develop a tool that determines the optimized curriculum is a lot simpler when the competency development only has one level to consider. However, this assumption does not accurately reflect the real world, as the competency model in use by the Civil Engineer career field is a tiered competency model with three tiers. Because of this difference in the way the competency development is modeled compared to how it actually occurs, the CPAT is hampered in its effectiveness when used by TCES faculty.

The other assumption made in the development of the CPAT that has major implication on its applicability is that the optimal solution is the sequence of courses is the sequence with the shortest duration. This means the CPAT does not consider when courses may be offered during the year and if there is any availability in a course for a student to register. This means that the CPAT could return a solution that may take the least amount of classroom time but may take the close to a year of real time due to including a course that's only offered once a year or because it includes a pair of courses that overlap in their scheduled time. However, a slightly less optimal solution (one that may take a few more class hours) may be able to be completed in only a few months of real time because of how the included courses are scheduled. Because of this and similar scenarios, the CPAT needs to have the capability to have scheduling information imported and considered while its determining the optimal solution for it to be effective in practice.

**5.4 Comparison of Optimization Techniques**

In this research, a genetic algorithm (Solver's Evolutionary algorithm) is used in the CPAT to determine the optimal set of classes or lessons for the desired competency development. However, using a genetic algorithm is not the only method of optimization that could work for this research problem. Another method that could be used is the particle swarm optimization algorithm, which is similar method to the genetic algorithm. The particle swarm optimization algorithm starts in a similar manner to the genetic algorithm, which is by randomly creating a random set of solutions as initial possible

solutions (Windarto 2014). The algorithm then begins to change those initial set of solutions by evolving them and retaining any new solutions that are better than the previously retained solution; however, unlike the genetic algorithm, the particle swarm optimization algorithm does not use any crossovers in the adaptation of the possible solutions. As the different solutions evolve over time and get better, the algorithm as whole determines what the overall solution is by using information from each of the retained solutions (Qinghai 2010). The particle swarm optimization algorithm converges when the individual solutions began to converge on the same solution (Qinghai 2010). One advantage of the particle swarm optimization algorithm is that it is less likely to prematurely converge because there is no crossover between the solutions so each of the individual solutions in the set develop uniquely from each other (Windarto 2014), but premature convergence still can occur and it is also a nondeterministic method as the random creation of the initial solution set means that the algorithm will not always produce the same result when ran with the same inputs (Qinghai 2010).

Another optimization method that could be used is to use a combinatorial approach. Since the number of courses of courses or lessons offered by TCES is a finite integer and the variable that determines if a given course or lesson is included in the optimal solution set is binary, there is a finite number of possible solutions the CPAT needs to evaluate and consider. Because of this, it is possible to assess every possible combination of courses or lessons as a possible solution by evaluating each combination's duration and competency development. After removing any combination

that does not meet the minimum competency development profile, the combination with the lowest duration will be the globally optimal solution. The advantage of this method is that it is deterministic and it will always return the globally optimal solution, unlike the previously discussed methods. However, this solution will come at the cost of immense computing power and time invested in executing this method, as there could be an incredible number of combinations of courses or lessons as the catalog of educational offerings considered increases due to the exponential nature of combinations.

A third optimization technique is to utilize network theory and approach the research problem as if it were a "shortest path problem". Network theory is the use of a spatial graph to represent all the variables that are connected in a system (Saleh and Mohamed 2018). This system is composed of nodes and edges; nodes are singular locations that represent items in a network and the edges represent the relationship between each node. These edges are assigned different weights, which is how the relationship between nodes are quantified. These edges can be assigned as many attributes as they need to fully model the system (Martins 1984). The shortest path problem attempts to determine the shortest distance between a given pair of nodes; this approach could be used to address this research problem in having the two nodes represent the initial state of competency development in a student at TCES and the final state of competency development (after the student has undergone the curriculum). The shortest path between these nodes would represent the most optimal sequence of courses that achieve that desired competency development. This optimization could utilize a

number of different network theory calculations, including Dijkstra's algorithm, A* search algorithm, or some variation of any shortest path algorithm (Ahuja et all, 1990). The advantage of this method is that it would guarantee the provided solution is the globally optimal solution without the computational power and time that a combinational method would require. However, the disadvantage of this method is that it requires more data and additional research to implement; since network theory is reliant on the network's existence, further research would need to be conducted in order to accurately model the relationship between courses and lessons at TCES, the descriptors they develop, and the duration of those educational offerings.

**5.5 Recommendations for Future Research**

There are many streams of research that can build from the research conducted in this thesis. These future endeavors can be categorized into three categories: improving the user experience of the CPAT, improving the CPAT by expanding its capabilities, and addressing the limitations of the CPAT.

The first category of future research topics is looking into improving the user experience of the tool. While the tool works, there are points where the user interacts with the tool that don't work as efficiently as possible; future research can investigate how to improve these interactions. One example is when the user determines which competencies they want the tool to develop in the curriculum or new course it builds. Currently, the tool just asks the user to input 1s in cells, which is not the most user friendly when choosing a variety of competencies or when trying to change a previous

selection to a new one. Future research should investigate how to improve this interaction, potentially investigating the incorporation of a Graphical User Interface (GUI) that may be more user friendly. Another point that could be improved for the user is when trying to determine which courses or lessons the CPAT determined was a part of the solution. Currently the tool just lists all of the available options and puts a 1 in the cell adjacent to it. This can be difficult for the user to quickly determine which units are a part of the solution, particularly when there is a lot of options. Improvement in determining the tool's solution would be a worthy effort for future research.

The second category of future research is improving the usefulness of the CPAT by adding capabilities to it. One such capability that should be researched is determining redundancy in TCES offerings by determining how often each descriptor is developed by coursework; if a course or lesson develops descriptors that are developed in a lot of other units, then faculty at TCES can consider either reducing the course or lesson to remove any redundant descriptor development or outright remove the course or lesson from the offerings. Another capability the CPAT could develop that would be of value to TCES would be to return more solutions than the singular determined optimal solution. Even if a solution is not the most optimal solution, it still can be a good solution and may be better when considering other factors, such as number of seats per class and available faculty. TCES may want to be able to see more than one solution when conducting analysis on their educational offerings.

The third category of future research topics to improve the CPAT is to address the limitations the tool currently has, both conceptually and technically. One of the big limitations of the CPAT is it assumes the competency model is binary; research needs to be done to determining how to distinguish between descriptor development over different levels of proficiency and to address these different tiers when building the curriculum or new course. Additionally, future research should be done to investigate other optimization programs and methods to determine if they are not hampered the technological limitations of Microsoft Excel's Solver tool and the Evolutionary algorithm. This future research should determine which program and optimization method is best suited for the needs of TCES.

**5.6 Research Summary**

The USAF is improving its evaluation and development processes through the integration of competencies and competency-based education. Doing so requires research into how to properly merge the existing process and structures of the USAF with these new ideas. This research effort set out to answer the research question "How can a competency-based educational curriculum be developed from existing processes and structures within the Civil Engineer career field, including the existing processes and structures within TCES?". This was done by defining the structure of competencies and identifying how competency descriptors can be related to educational lesson objectives by using the principles of competency-based education. This research then used this relationship in the Competency Profile Analysis Tool (CPAT), a tool that determines the

optimal curriculum or set of lessons that develops a desired competency profile from the Civil Engineer career field's competency model.

## Appendix A: Synthetic Case Study Data

### Table A1: List of Synthetic Courses, Lessons, and Lesson Objectives

| Courses | Lessons | Lesson Objectives |
|---|---|---|
| EGN1 | L1 | O1 |
| EGN2 | L2 | O2 |
| EGN3 | L3 | O3 |
| EGN4 | L4 | O4 |
| EGN5 | L5 | O5 |
| EGN6 | L6 | O6 |
| EGN7 | L7 | O7 |
| EGN8 | L8 | O8 |
| EGN9 | L9 | O9 |
| EGN10 | L10 | O10 |
| EGN11 | L11 | O11 |
| EGN12 | L12 | O12 |
| EGN13 | L13 | O13 |
| EGN14 | L14 | O14 |
| EGN15 | L15 | O15 |
| EGN16 | L16 | O16 |
| EGN17 | L17 | O17 |
| EGN18 | L18 | O18 |
| EGN19 | L19 | O19 |
| EGN20 | L20 | O20 |
| EGN21 | L21 | O21 |
| EGN22 | L22 | O22 |
| EGN23 | L23 | O23 |
| EGN24 | L24 | O24 |
| EGN25 | L25 | O25 |
| | L26 | O26 |
| | L27 | O27 |
| | L28 | O28 |
| | L29 | O29 |
| | L30 | O30 |
| | L31 | O31 |
| | L32 | O32 |
| | L33 | O33 |
| | L34 | O34 |
| | L35 | O35 |
| | L36 | O36 |
| | L37 | O37 |
| | L38 | O38 |
| | L39 | O39 |
| | L40 | O40 |

**Table A1 (cont.): List of Synthetic Courses, Lessons, and Lesson Objectives**

| Courses | Lessons | Lesson Objectives |
|---|---|---|
| | L41 | O41 |
| | L42 | O42 |
| | L43 | O43 |
| | L44 | O44 |
| | L45 | O45 |
| | L46 | O46 |
| | L47 | O47 |
| | L48 | O48 |
| | L49 | O49 |
| | L50 | O50 |
| | L51 | O51 |
| | L52 | O52 |
| | L53 | O53 |
| | L54 | O54 |
| | L55 | O55 |
| | L56 | O56 |
| | L57 | O57 |
| | L58 | O58 |
| | L59 | O59 |
| | L60 | O60 |
| | L61 | O61 |
| | L62 | O62 |
| | L63 | O63 |
| | L64 | O64 |
| | L65 | O65 |
| | L66 | O66 |
| | L67 | O67 |
| | L68 | O68 |
| | L69 | O69 |
| | L70 | O70 |
| | L71 | O71 |
| | L72 | O72 |
| | L73 | O73 |
| | L74 | O74 |
| | L75 | O75 |
| | L76 | O76 |
| | L77 | O77 |
| | L78 | O78 |
| | L79 | O79 |
| | L80 | O80 |
| | L81 | O81 |
| | L82 | O82 |
| | L83 | O83 |
| | L84 | O84 |
| | L85 | O85 |

### Table A1 (cont.): List of Synthetic Courses, Lessons, and Lesson Objectives

| Courses | Lessons | Lesson Objectives |
|---|---|---|
| | L86 | O86 |
| | L87 | O87 |
| | L88 | O88 |
| | L89 | O89 |
| | L90 | O90 |
| | L91 | O91 |
| | L92 | O92 |
| | L93 | O93 |
| | L94 | O94 |
| | L95 | O95 |
| | L96 | O96 |
| | L97 | O97 |
| | L98 | O98 |
| | L99 | O99 |
| | L100 | O100 |
| | | O101 |
| | | O102 |
| | | O103 |
| | | O104 |
| | | O105 |
| | | O106 |
| | | O107 |
| | | O108 |
| | | O109 |
| | | O110 |
| | | O111 |
| | | O112 |
| | | O113 |
| | | O114 |
| | | O115 |
| | | O116 |
| | | O117 |
| | | O118 |
| | | O119 |
| | | O120 |
| | | O121 |
| | | O122 |
| | | O123 |
| | | O124 |
| | | O125 |
| | | O126 |
| | | O127 |
| | | O128 |
| | | O129 |
| | | O130 |

**Table A1 (cont.): List of Synthetic Courses, Lessons, and Lesson Objectives**

| Courses | Lessons | Lesson Objectives |
|---|---|---|
| | | O131 |
| | | O132 |
| | | O133 |
| | | O134 |
| | | O135 |
| | | O136 |
| | | O137 |
| | | O138 |
| | | O139 |
| | | O140 |
| | | O141 |
| | | O142 |
| | | O143 |
| | | O144 |
| | | O145 |
| | | O146 |
| | | O147 |
| | | O148 |
| | | O149 |
| | | O150 |

**Table A2.1: List of Synthetic Courses and Their Lessons (Lessons 1 through 11)**

| Course | Length | Lesson | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| EGN1 | 87 | L16 | L69 | L1 | L61 | L77 | L48 | L76 | L29 | L100 | L35 | L49 |
| EGN2 | 135 | L11 | L21 | L56 | L29 | L89 | L22 | L52 | L96 | L50 | L2 | L56 |
| EGN3 | 136 | L28 | L56 | L52 | L22 | L83 | L96 | L38 | L36 | L81 | L65 | L65 |
| EGN4 | 32 | L17 | L42 | L82 | L67 | L38 | L74 | | | | | |
| EGN5 | 109 | L3 | L30 | L73 | L94 | L36 | L45 | L90 | L31 | L71 | L97 | L41 |
| EGN6 | 122 | L94 | L94 | L88 | L85 | L11 | L88 | L30 | L68 | L39 | L90 | L92 |
| EGN7 | 128 | L100 | L9 | L77 | L21 | L46 | L39 | L79 | L57 | L40 | L47 | L65 |
| EGN8 | 93 | L35 | L27 | L1 | L10 | L85 | L19 | L98 | L87 | L72 | L100 | L74 |
| EGN9 | 150 | L97 | L56 | L81 | L1 | L69 | L38 | L91 | L39 | L40 | L21 | L39 |
| EGN10 | 30 | L39 | L35 | L28 | L37 | L89 | | | | | | |
| EGN11 | 78 | L66 | L65 | L44 | L72 | L9 | L2 | L88 | L25 | L18 | L33 | L59 |
| EGN12 | 92 | L79 | L76 | L49 | L27 | L44 | L80 | L97 | L62 | L81 | L89 | L35 |
| EGN13 | 93 | L94 | L2 | L27 | L8 | L27 | L14 | L51 | L45 | L68 | L49 | L85 |
| EGN14 | 81 | L16 | L98 | L67 | L9 | L90 | L55 | L47 | L49 | L18 | L84 | L75 |
| EGN15 | 6 | L44 | | | | | | | | | | |
| EGN16 | 118 | L26 | L15 | L32 | L28 | L55 | L52 | L91 | L14 | L6 | L11 | L35 |
| EGN17 | 65 | L61 | L61 | L17 | L41 | L85 | L59 | L32 | L100 | L47 | L9 | L86 |
| EGN18 | 67 | L37 | L82 | L3 | L85 | L66 | L10 | L5 | L32 | L6 | L99 | L16 |
| EGN19 | 9 | L3 | L54 | | | | | | | | | |
| EGN20 | 80 | L36 | L9 | L66 | L62 | L51 | L65 | L15 | L89 | L93 | L77 | L58 |
| EGN21 | 57 | L40 | L44 | L49 | L15 | L26 | L76 | L46 | | | | |
| EGN22 | 65 | L19 | L15 | L83 | L2 | L78 | L77 | L61 | L23 | L47 | L44 | L91 |
| EGN23 | 7 | L72 | L48 | | | | | | | | | |
| EGN24 | 92 | L92 | L47 | L30 | L58 | L97 | L7 | L24 | L6 | L76 | L50 | L55 |
| EGN25 | 21 | L77 | L78 | L58 | L60 | | | | | | | |

**Table A2.2: List of Synthetic Courses and Their Lessons (Lessons 12 through 25)**

| Course | Lesson | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| EGN1 | L45 | L86 | L74 | L96 | L99 | L39 | | | | | | | |
| EGN2 | L56 | L11 | L79 | L29 | L79 | L87 | L22 | L46 | L37 | | | | |
| EGN3 | L92 | L33 | L6 | L96 | L29 | L81 | L95 | L73 | L23 | L73 | L54 | | |
| EGN4 | | | | | | | | | | | | | |
| EGN5 | L28 | L3 | L71 | L96 | L32 | L6 | L72 | L46 | L43 | L69 | | | |
| EGN6 | L11 | L3 | L83 | L10 | L40 | L80 | L84 | L86 | L43 | L29 | L16 | L35 | L2 |
| EGN7 | L27 | L15 | L93 | L54 | L9 | L36 | L25 | L73 | L32 | L46 | L46 | L44 | |
| EGN8 | L30 | L28 | L18 | L78 | L52 | L12 | L59 | L42 | L81 | | | | |
| EGN9 | L94 | L84 | L62 | L45 | L90 | L88 | L43 | L37 | L100 | L95 | L24 | L83 | L84 |
| EGN10 | | | | | | | | | | | | | |
| EGN11 | L63 | | | | | | | | | | | | |
| EGN12 | L65 | L22 | L28 | L82 | | | | | | | | | |
| EGN13 | L44 | L60 | L17 | L25 | L8 | | | | | | | | |
| EGN14 | L74 | L97 | | | | | | | | | | | |
| EGN15 | | | | | | | | | | | | | |
| EGN16 | L24 | L91 | L78 | L99 | L45 | L99 | L31 | L98 | L4 | | | | |
| EGN17 | L48 | L79 | L14 | | | | | | | | | | |
| EGN18 | L72 | | | | | | | | | | | | |
| EGN19 | | | | | | | | | | | | | |
| EGN20 | L86 | L91 | L8 | | | | | | | | | | |
| EGN21 | | | | | | | | | | | | | |
| EGN22 | L87 | | | | | | | | | | | | |
| EGN23 | | | | | | | | | | | | | |
| EGN24 | L93 | L81 | L56 | L55 | | | | | | | | | |
| EGN25 | | | | | | | | | | | | | |

## Table A3: List of Synthetic Lessons and Their Objectives

| Lesson | Length | Objective | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| L1 | 4 | O88 | O87 | O64 | O101 | | | | | | |
| L2 | 8 | O70 | O1 | O49 | O11 | O112 | O77 | O35 | O55 | | |
| L3 | 1 | O81 | | | | | | | | | |
| L4 | 5 | O102 | O142 | O13 | O140 | O95 | | | | | |
| L5 | 10 | O71 | O15 | O113 | O54 | O99 | O67 | O121 | O97 | O148 | O101 |
| L6 | 9 | O141 | O122 | O45 | O83 | O76 | O71 | O36 | O136 | O73 | |
| L7 | 3 | O123 | O63 | O50 | | | | | | | |
| L8 | 7 | O3 | O19 | O150 | O76 | O21 | O141 | O79 | | | |
| L9 | 2 | O62 | O61 | | | | | | | | |
| L10 | 2 | O145 | O95 | | | | | | | | |
| L11 | 7 | O72 | O56 | O124 | O70 | O3 | O90 | O102 | | | |
| L12 | 4 | O45 | O47 | O23 | O104 | | | | | | |
| L13 | 3 | O61 | O149 | O35 | | | | | | | |
| L14 | 9 | O55 | O29 | O128 | O21 | O75 | O51 | O21 | O9 | O93 | |
| L15 | 7 | O120 | O92 | O84 | O5 | O55 | O113 | O22 | | | |
| L16 | 2 | O45 | O125 | | | | | | | | |
| L17 | 2 | O119 | O57 | | | | | | | | |
| L18 | 5 | O56 | O31 | O5 | O48 | O145 | | | | | |
| L19 | 9 | O136 | O106 | O74 | O147 | O133 | O144 | O117 | O9 | O51 | |
| L20 | 7 | O32 | O10 | O39 | O138 | O133 | O38 | O99 | | | |
| L21 | 5 | O83 | O31 | O110 | O4 | O90 | | | | | |
| L22 | 8 | O145 | O110 | O25 | O109 | O126 | O28 | O124 | O102 | | |
| L23 | 9 | O125 | O73 | O137 | O55 | O103 | O107 | O43 | O41 | O135 | |
| L24 | 5 | O117 | O138 | O138 | O107 | O68 | | | | | |
| L25 | 8 | O96 | O48 | O106 | O83 | O81 | O66 | O83 | O142 | | |
| L26 | 8 | O121 | O43 | O45 | O121 | O82 | O144 | O2 | O71 | | |
| L27 | 1 | O48 | | | | | | | | | |
| L28 | 8 | O32 | O63 | O39 | O46 | O3 | O125 | O62 | O67 | | |
| L29 | 10 | O30 | O25 | O78 | O2 | O142 | O45 | O142 | O76 | O70 | O107 |
| L30 | 6 | O52 | O81 | O29 | O82 | O136 | O122 | | | | |
| L31 | 6 | O83 | O136 | O18 | O84 | O122 | O36 | | | | |
| L32 | 5 | O82 | O132 | O86 | O15 | O55 | | | | | |
| L33 | 10 | O88 | O100 | O35 | O47 | O7 | O91 | O96 | O102 | O86 | O59 |
| L34 | 4 | O110 | O96 | O110 | O94 | | | | | | |
| L35 | 3 | O145 | O143 | O15 | | | | | | | |
| L36 | 1 | O97 | | | | | | | | | |
| L37 | 5 | O96 | O117 | O122 | O125 | O79 | | | | | |
| L38 | 8 | O82 | O119 | O128 | O122 | O87 | O17 | O68 | O99 | | |
| L39 | 7 | O88 | O118 | O47 | O23 | O126 | O3 | O15 | | | |
| L40 | 8 | O146 | O79 | O5 | O36 | O70 | O53 | O124 | O50 | | |
| L41 | 1 | O130 | | | | | | | | | |
| L42 | 2 | O8 | O119 | | | | | | | | |
| L43 | 7 | O20 | O65 | O8 | O121 | O133 | O104 | O88 | | | |

## Table A3 (cont.): List of Synthetic Lessons and Their Objectives

| Lesson | Length | Objective | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| L44 | 6 | O108 | O130 | O129 | O107 | O9 | O30 | | | | |
| L45 | 8 | O45 | O85 | O63 | O118 | O94 | O74 | O6 | O61 | | |
| L46 | 10 | O120 | O71 | O75 | O53 | O27 | O97 | O103 | O135 | O69 | O82 |
| L47 | 4 | O83 | O117 | O108 | O11 | | | | | | |
| L48 | 2 | O95 | O90 | | | | | | | | |
| L49 | 10 | O147 | O16 | O45 | O70 | O74 | O46 | O4 | O103 | O141 | O122 |
| L50 | 6 | O145 | O40 | O109 | O79 | O140 | O120 | | | | |
| L51 | 8 | O125 | O141 | O149 | O72 | O107 | O81 | O29 | O91 | | |
| L52 | 2 | O135 | O25 | | | | | | | | |
| L53 | 9 | O22 | O70 | O10 | O7 | O85 | O67 | O96 | O35 | O139 | |
| L54 | 8 | O142 | O91 | O11 | O79 | O94 | O54 | O70 | O137 | | |
| L55 | 7 | O131 | O143 | O50 | O32 | O125 | O74 | O53 | | | |
| L56 | 10 | O146 | O9 | O132 | O29 | O62 | O117 | O2 | O122 | O103 | O58 |
| L57 | 8 | O45 | O9 | O27 | O1 | O18 | O118 | O107 | O78 | | |
| L58 | 9 | O33 | O128 | O99 | O8 | O21 | O109 | O106 | O118 | O72 | |
| L59 | 7 | O87 | O86 | O7 | O103 | O116 | O71 | O10 | | | |
| L60 | 7 | O113 | O51 | O32 | O134 | O121 | O49 | O1 | | | |
| L61 | 5 | O84 | O107 | O92 | O33 | O12 | | | | | |
| L62 | 6 | O124 | O60 | O29 | O72 | O147 | O28 | | | | |
| L63 | 8 | O31 | O69 | O102 | O39 | O98 | O86 | O125 | O131 | | |
| L64 | 1 | O67 | | | | | | | | | |
| L65 | 7 | O37 | O87 | O54 | O95 | O150 | O44 | O109 | | | |
| L66 | 10 | O93 | O54 | O78 | O142 | O141 | O36 | O78 | O61 | O25 | O48 |
| L67 | 6 | O35 | O59 | O145 | O10 | O15 | O136 | | | | |
| L68 | 4 | O14 | O123 | O81 | O31 | | | | | | |
| L69 | 1 | O62 | | | | | | | | | |
| L70 | 3 | O48 | O128 | O134 | | | | | | | |
| L71 | 8 | O141 | O140 | O127 | O116 | O122 | O18 | O80 | O52 | | |
| L72 | 5 | O23 | O68 | O83 | O123 | O130 | | | | | |
| L73 | 4 | O141 | O129 | O72 | O24 | | | | | | |
| L74 | 5 | O63 | O51 | O72 | O111 | O6 | | | | | |
| L75 | 10 | O49 | O49 | O139 | O4 | O41 | O7 | O85 | O123 | O14 | O2 |
| L76 | 8 | O148 | O110 | O73 | O46 | O25 | O150 | O29 | O10 | | |
| L77 | 2 | O106 | O138 | | | | | | | | |
| L78 | 3 | O49 | O148 | O144 | | | | | | | |
| L79 | 4 | O49 | O144 | O69 | O128 | | | | | | |
| L80 | 4 | O43 | O94 | O8 | O125 | | | | | | |
| L81 | 5 | O27 | O94 | O56 | O105 | O92 | | | | | |
| L82 | 9 | O7 | O72 | O80 | O131 | O11 | O50 | O12 | O131 | O55 | |
| L83 | 5 | O142 | O143 | O112 | O8 | O51 | | | | | |
| L84 | 6 | O4 | O109 | O65 | O89 | O59 | O18 | | | | |
| L85 | 5 | O89 | O24 | O62 | O16 | O64 | | | | | |
| L86 | 7 | O115 | O125 | O62 | O135 | O141 | O66 | O57 | | | |

**Table A3 (cont.): List of Synthetic Lessons and Their Objectives**

| Lesson | Length | Objective | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| L87 | 2 | O111 | O59 | | | | | | | | |
| L88 | 2 | O93 | O89 | | | | | | | | |
| L89 | 7 | O149 | O75 | O50 | O63 | O130 | O19 | O32 | | | |
| L90 | 10 | O85 | O41 | O73 | O106 | O7 | O83 | O121 | O79 | O49 | O48 |
| L91 | 5 | O10 | O5 | O139 | O50 | O44 | | | | | |
| L92 | 5 | O92 | O112 | O150 | O133 | O131 | | | | | |
| L93 | 2 | O29 | O18 | | | | | | | | |
| L94 | 2 | O115 | O6 | | | | | | | | |
| L95 | 7 | O149 | O7 | O44 | O147 | O84 | O112 | O68 | | | |
| L96 | 2 | O104 | O119 | | | | | | | | |
| L97 | 6 | O74 | O86 | O146 | O11 | O40 | O111 | | | | |
| L98 | 8 | O65 | O51 | O38 | O103 | O96 | O24 | O58 | O79 | | |
| L99 | 4 | O127 | O6 | O4 | O144 | | | | | | |
| L100 | 7 | O89 | O33 | O135 | O48 | O127 | O42 | O49 | | | |

## Table A4: List of Synthetic Objectives and the Descriptors They Develop

| Lesson Objective | Descriptor 1 | Descriptor 2 | Descriptor 3 |
|---|---|---|---|
| O1 | 1.1.2 | | |
| O2 | 7.1.5 | 7.3.2 | |
| O3 | 1.1.5 | 7.2.2 | 7.3.2 |
| O4 | 7.1.5 | 7.1.1 | 6.3.3 |
| O5 | 3.2.2 | | |
| O6 | 5.1.4 | 1.3.1 | 1.1.3 |
| O7 | 6.3.5 | | |
| O8 | 1.1.1 | 1.4.3 | 4.1.4 |
| O9 | 5.2.3 | 6.2.1 | |
| O10 | 6.3.5 | 5.2.1 | |
| O11 | 6.3.2 | 4.1.4 | |
| O12 | 6.2.3 | 1.1.3 | 4.1.4 |
| O13 | 4.1.3 | 7.1.4 | |
| O14 | 7.2.1 | 7.1.1 | 4.1.1 |
| O15 | 1.2.3 | 4.1.1 | 6.3.1 |
| O16 | 1.1.2 | 2.1.3 | |
| O17 | 3.1.3 | | |
| O18 | 3.1.1 | | |
| O19 | 3.1.2 | 1.1.1 | |
| O20 | 6.3.1 | 7.3.3 | 5.1.4 |
| O21 | 6.3.4 | 7.1.5 | |
| O22 | 7.1.1 | 5.3.1 | |
| O23 | 4.1.1 | 1.2.1 | 1.2.2 |
| O24 | 6.1.3 | 4.1.3 | |
| O25 | 7.1.5 | 7.3.1 | 6.1.2 |
| O26 | 7.1.3 | | |
| O27 | 4.1.5 | 3.1.3 | 7.3.3 |
| O28 | 1.4.2 | 7.2.4 | 6.2.2 |
| O29 | 4.1.3 | 7.1.5 | |
| O30 | 7.1.6 | 7.2.4 | |
| O31 | 2.1.5 | 2.1.2 | 6.1.1 |
| O32 | 5.1.3 | 6.1.3 | |
| O33 | 4.1.4 | | |
| O34 | 7.2.4 | 1.4.4 | 2.1.3 |
| O35 | 7.2.4 | | |
| O36 | 7.1.6 | 6.3.4 | 7.3.1 |
| O37 | 7.1.7 | 3.2.1 | |
| O38 | 6.3.3 | 3.1.2 | 2.2.5 |
| O39 | 1.4.5 | 2.1.1 | |
| O40 | 6.2.2 | | |
| O41 | 2.2.3 | | |
| O42 | 3.3.3 | | |
| O43 | 7.2.1 | 2.2.4 | 2.1.1 |
| O44 | 6.3.2 | | |
| O45 | 4.2.3 | 1.4.4 | 5.2.2 |

**Table A4 (cont.): List of Synthetic Objectives and the Descriptors They Develop**

| Lesson Objective | Descriptor 1 | Descriptor 2 | Descriptor 3 |
|---|---|---|---|
| O46 | 7.1.2 | 6.3.3 | |
| O47 | 7.1.5 | | |
| O48 | 7.3.1 | 6.1.3 | |
| O49 | 6.3.4 | 5.2.4 | |
| O50 | 1.1.3 | | |
| O51 | 6.3.3 | 1.1.5 | |
| O52 | 4.1.5 | | |
| O53 | 1.1.4 | 7.1.6 | 1.1.5 |
| O54 | 3.2.2 | 1.4.4 | |
| O55 | 1.4.2 | 5.1.1 | 7.3.3 |
| O56 | 1.4.2 | 1.3.3 | 2.2.2 |
| O57 | 7.1.1 | | |
| O58 | 6.2.1 | 3.1.1 | |
| O59 | 1.4.3 | | |
| O60 | 2.1.2 | 7.1.6 | 7.1.1 |
| O61 | 7.2.1 | | |
| O62 | 1.4.5 | 6.3.2 | 4.1.5 |
| O63 | 5.1.2 | 5.3.1 | |
| O64 | 2.1.4 | | |
| O65 | 5.1.3 | 6.3.4 | |
| O66 | 7.1.7 | | |
| O67 | 5.2.3 | 4.2.3 | 5.1.2 |
| O68 | 5.2.4 | 6.1.3 | |
| O69 | 3.1.2 | 3.3.3 | |
| O70 | 3.3.3 | | |
| O71 | 7.2.2 | | |
| O72 | 1.4.5 | 1.1.4 | 7.3.2 |
| O73 | 6.3.3 | 6.3.2 | 4.1.5 |
| O74 | 5.3.1 | | |
| O75 | 3.1.2 | 6.3.6 | |
| O76 | 6.2.1 | 4.2.3 | |
| O77 | 6.3.2 | 7.2.5 | |
| O78 | 7.1.5 | 6.3.4 | 1.3.3 |
| O79 | 7.3.2 | 3.3.3 | |
| O80 | 1.1.2 | 7.2.3 | |
| O81 | 3.2.1 | | |
| O82 | 5.2.2 | 6.3.6 | |
| O83 | 1.1.4 | 3.1.1 | |
| O84 | 1.4.3 | | |
| O85 | 2.1.4 | | |
| O86 | 5.2.1 | 6.1.1 | 4.2.1 |
| O87 | 5.2.2 | | |
| O88 | 4.2.1 | | |
| O89 | 7.2.4 | 2.1.4 | 3.1.3 |
| O90 | 5.2.2 | 4.2.3 | 2.2.1 |

**Table A4 (cont.): List of Synthetic Objectives and the Descriptors They Develop**

| Lesson Objective | Descriptor 1 | Descriptor 2 | Descriptor 3 |
|---|---|---|---|
| O91 | 3.2.2 | 6.2.2 | 6.1.1 |
| O92 | 6.3.2 | 7.1.6 | 2.1.2 |
| O93 | 7.1.1 | | |
| O94 | 4.2.2 | 2.2.2 | 7.1.4 |
| O95 | 6.3.6 | | |
| O96 | 6.2.1 | | |
| O97 | 1.2.1 | 7.2.5 | 4.1.2 |
| O98 | 4.1.1 | | |
| O99 | 4.2.1 | | |
| O100 | 2.1.3 | | |
| O101 | 3.1.3 | 7.3.2 | 1.1.5 |
| O102 | 6.3.3 | 7.1.2 | |
| O103 | 5.2.4 | | |
| O104 | 1.4.2 | | |
| O105 | 6.3.5 | 5.2.2 | 2.2.1 |
| O106 | 1.3.1 | 1.4.4 | |
| O107 | 5.2.3 | | |
| O108 | 1.1.2 | 2.1.2 | 1.2.1 |
| O109 | 1.1.3 | | |
| O110 | 1.1.2 | | |
| O111 | 3.1.3 | 7.2.5 | 7.1.3 |
| O112 | 1.1.1 | 1.4.1 | |
| O113 | 7.1.7 | 5.3.1 | |
| O114 | 7.1.6 | | |
| O115 | 1.4.4 | | |
| O116 | 3.1.1 | | |
| O117 | 6.1.3 | | |
| O118 | 7.1.7 | | |
| O119 | 7.1.6 | 6.3.6 | 7.1.7 |
| O120 | 1.1.5 | | |
| O121 | 2.1.5 | | |
| O122 | 6.2.2 | 4.2.1 | |
| O123 | 3.1.1 | | |
| O124 | 7.1.3 | | |
| O125 | 6.3.4 | 4.2.3 | |
| O126 | 4.2.1 | 1.4.3 | |
| O127 | 6.2.1 | | |
| O128 | 2.2.3 | | |
| O129 | 5.3.1 | | |
| O130 | 1.4.2 | 4.2.2 | 3.1.3 |
| O131 | 1.1.1 | 1.2.3 | |
| O132 | 4.2.1 | | |
| O133 | 6.1.3 | | |
| O134 | 4.1.3 | | |
| O135 | 2.2.5 | 7.3.3 | |

**Table A4 (cont.): List of Synthetic Objectives and the Descriptors They Develop**

| Lesson Objective | Descriptor 1 | Descriptor 2 | Descriptor 3 |
|---|---|---|---|
| O136 | 2.1.4 | | |
| O137 | 2.2.5 | 5.2.3 | |
| O138 | 6.3.2 | 7.2.4 | |
| O139 | 1.3.1 | 1.3.2 | 6.3.6 |
| O140 | 7.1.7 | 2.2.5 | |
| O141 | 7.1.1 | 6.2.1 | |
| O142 | 7.2.5 | 5.1.1 | |
| O143 | 7.1.2 | 4.1.1 | |
| O144 | 1.4.1 | 3.3.3 | |
| O145 | 6.3.3 | 5.3.1 | |
| O146 | 6.3.4 | | |
| O147 | 6.1.1 | 6.2.1 | 1.3.3 |
| O148 | 7.1.4 | 7.2.2 | 7.1.6 |
| O149 | 1.4.1 | 2.2.5 | |
| O150 | 5.1.1 | 7.1.3 | |

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**14. ABSTRACT**
The United States Air Force needs to ensure its Airmen are receiving the best possible education so that they can perform their jobs as effectively as possible. One way to improve the evaluation and development of its Airmen is to incorporate the use of competencies to develop standards for performance and use competency-based education principles to improve the quality of education delivered to the Airmen. One of the educational centers of the United States Air Force is The Civil Engineer School. However, The Civil Engineer School needs a way to evaluate its current coursework on how well it develops competencies in Airmen and a way to create curriculums for future educational programs that focus on development of a particular competency profile.

This research accomplishes both of those tasks by using the building block of competency models, descriptors. By deriving from the principles of competencies and competency-based education evaluation criteria, a methodology for determining competency development from a course is created by relating the coursework to the competency model's descriptors. Once the descriptors have been related to coursework, an optimization tool can be used to develop curriculums based on a given competency The Civil Engineer School desires to develop. This research provides one such tool, using Microsoft Excel to determine the curriculum that meets the desired competency development in the shortest time using existing coursework or to build a new course that accomplishes the desired competency development in the shortest time using existing coursework.

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