



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**OPTIMALLY SCHEDULING BASIC COURSES AT THE
DEFENSE LANGUAGE INSTITUTE USING INTEGER
PROGRAMMING**

by

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September 2005

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**OPTIMALLY SCHEDULING BASIC COURSES AT THE DEFENSE
LANGUAGE INSTITUTE USING INTEGER PROGRAMMING**

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ABSTRACT

The Defense Language Institute (DLI) offers 23 beginning language courses and in 2004 began to provide a smaller class size for these courses. Restrictions on when classes can begin and a limited number of instructors prevent all students from being trained in a smaller class. This thesis develops integer linear programs (ILPs) that generate schedules for all student classes and maximize the number of smaller class starts for a given number of instructors. Secondary scheduling goals include avoiding weekly changes to instructor levels and scheduling preferences such as the number of classes to start simultaneously. The ILPs solve in less than one minute and offer a significant improvement in the number of students that may be trained in the smaller class size. Computational results using real data for the Arabic, Chinese-Mandarin, and Persian-Farsi courses verify the ILPs find feasible multiyear schedules that incorporate the DLI's scheduling preferences while exceeding the DLI's published schedule results. For example, the ILPs find schedules for Arabic that train 8%, 34% and 76% of students in the smaller class in 2006, 2007, and 2008, whereas DLI's manual schedules at best can train 8%, 7% and 64%.

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THESIS DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

The Defense Language Institute Foreign Language Center (DLIFLC or DLI) trains military personnel to become foreign language specialist in 23 languages and dialects. Most language training occurs in three levels: basic, intermediate, and advanced. A DLI course lasts from 2 to 63 weeks depending on the language and level of training. Students train in course sections; the typical section consists of ten students and two instructors. A new program instituted in 2004 has two instructors train no more than six students in a basic course section. The DLI terms such a section a *pep section*. The DLI seeks to increase the number pep sections offered in all basic courses.

This thesis develops integer linear programs (ILPs) that generate multiyear schedules for all basic courses. The ILPs developed, henceforth referred to as Optimal Course Scheduling (OCS), maximize the number of pep sections scheduled. Secondary objectives improve the quality of the schedules generated.

We evaluate OCS using real data for the Arabic, Chinese-Mandarin, and Persian-Farsi courses for fiscal years 2006 through 2008 and compare the results to the DLI's published schedules for these courses. For Arabic, we match the percentage of students trained in pep sections for 2006 with 8 percent and increase the percentage of students trained in pep sections for 2007 and 2008 from 7 percent to 34 percent, and 64 percent to 73 percent, respectively. Chinese-Mandarin and Persian-Farsi have similar results. OCS multiyear scheduling significantly increases the percentage of students that may be trained in pep sections offering a considerable advantage over the current single-year schedules produced manually by the DLI.

OCS multiyear scheduling increases the percentage of students trained in pep sections by starting more sections earlier in the schedule. This reduces the number of sections that are carried over into the following year. This not only allows more pep sections to be scheduled, it also reduces the number of instructors required in future years. Manual scheduling perpetuates the inefficiencies produced by excess carryover sections.

OCS solves on a personal computer in less than one minute allowing us to quickly answer scheduling questions. One question we assisted the DLI answer is, “What is the minimum number of instructors required to train at least 25 percent of the 2006 students in pep sections?” For Arabic 265 instructors are required. Chinese-Mandarin requires 124 instructors, and Persian-Farsi requires 60 instructors.

The DLI is currently planning to implement OCS. OCS will help the DLI significantly reduce the time to generate schedules and provide more insight into the long-term effects of policy and scheduling changes.

I. INTRODUCTION

The Defense Language Institute Foreign Language Center (DLIFLC or DLI) trains military personnel to become foreign language specialist in 23 languages and dialects. Most language training occurs in three levels: basic, intermediate, and advanced within a course that lasts from 2 to 63 weeks. Students train in course sections; the typical section consists of ten students and two instructors. A new program instituted in 2004 has two instructors train no more than six students in a basic course section. The DLI terms such a section a *pep section* and seeks to increase the number pep sections offered in all basic courses. This thesis develops integer linear programs (ILPs) that generate schedules for all basic courses. The main objective of the ILPs, henceforth referred to as Optimal Course Scheduling (OCS), is to maximize the number of pep sections scheduled. Secondary objectives seek to improve the quality of the schedules generated.

A. DEFENSE LANGUAGE INSTITUTE

The DLI has served as the premier foreign language institution for the U.S. military for over 60 years. Instruction focuses on the individual learner and his or her proficiency. In addition to the basic, intermediate, and advanced levels of instruction, there are special programs that emphasize training needed for specific assignments. The DLI also provides refresher and sustaining courses. All qualified graduates in the basic levels of training receive an Associate of Arts degree. [DLI 2005]

The DLI employs approximately 900 civilian instructors and nearly 100 military instructors. Most civilian instructors are first-language speakers of the languages they teach. All four military branches have representation on the staff at the DLI. [DLI 2005]

The DLI accommodates up to 3,500 students. All instruction takes place in one of nine schools. A civilian chair coordinates instruction for each language. The schools are under the direction of a civilian Dean responsible for curriculum implementation and administration. An Associate Dean is a senior military officer who provides administrative support and monitors student progress. The DLI Scheduling Department schedules all courses taught. [DLI 2005]

B. SCHEDULING AT THE DLI

Kunzman [1993] describes manual scheduling and scheduler responsibilities at the DLI. Manual scheduling is still employed. The Army Training Requirements Resource System (ATRRS) provides the projected student requirements for each course. The scheduler uses a Microsoft Excel spreadsheet and a customized software program to create master schedules, but the starting dates for each course are chosen at the discretion of the scheduler. The scheduler's goal is to schedule enough sections to meet all student requirements while minimizing the number of instructors not teaching.

1. DLI Course Scheduling Terminology

There are four *categories* of course lengths (I, II, III, and IV). Each course belongs to only one language category. Categories I, II, III, and IV are lengths 25, 34, 47, and 63 weeks, respectively. Beginning in fiscal year 2007 each category will increase by one week.

A *student requirement* refers to the number of students programmed to be trained in a given course during a fiscal year. The DLI hires and releases instructors on a yearly basis to teach specific language courses. Two instructors teach a section of a course. Typically, instructors work in teams of six covering a cohort of three to six sections and train the same cohort until completion. A *pep* section refers to sections with a maximum student-to-instructor ratio of 6:2, while a *non-pep* section refers to sections with a maximum student-to-instructor ratio of 10:2. The DLI screens students by aptitude testing and assigns them to sections based upon their score.

There are four important dates that must be scheduled: 1) the *report date* for students, 2) the *start date* to begin instruction, 3) the *close date* is the last official day for training, 4) and the *graduation date*. A *course schedule* designates how many sections start training (start date) during each week of a fiscal year. Given the start date, the report date, close date, and graduation date are known.

2. Course Schedule Requirements

Each course schedule must:

- meet all student requirements each fiscal year,

- not exceed the total available instructors for any given week of the fiscal year,
- start only all pep sections or all non-pep sections during a given week of the fiscal year,
- meet length of training requirements as determined by language category (an additional day of training is scheduled for each day missed due to a holiday),
- limit the number of simultaneous section starts to six per week with a preference of three,
- assign each instructor to only one section, with each section requiring two instructors,
- have no closing dates or graduation dates scheduled in January, and
- have no start dates on holidays or after Thanksgiving until January.

C. POTENTIAL SCHEDULE LIMITATIONS

The DLI develops a single year's schedule manually. This can require substantial time and there is no guarantee that the schedule will have the maximum number of pep sections. In addition, a single-year schedule may suffer from year-end effects by ignoring future requirements. OCS can help overcome these potential limitations.

Instructor limitations prevent every section from being pep sections; some non-pep sections are necessary to meet training requirements. Many pep and non-pep start date combinations may exist and finding an optimal arrangement by inspection can be difficult and time consuming.

Single-year schedules limit long-term planning and encourage year-end effects. By not considering future requirements, the number of pep sections in future years may be unnecessarily limited. Estimates of student and instructor levels for future years are available.

OCS automates the production of multiyear schedules that maximize the number of pep sections scheduled. This automation produces schedules quicker than developing

them manually. Automated scheduling needs to be easily implemented and understood by the scheduler to be effective. D. de Werra [1985] emphasizes that

It is essential that the codes be made easy to use, that the method be almost transparent to the user; feeling and understanding how the procedure works may help the scheduler to reach a good solution in a reasonable number of runs. To increase the chances of survival of such a program, the user should have a direct access to it; he should definitely not have to go to a computing center outside the school.

D. OBJECTIVES

The goal of this thesis is to create personal computer (PC) solvable ILPs which maximize the number of pep sections scheduled in a multiyear schedule. Secondary goals include avoiding weekly changes to instructor levels within and between fiscal years, maximizing the number of times at least three sections start simultaneously, and reducing year-end effects.

The models need to be persistent. Model persistence seeks to minimize unnecessary changes to a previous solution as adjustments are made [Brown, Dell, and Wood 1997]. For the OCS models, persistence minimizes the unnecessary rescheduling of later section start dates when a schedule change is made.

E. THESIS OUTLINE

Chapter II surveys research related to the development of course schedules. Chapter III presents and discusses the OCS models developed for the DLI. Chapter IV reviews schedules produced using fiscal year 2006 through fiscal year 2008 data. Chapter V provides conclusions.

II. SCHEDULING RESEARCH

The Operations Research literature classifies a course schedule as a type of timetable. Timetabling is the process of generating timetables. Drexl and Salewski [1997] note that “in the literature, usually no clear distinction is made between timetabling and course scheduling.”

Scheduling studies published in the literature are numerous. Ernst, Jiang, Krishnamoorthy, and Sier [2004] review applications for staff scheduling including transportation systems, call centers, health care systems, emergency systems, utilities, retail businesses, and manufacturing. Blochliger [2004] provides a tutorial for staff scheduling models. We limit our review to educational timetabling.

The typical educational timetabling activities are scheduling examinations, scheduling course offerings, and scheduling class-teacher assignments. D. de Werra [1985] presents an introduction to these timetabling activities. Kunzman [1993] surveys some early timetabling research in these areas and briefly discusses the computational complexity of timetable models. Carrasco and Pato [2004] provide a good summary of current research.

Scheduling exams and course scheduling have similar objectives. They both seek to produce timetables that schedule opportunities for all exams or courses to be taken with a minimum number of conflicts while incorporating student and instructor preferences. Models of these timetables become more complex as the number of exams, courses, facilities, and other requirements grow.

Class-teacher scheduling seeks to match students in a given curriculum with instructors to complete a series of lectures that meet all training requirements. Models of class-teacher timetables grow in complexity as the number of instructor-course combinations increase and as more training requirements are imposed.

The DLI produces class-teacher timetables. Fortunately, the course offerings at the DLI have separate faculty for each language course, students take only one course at a time, and sufficient facilities exist to omit classrooms as a constraint.

D. de Werra [1985] explains educational timetabling in two steps. The first step defines curricula and provides resources such as classrooms and instructors. The second step allocates these resources in a timetable. The timetable must meet the curricular training requirements and incorporate resource allocation preferences.

Carrasco and Plato [2004] observe that “in practice, the timetabling task is often performed manually, through a slow trial-and-error procedure.” This iterative approach typically involves the use of a computer program implementing a timetabling model to find an initial feasible solution that satisfies all training requirements and resource constraints. The scheduler then manually adjusts the timetable to better reflect the preferred allocation of resources and sets the preferences as hard constraints. The process is repeated until an acceptable timetable is generated. Daskalki, Birbas, and Housos [2004] add that most institutions attempt to “replicate the timetables of previous years with minor changes to accommodate newly developed situations.”

A goal for timetable modelers is to find general mathematical models capable of generating educational timetables. However, most models are designed specifically to fit the needs of institutions because most educational programs are unique [Daskalaki, et al., 2004]. These specific models become increasingly complex as the number of resource constraints grow. Drexel and Salewski [1997] present a thorough treatise on the effects of constraints on educational timetable models.

The complexity of timetable models can prevent some instances from being solved optimally in a practical amount of time. Daskalaki, et al. [2004] clarify that the timetabling problem is NP-complete in most forms.

The uniqueness of educational timetables and the difficulty in implementing efficient timetable models has led to numerous modeling approaches. Asratian and de Werra [2002] present a generalized class-teacher model that uses a bipartite graph to assign instructors to classes requiring group lectures. Others incorporate heuristic search techniques such as tabu search [de Werra 1997] and iterative search techniques [Meisels and Kaplansky 2004]. Carrasco and Pato [2004] generate and compare a neural network and a simulation annealing algorithm.

Daskalaki, et al. [2004] report that advances in ILP solvers and increases in computer speed now allow solutions to many large ILP timetable models using branch and bound and other similar techniques. Daskalaki, et al. [2004] provide an example of an ILP that produces a course timetable for a large five-year Engineering Department with many course offerings and a large faculty. Their ILP includes both hard and soft constraints. The hard constraints ensure feasible timetables. Soft constraints, expressed as a linear cost function, help find the most preferable timetable. Solutions to his ILP are feasible timetables that allocate resources preferably at or near optimality in a single step. The OCS models use both hard and soft constraints in a similar fashion.

Kunzman [1993] developed and solved ILPs to prescribe a schedule for each course taught at the DLI using commercially available optimization software. He solved the ILPs on the Naval Postgraduate School's (NPS) AMDAHL 5990-700A mainframe. Kunzman's main objective was to minimize the number of instructors required. Secondary objectives included avoiding weekly changes to instructor levels by language over a three year period, maximizing the number of times three sections start simultaneously, and minimizing instructor down time. The overarching metric was dollar savings based upon minimizing the number of instructor-years.

Except for the initial implementation reported by Kunzman, the DLI did not use the ILPs described in his thesis. As soon as the DLI made some scheduling changes, they returned to manual scheduling. This thesis addresses needed modeling changes and develops PC solvable ILPs (OCS) that allow scheduling changes to be more easily made by the user.

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III. OCS FORMULATIONS

OCS consists of three ILPs. The first two ILPs (OCS_1 and OCS_2) generate a schedule by sequential execution. The third ILP (OCS_3) incorporates persistence for use in generating a revised schedule. OCS_1 determines the maximum number of pep sections that can be scheduled. OCS_1 allows discounting by week to encourage more pep sections to occur during the first year. OCS_2 determines an optimized schedule that minimizes the change in instructor level between weeks while maintaining the number of pep sections found in OCS_1 . The net result is an optimized schedule that indicates the type (pep or non-pep) and number of sections to begin training during each week of typically a three-year schedule.

A. OCS_1

OCS_1 produces a schedule with the maximum number of discounted pep sections. The constraints ensure the schedule meets the student requirement, stays within the available inventory of instructors, and starts only pep or non-pep sections during any week. The number of pep sections is subsequently constrained in OCS_2 . OCS_1 is also capable of determining the minimum number of instructors required to achieve a desired percentage of pep sections scheduled.

INDICES:

- w, w' weeks
- y fiscal year
- s number of simultaneous section starts

SETS:

- W_y set of weeks in fiscal year y
- AW set of allowed section start weeks
- IN_w set of section start weeks that are still in session during week w

PARAMETERS:

- c_s number of section starts s
- $prev_w$ number of sections in progress during week w (from prior decisions)
- $inst_w$ total number of instructors available for week w
- req_y student requirement for fiscal year y
- pep number of students per pep section
- $npep$ number of students per non-pep section
- dis_w discount coefficient for week w

DECISION VARIABLES (all binary):

- P_{sw} 1 if s pep sections start at the beginning of week w and zero otherwise
- N_{sw} 1 if s non-pep sections start at the beginning of week w and zero otherwise
- PB_w 1 if any pep sections start at the beginning of week w and zero otherwise
- NB_w 1 if any non-pep sections start at the beginning of week w and zero otherwise

CONSTRAINTS AND OBJECTIVE FUNCTION:

$$\text{maximize } \sum_s \sum_{w \in AW} dis_w c_s P_{sw}$$

subject to:

$$(1) \quad \sum_s \sum_{w \in AW \cap W_y} pep_w c_s P_{sw} + \sum_s \sum_{w \in AW \cap W_y} npep_w c_s N_{sw} \geq req_y, \forall y$$

$$(2) \quad 2 \left(prev_w + \sum_s \sum_{w' \in IN_w} c_s P_{sw'} + \sum_s \sum_{w' \in IN_w} c_s N_{sw'} \right) \leq inst_w, \forall w$$

$$(3) \quad \sum_s P_{sw} \leq PB_w, \forall w \in AW$$

$$(4) \quad \sum_s N_{sw} \leq NB_w, \forall w \in AW$$

$$(5) \quad PB_w + NB_w \leq 1, \forall w \in AW$$

$$P_{sw}, N_{sw} \text{ binary}, \forall s, w$$

$$PB_w, NB_w \text{ binary}, \forall w$$

CONSTRAINT EXPLANATION:

Constraint set (1) ensures the schedule meets the student requirement for each fiscal year. Constraint set (2) prevents exceeding the number of instructors available each week. Constraint sets (3) to (5) ensure that sections starting in a given week are either all pep or all non-pep.

The objective function expresses the discounted number of pep sections starts. It may be advantageous to schedule pep sections earlier in the schedule even if doing so results in slightly fewer pep sections than is possible using undiscounted pep sections.

The $inst_w$ values are typically the same within each fiscal year. The minimum number of instructors required for fiscal y is determined by lowering the number of instructors available until requirements can no longer be satisfied. The minimum number of instructors needed to achieve a certain percentage of pep sections scheduled is found similarly.

B. OCS₂

OCS₂ includes the same constraints as OCS₁ along with others to avoid weekly changes to instructor levels and maintain the number of pep sections found in OCS₁. The objective function uses a piece-wise linear cost function to minimize the deviations in instructor levels from week to week. The OCS₂ formulation maintains the same notation as OCS₁. Only new notation is shown below along with the complete formulation.

NEW INDICES:

l level

NEW PARAMETERS:

$pscd_y$ the number of pep sections to schedule during fiscal year y (found in OCS₁)

d_l cost incurred per assigned instructor decrease from week w to $w-1$ within level l

u_l cost incurred per assigned instructor increase from week w to $w-1$ within level l

$pmax_l$ the maximum increase in assigned instructors from week w to $w-1$ within level l

$nmax_l$ the maximum decrease in assigned instructors from week w to $w-1$ within level l

NEW DECISION VARIABLES:

Nonnegative Variables (implicitly integer):

I_w the number of assigned instructors during week w

PD_{wl} the increase in assigned instructors during week w within level l

ND_{wl} the decrease in assigned instructors during week w within level l

CONSTRAINTS AND OBJECTIVE FUNCTION:

Minimize $\sum_l \sum_w dis_w (d_l ND_{wl} + u_l PD_{wl})$

subject to:

$$(1) \quad \sum_s \sum_{w \in AW \cap W_y} pep_w c_s P_{sw} + \sum_s \sum_{w \in AW \cap W_y} npep_w c_s N_{sw} \geq req_y, \forall y$$

$$(2) \quad 2 \left(prev_w + \sum_s \sum_{w' \in IN_w} c_s P_{sw'} + \sum_s \sum_{w' \in IN_w} c_s N_{sw'} \right) \leq inst_w, \forall w$$

$$(3) \quad \sum_s P_{sw} \leq PB_w, \forall w \in AW$$

$$(4) \quad \sum_s N_{sw} \leq NB_w, \forall w \in AW$$

$$(5) \quad PB_w + NB_w \leq 1, \forall w \in AW$$

$$(6) \quad 2 \left(prev_w + \sum_s \sum_{w' \in IN_w} c_s P_{sw'} + \sum_s \sum_{w' \in IN_w} c_s N_{sw'} \right) = I_w, \forall w$$

$$(7) \quad \sum_l (PD_{wl} - ND_{wl}) = I_w - I_{w-1}, \forall w$$

$$(8) \quad \sum_s \sum_{w \in AW \cap W_y} c_s P_{sw} = pscd_y, \forall y$$

$$(9) \quad PD_{wl} \leq pmax_l, \forall w \in AW, l$$

$$(10) \quad ND_{wl} \leq nmax_l, \forall w \in AW, l$$

$$P_{sw}, N_{sw} \text{ binary}, \forall s, w$$

$$PB_w, NB_w \text{ binary}, \forall w$$

$$I_w \geq 0, \forall w$$

$$PD_{wl}, ND_{wl} \geq 0, \forall w, l$$

CONSTRAINT EXPLANATION:

Constraint sets (1) to (5) are the same as OCS_1 . Constraint set (6) determines the total number of instructors assigned for week w . Constraint set (7) determines the change in the number of instructors from week to week. Constraint set (8) ensures the number of pep sections scheduled each year equals the number determined by OCS_1 . Constraint sets (9) and (10) limit the PD_{wl} and ND_{wl} variables.

The objective function coefficients express a preference for changing the number of sections from week to week. Each coefficient has implicit units of instructor/instructor. For example, a d_l value of ten and u_l value of one implies a preference of increasing the instructor level by less than ten over decreasing the instructor level by one. The use of upper bounds at different levels, l , allows increasing penalty per unit change. For example, if $pmax_1 = 6$, $pmax_2 = 2$ and $u_1 < u_2$, there is an extra penalty per instructor added above six.

C. OCS_3

OCS_3 seeks to find a feasible and persistent revised schedule after making a change to a previously published schedule. We expect a typical change to be in the form of some new section starts that were not planned on previously. The objective function minimizes the differences between the new schedule and the published schedule in terms of sections scheduled per week, total pep sections scheduled, and avoiding weekly changes to instructor levels. We assume the published schedule is fixed until a given week, there are a set of new section starts not previously planned, and a remaining set of weeks (after the fixed weeks) where OCS_3 finds a schedule. The OCS_3 formulation

maintains the same notation as OCS_1 and OCS_2 . Only new notation is shown below along with the complete formulation.

NEW SETS:

- MW set of new section start weeks (not previously planned)
- SW set of section start weeks fixed from the published schedule
- TW set of weeks that OCS_3 will schedule

NEW PARAMETERS:

- $cdev$ cost of making a change to the published schedule's section starts
- $pdev$ cost of making a change to the published schedule's number of pep starts
- $fixp_w$ the number of fixed pep section starts in week w
- $fixn_w$ the number of fixed non-pep section starts in week w
- $pskd_w$ the number of pep sections starts in week w from the published schedule
- $nskd_w$ the number of non-pep sections starts in week w from the published schedule

NEW DECISION VARIABLES:

Nonnegative Variables (implicitly integer):

- UP_w the increase in the number of starts from the previous schedule for week w
- DWN_w the decrease in the number of starts from the previous schedule for week w
- $PCHG$ the change in the number of total pep sections from the previous schedule

CONSTRAINTS AND OBJECTIVE FUNCTION:

$$\text{minimize } \sum_l \sum_w (d_l ND_{wl} + u_l PD_{wl}) + cdev \left(\sum_w (UP_w + DWN_w) \right) + pdev PCHG$$

subject to:

(1)

$$\sum_s \sum_{w \in TW \cap W_y} (c_s \text{ pep } P_{sw} + c_s \text{ npep } N_{sw}) + \sum_{w \in SW \cap W_y} (\text{ pep } pskd_w + \text{ npep } nskd_w) \geq req_y, \forall y$$

(2)

$$2 \left(prev_w + \sum_s \sum_{w' \in IN_w \cap TW} c_s (P_{sw'} + N_{sw'}) + \sum_{w' \in IN_w \cap SW} (pskd_{w'} + nskd_{w'}) \right) \leq inst_w, \forall w$$

$$(3) \quad \sum_s P_{sw} \leq PB_w, \forall w \in AW$$

$$(4) \quad \sum_s N_{sw} \leq NB_w, \forall w \in AW$$

$$(5) \quad PB_w + NB_w \leq 1, \forall w \in AW$$

$$(6) \quad 2 \left(prev_w + \sum_s \sum_{w' \in IN_w \cap TW} c_s (P_{sw'} + N_{sw'}) + \sum_{w' \in IN_w \cap SW} (pskd_{w'} + nskd_{w'}) \right) = I_w, \forall w$$

$$(7) \quad \sum_l (PD_{wl} - ND_{wl}) = I_w - I_{w-1}, \forall w$$

$$(8) \quad \sum_s \sum_{w \in TW} (c_s P_{sw}) + PCHG \geq \sum_{w \in TW} pskd_w$$

$$(9) \quad \sum_s (c_s P_{sw}) = fixp_w, \forall w \in MW$$

$$(10) \quad \sum_s (c_s N_{sw}) = fixn_w, \forall w \in MW$$

$$(11) \quad pskd_w + nskd_w - \sum_s c_s P_{sw} - \sum_s c_s N_{sw} = UP_w, \forall w \in TW$$

$$(12) \quad \sum_s c_s P_{sw} + \sum_s c_s N_{sw} - pskd_w - nskd_w = DWN_w, \forall w \in TW$$

$$P_{sw}, N_{sw} \text{ binary}, \forall s, w$$

$$PB_w, NB_w \text{ binary}, \forall w$$

$$I_w, UP_w, DWN_w \geq 0, \forall w$$

$$PD_{wl}, ND_{wl} \geq 0, \forall w, l$$

$$PCHG \geq 0$$

CONSTRAINT EXPLANATION:

Constraint sets (1) to (7) are the same as in OCS₂ except where fixed decisions cause differences. Constraint (8) determines the change in pep section starts for the new

schedule. Constraint sets (9) to (10) sets the manually scheduled sections as hard constraints. Constraint sets (11) and (12) determine the increases and decreases in the number of sections from a previous schedule for week w .

The objective function expresses the change from the published schedule. The $cdev$ objective coefficient has units of section/section and specifies the cost of gaining a section or losing a section in the new schedule. The $pdev$ coefficient has the same units as $cdev$ and specifies the preference of losing a pep section in the new schedule. The other coefficients have the same interpretation as in OCS_2 .

IV. COMPUTATIONAL RESULTS

Using data provided by the DLI, this chapter evaluates OCS schedules generated for three representative basic courses and compares them to the schedules produced manually by the DLI for fiscal year 2006. The basic courses evaluated are Arabic, Chinese-Mandarin, and Persian-Farsi (test courses). Arabic is a category IV language and has the largest student requirement and available instructor inventory of all basic courses. Chinese-Mandarin is a category IV language; Persian-Farsi is a category III language and has the largest student requirement and available instructor inventory of any category III language.

The DLI provided their fiscal year 2006 schedules as of July 26, 2005, for the test courses. These schedules along with estimates of student requirements and available instructors for fiscal years 2007 and 2008 provide the data used to generate the OCS schedules for the test courses. Hereafter, the term *OCS schedule* refers to one of the schedules generated for the test courses using OCS, and a *manual schedule* refers to one of the DLI's fiscal year 2006 schedules for the test courses.

This chapter presents OCS schedules for each test course using the July 2005 data. The schedules seek to answer the following questions:

- Does OCS produce face-valid schedules?
- What are the solve times for OCS?
- Does OCS aid in scheduling more pep section starts?
- Does OCS aid in avoiding weekly changes to instructor levels?
- Do multiyear schedules aid in reducing year-end effects and scheduling more pep starts in future years?
- What instructor level allows 25 percent of the student requirement to be trained in pep sections during fiscal year 2006?
- Does OCS₃ produced favorable schedules with respect to pep section starts?

A. DESCRIPTION OF DATA

Table 1 displays the course lengths for each basic course. Table 2 displays the student requirement (req_y) for fiscal year 2006, the programmed student requirement for fiscal year 2007, and the projected student requirement for fiscal year 2008 for the test courses. The 2006 requirements are fully funded and used by the DLI to produce its fiscal year 2006 schedules. Programmed totals seek funding in the next budget cycle; projected totals are for planning purposes only. The DLI's fiscal year 2006 schedules provided the 2006 values; the DLI provided an ATRRS report dated April 6, 2005, for the programmed and projected 2007 and 2008 values.

Table 2 also displays the estimates for the number of available instructors ($inst_w$) for the test courses. The DLI's fiscal year 2006 schedules supply the 2006 values. The DLI provided estimates for the number of available instructors for fiscal year 2007 and 2008.

The DLI's fiscal year 2005 schedules provide the number of carryover sections from prior years ($prev_w$) for each week of 2006. Finding the set of valid start weeks (AW) is done by counting days of training to ensure the close and graduation dates fall on allowed days; a computer program written by the author in Java performs these calculations. Table 3 displays the $prev_w$ values for the test courses. The Java program also counts the number of training weeks required for each section start. These values are typically higher than the course lengths in Table 1 due to the additional days added for holidays. This thesis uses close dates instead of graduation dates to calculate both the course lengths and the end of an instruction period for an instructor assigned to a section. OCS schedules presented here allow instructors to be assigned to a new section after a close date.

This thesis uses an annual discount rate of 3.7 percent which corresponds to a weekly discount rate (dis_w) of 0.07 percent. This is the rate published by the United States Office of Management and Budget (OMB) for performing a three year cost-benefit study [OMB 2005].

This thesis permits three, four, five, and six sections to be scheduled per week (c_s) for the test courses. Instruction of Arabic takes place in three different buildings with each building having an assigned number of instructors. Chinese-Mandarin instruction

takes place in two buildings. The DLI schedules courses in these languages separately by building. The DLI also currently allows the scheduling of two through nine pep section starts per week. Scheduling courses by school allows more sections to start per week and scheduling two through nine pep sections may permit more pep sections; however, at the request of the DLI scheduler, OCS treats the instructors as belonging to a single school and only allows three through six sections to begin any week. This provides a more even distribution of students being trained throughout the year and adds more flexibility for the scheduler to schedule additional starts as needed.

This thesis uses four levels l for OCS₂. We use d_l values of 1.0 for all levels and u_l values of 0.08, 0.10, and 0.13, and 0.17 for levels 1, 2, 3, and 4, respectively. The u_l values selected are the reciprocals of 12, 10, 8, and 6 which correspond to the number of instructors required to teach 6, 5, 4, and 3 sections, respectively. These values along with $pdmax_l$ values of 3, 3, and 3, for levels 1, 2, and 3, respectively, express a preference for increasing the available instructors at a rate of six per week. This reinforces the desire to schedule three-section starts. The value of $pdmax_4$ is unbounded to allow OCS to generate a feasible schedule for any increase.

There is no desire to decrease the instructor levels since the goal is to schedule more pep section starts. Therefore, there is no preference to how the instructor levels decrease per week: $nmax_l$ is unbounded for all levels. The d_l values of 1.0 for all levels ensure the decrease in instructor level is minimized for any week.

TABLE 1. BASIC COURSES

The DLI basic courses and their course length in weeks.

Language	Category	2006 Course Length	2007-2008 Course Length
Italian	I	25	26
French	I	26	26
Spanish	I	26	26
Portuguese	I	25	26
German	II	34	35
Hebrew	III	47	48
Kurdish	III	47	48
Pashtu	III	47	48
Persian-Afghan	III	47	48
Persian-Farsi	III	47	48
Russian	III	48	48
Tagalog	III	47	48
Thai	III	47	48
Turkish	III	47	48
Uzbek	III	47	48
Arabic	IV	63	64
Chinese-Mandarin	IV	63	64
Japanese	IV	63	64
Korean	IV	63	64

TABLE 2. STUDENT REQUIREMENTS AND INSTRUCTORS

The student requirement (req_y) and the available instructors ($inst_w$) for fiscal year 2006, the programmed student requirement and instructors for fiscal year 2007, and the projected student requirement and instructors for fiscal year 2008.

Language	2006		2007		2008	
	req_y	$inst_w$	req_y	$inst_w$	req_y	$inst_w$
Arabic	872	246	829	268	828	290
Chinese-Mandarin	404	114	377	114	345	112
Persian-Farsi	264	68	210	70	218	70

TABLE 3. CARRYOVER SECTIONS

The number of carryover sections in session during week w for the test courses. For example, there are 91 sections of basic Arabic in session during weeks 7-11.

Week w	Arabic $prev_w$	Week w	Chinese-Mandarin $prev_w$	Week w	Persian-Farsi $prev_w$
1-5	100	1-11	43	1-2	30
6	94	12-25	38	3-6	24
7-11	91	26-30	31	7-11	18
12-19	86	31-35	25	12-21	15
20-23	83	36-40	17	22-26	14
24-25	77	41-49	14	27-37	8
26-29	73	50-55	13	38-49	5
30-35	69	56-70	4	50-156	0
36	63	71-156	0		
37	60				
38-40	55				
41	52				
42-43	46				
44-49	37				
50-52	26				
53-57	18				
58	12				
59-63	4				
64-153	0				

B. COMPUTATIONAL PERFORMANCE

This thesis solves OCS using GAMS IDE (rev 138) [GAMS 2005] and CPLEX solver (version 9.0) [CPLEX 2005] on a Dell Precision 340 PC with 1 GB of RAM and an Intel Pentium 4 processor. OCS generates face-valid schedules typically in under one minute when accepting the first solution guaranteed to be within one percent of optimal. The Arabic course takes the most time to solve. OCS₁ for Arabic has about 1,000 integer variables, 500 constraints, and 50,000 nonzero entries in the constraint matrix. OCS₂ for Arabic has about 2,000 variables (1,000 integer), 700 constraints, and 90,000 nonzero entries in the constraint matrix. OCS₃ for Arabic has about 2,700 variables (1,500 integer), 1,100 constraints, and 100,000 nonzero entries in the constraint matrix.

C. OCS SCHEDULES

Table 4 displays the pep section starts summary for fiscal years 2006 through 2008 for OCS schedules with the manual schedules' results for comparison. For 2006, the OCS schedules start the same percentage of pep section starts for Arabic and Chinese-Mandarin and a larger percentage of pep section starts for Persian-Farsi.

Table 5 reports OCS section starts and manual section starts for 2006. The OCS schedules adhere to the DLI's preferences for scheduling section starts, but the manual schedules do not always adhere to these preferences. Arabic's manual schedule has 14 and 15 sections scheduled for weeks 42 and 45, respectively. Likewise, Chinese-Mandarin's manual schedule starts seven and nine sections in weeks 27 and 32, respectively. This schedule also starts three non-pep sections and three pep sections during week 41 at different schools. Persian-Farsi's manual schedule starts nine pep sections during week seven.

TABLE 4. PEP SECTION SUMMARY

The percentage of students scheduled by OCS to be trained in pep sections for fiscal years 2006 through 2008 along with the DLI's manual schedules' percentages for fiscal year 2006. OCS schedules at least as many pep section starts as the manual schedules for each test course.

Fiscal Year	Arabic <i>Manual % Pep</i>	Arabic <i>OCS % Pep</i>	Chinese- Mandarin <i>Manual % Pep</i>	Chinese- Mandarin <i>OCS % Pep</i>	Persian- Farsi <i>Manual % Pep</i>	Persian- Farsi <i>OCS % Pep</i>
2006	8 %	8 %	13 %	13 %	43 %	88 %
2007	--	34 %	--	37 %	--	100 %
2008	--	76 %	--	28 %	--	86 %

TABLE 5. OCS SCHEDULING SUMMARY

The OCS starts per week for fiscal year 2006. The values indicate the number of sections scheduled to start week w with pep sections indicated by a P and non-pep sections indicated by an N . For example, Arabic's OCS schedule starts six pep sections (6P) at the start of week one. OCS finds feasible schedules that incorporate the DLI's scheduling preference for each test course.

Week	Arabic	Arabic	Week	Chinese-Mandarin	Chinese-Mandarin	Week	Persian-Farsi	Persian-Farsi
w	<i>Manual starts</i>	<i>OCS starts</i>	w	<i>Manual starts</i>	<i>OCS starts</i>	w	<i>Manual starts</i>	<i>OCS starts</i>
1	--	6P	1	--	6P	1	--	4P
3	6N	6P	3	3P	3P	3	2N	6P
4	--	4N	4	--	4N	7	9P	6P
5	--	4N	15	6N	3N	15	3N	--
6	--	6N	20	3N	3N	19	--	3P
7	6P	6N	26	--	6N	20	3N	--
15	6N	5N	27	7N	--	27	--	4P
16	3P	--	31	--	6N	28	6N	3P
20	--	3N	32	9N	--	37	6N	--
21	3P	--	36	--	6N	39	5P	--
23	3N	--	37	6N	--	38	--	3P
24	--	6N	41	3P/3N	3N	50	--	3N
25	6N	--	52	1N	4N	51	5P	--
26	--	4N				52		6P
27	6N	--						
30	--	4N						
31	6N	--						
36	--	6N						
37	6N	4N						
38	6N	5N						
41	--	3N						
42	15N	5N						
43	--	3N						
44	--	6N						
45	14N	3N						
52	6N	6N						

Figures 1 through 3 are plots of the weekly instructor levels for both the OCS₁ and OCS₂ schedules. The figures indicate OCS₂ is successful in avoiding weekly changes to instructor levels. Figure 1 illustrates a growing number of Arabic instructors over the three year period scheduled. Figure 2 illustrates a steady state Chinese-Mandarin course for the first two years with a decline in the last year scheduled. Figure 3 has identical graphs for the OCS₁ and OCS₂ generated schedules. An identical graph is not surprising due to the high percentage of pep sections scheduled by OCS₁ for Persian-Farsi which limits the ability of OCS₂ to make scheduling adjustments.

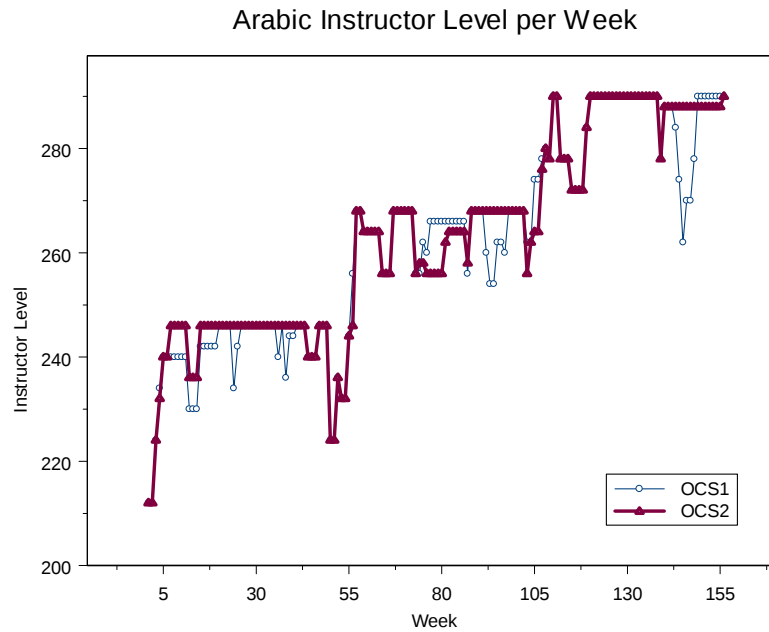


FIGURE 1. OCS₁ AND OCS₂ ARABIC INSTRUCTOR LEVELS

The number of Arabic instructors assigned to sections by the OCS₁ schedule (circles) and by the OCS₂ schedule (triangles). Both OCS₁ and OCS₂ have the same number of pep section starts, but OCS₂ is better at avoiding weekly changes to instructor levels. OCS₂ avoids the large OCS₁ decrease in instructor levels during the weeks preceding 104 and 156.

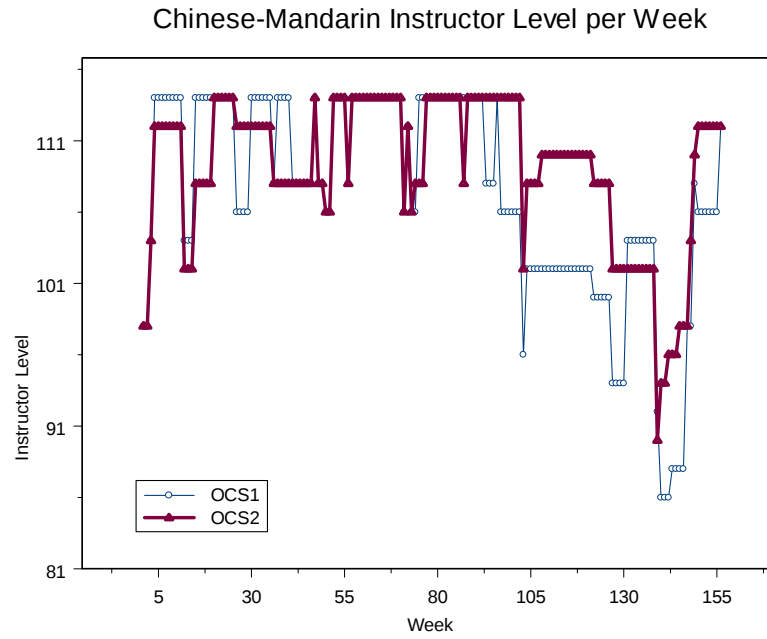


FIGURE 2. OCS_1 AND OCS_2 CHINESE-MANDARIN INSTRUCTOR LEVELS

The number of Chinese-Mandarin instructors assigned to sections by the OCS_1 schedule (circles) and by the OCS_2 schedule (triangles). As in Arabic (Figure 1), we see OCS_2 is able to better avoid weekly changes to instructor levels.

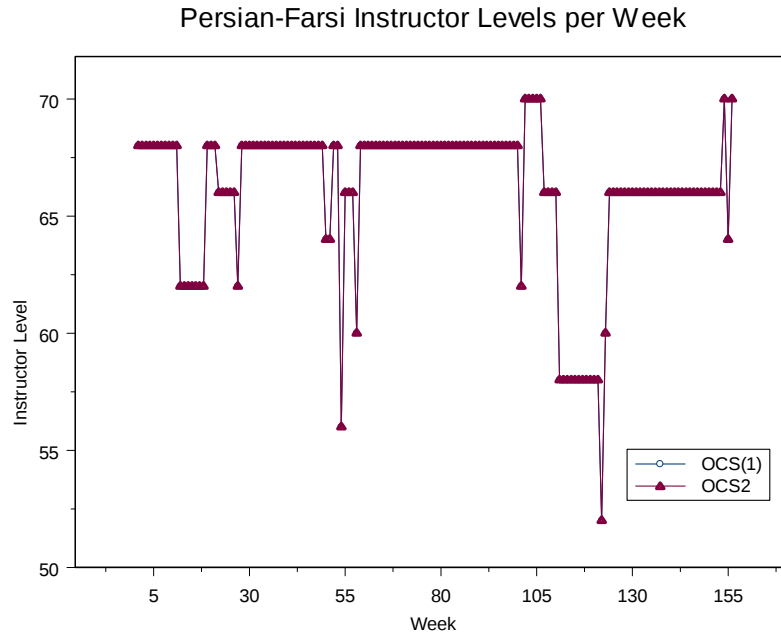


FIGURE 3. OCS₁ AND OCS₂ PERSIAN-FARSI INSTRUCTOR LEVELS

The number of Persian-Farsi instructors assigned to sections by the OCS₁ schedule (circles) and by the OCS₂ schedule (triangles). The OCS₁ and OCS₂ plots are identical because the high percentage of pep sections limits the ability of OCS₂ to smooth the weekly instructor level variability.

We want to see the possible value of multiyear scheduling so we let OCS schedule fiscal years 2007 and 2008 using the 2006 manual schedule's carryover sections and compare this with using the 2006 OCS carryover sections. Table 6 displays the resulting pep sections starts summary for both. For Arabic and Chinese-Mandarin, using OCS aids in increasing the number of pep sections scheduled in future years. OCS maintains the number of pep sections scheduled for Persian-Farsi, but requires fewer instructors to do so and schedules more pep section starts in 2006. OCS increases the number of pep sections scheduled and reduces the required number of instructors in future years by generating fewer carryover sections.

Figures 4 through 6 are plots of the instructor level per week. Each figure has two plots: one plot is from an OCS 2007 and 2008 schedule using the manual schedule's carryover sections, and the other plot is from an OCS schedule using the OCS schedule's carryover sections. The large drop in instructor level for Chinese-Mandarin and Persian-Farsi in Figure 5 and 6, respectively, indicates that more instructors are available than required for fiscal year 2008.

TABLE 6. FUTURE YEAR PEP SECTION STARTS

The percentage of students scheduled by OCS to be trained in pep sections for fiscal years 2007 through 2008 using the carryover sections from both the manual schedule and the OCS schedule. OCS significantly increases the percentage of students trained in pep sections.

Fiscal Year	Arabic <i>Manual % Pep</i>	Arabic <i>OCS % Pep</i>	Chinese- Mandarin <i>Manual % Pep</i>	Chinese- Mandarin <i>OCS % Pep</i>	Persian- Farsi <i>Manual % Pep</i>	Persian- Farsi <i>OCS % Pep</i>
2006	8 %	8 %	13 %	13 %	43 %	88 %
2007	7 %	34 %	13 %	37 %	100 %	100 %
2008	64 %	76 %	22 %	28 %	86 %	86 %

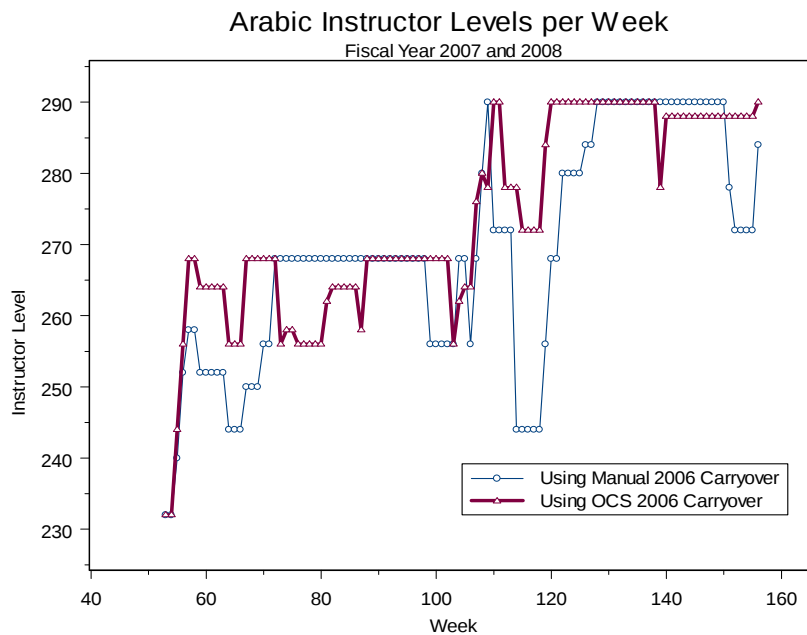


FIGURE 4. ARABIC CARRYOVER SECTIONS

Arabic instructor levels per week from an OCS schedule using the fiscal year 2006 manual schedule's carryover sections (circles) and an OCS schedule using the fiscal year 2006 OCS schedule's carryover sections (triangles). The large drop in instructor levels for weeks 110 through 125 for the OCS plot using manual carryover sections is due to the carryover sections ending. OCS reduces these carryover section effects in future years. This allows more pep sections (see Table 6), better avoids weekly changes to instructor levels, and requires fewer instructors in future years.

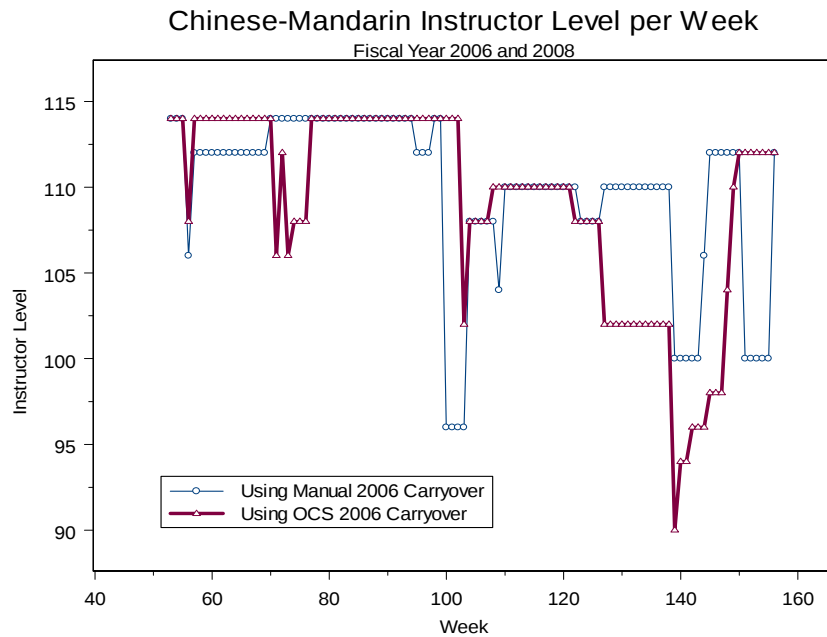


FIGURE 5. CHINESE-MANDARIN CARRYOVER SECTIONS

Chinese-Mandarin instructor levels per week from an OCS schedule using the fiscal year 2006 manual schedule's carryover sections (circles) and an OCS schedule using the fiscal year 2006 OCS schedule's carryover sections (triangles). This figure illustrates OCS advantages as discussed in Figure 4. The large difference in instructor levels for the two plots from week 125 to week 150 results from the difference in carryover sections still in session.

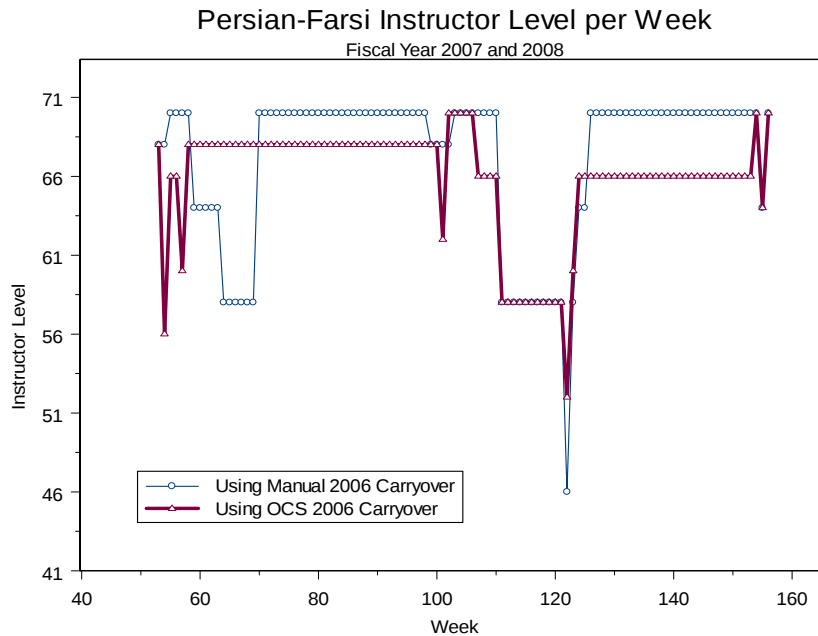


FIGURE 6. PERSIAN-FARSI CARRYOVER SECTIONS

Persian-Farsi instructor levels per week from an OCS schedule using the fiscal year 2006 manual schedule's carryover sections (circles) and an OCS schedule using the fiscal year 2006 OCS schedule's carryover sections (triangles). This figure illustrates OCS advantages as discussed in Figure 4.

At the DLI's request, preliminary OCS models assisted the DLI in determining how many instructors to hire in 2006. The DLI's goal is to teach at least 25 percent of the student requirement in pep sections. Table 7 displays the OCS determined minimum number of instructors required in fiscal year 2006 to achieve at least 25 percent of the student requirement to be trained in pep sections. Arabic and Chinese-Mandarin require adding instructors in 2006; Persian-Farsi may decrease the available number of instructors.

OCS aids in identifying future year effects of assigning more instructors in the current year. Achieving the 25 percent goal in 2006 is possible with fewer Persian-Farsi instructors, but doing so generates too many carryover sections for the 2007 schedule to remain feasible given its estimated instructor levels. Identifying such an effect requires multiyear scheduling.

TABLE 7. MINIMUM INSTRUCTORS REQUIRED FOR AT LEAST 25 PERCENT PEP IN 2006

The OCS determined minimum number of instructors needed for at least 25 percent of the student requirement for 2006 to be trained in pep sections.

Arabic		Chinese-Mandarin		Persian-Farsi	
<i>% Pep</i>	<i>Instructors Required</i>	<i>% Pep</i>	<i>Instructors Required</i>	<i>% Pep</i>	<i>Instructors Required</i>
34 %	265	28 %	124	44 %	60

This thesis employs a realistic schedule change to evaluate the effect of using OCS₃. The schedule change assumes the first quarter of fiscal year 2006 is in progress and can not be changed and three non-pep sections must be manually scheduled during week 17 due to an increased student requirement.

Each section addition requires in week 17 adding additional instructors to cover these new sections. This results in an additional six instructors to cover the manually scheduled section until course completion. The new student requirement is now 902.

This thesis uses OCS₃ cost coefficient values of one and two for *cdev* and *pdev*, respectively. This implies a two-to-one preference of not changing the number of pep

sections scheduled over changing the previous schedule. We assume the goal of the scheduler is to minimize the changes in the previously published schedule for 2006 while maximizing the number of pep sections scheduled in future years. Therefore, we use OCS₃ to generate the remainder of the 2006 schedule, and we use OCS₁ and OCS₂ to generate the 2007 and 2008 schedules. This schedule is compared to a revised schedule generated by OCS₁ and OCS₂ only.

Table 8 displays the impact on the number of pep sections scheduled for Arabic and Table 9 displays the 2006 Arabic course schedules. Chinese-Mandarin and Persian-Farsi courses produced similar results. For Arabic, OCS₃ found a schedule that does not change the remainder of the published schedule after inserting the three sections at the start of week 17 but at a cost of decreasing the number of students trained in pep sections in 2007 by 6 percent. The scheduler must weigh the cost of revising the published schedule for the remainder of the year against the cost of decreasing the number of students trained in pep sections in 2007.

TABLE 8. OCS₃ IMPACT ON PEP SECTIONS SCHEDULED

The percent of students trained in pep sections for a new OCS schedule and an OCS₃ schedule for the scenario where no first quarter schedule changes are made and week 17 requires scheduling three non-pep sections. These results indicate a new OCS schedule is preferred to the OCS₃ schedule with respect to pep sections in future years.

Fiscal Year	Arabic	Arabic
	<i>New OCS Schedule % Pep</i>	<i>OCS₃ % Pep</i>
2006	8 %	8 %
2007	40 %	34 %
2008	76 %	76 %

TABLE 9. OCS AND OCS₃ SCHEDULES

The Arabic original schedule, the OCS₃ revised schedule, and the revised OCS schedule for fiscal year 2006 for the scenario where no first quarter schedule changes are made and week 17 requires adding three non-pep sections. The values in the table indicate the number of sections scheduled to start week w with pep sections indicated by a P and non-pep sections indicated by an N . The OCS₃ revised schedule for 2006 does not make any additional schedule changes after week 17 at a cost of 6 percent of students trained in pep sections in 2007 (see Table 8). The revised schedule for 2006 using OCS₁ and OCS₂ has several changes after week 17 (in bold) but allows 6 percent more students to be trained in pep sections in 2007 (see Table 8). The DLI must weigh this tradeoff.

Week w	Arabic <i>Original OCS</i>	Arabic <i>OCS₃</i>	Arabic <i>New OCS</i>
1	6P	6P	6P
3	6P	6P	6P
4	4N	4N	4N
5	4N	4N	4N
6	6N	6N	6N
7	6N	6N	6N
15	5N	5N	5N
17	--	3N	3N
20	3N	3N	3N
24	6N	6N	6N
26	4N	4N	4N
30	4N	4N	4N
36	3N	3N	--
37	4N	4N	6N
38	5N	5N	5N
40	--	--	3N
41	3N	3N	3N
42	5N	5N	6N
43	3N	3N	--
44	6N	6N	6N
45	3N	3N	3N
46	--	--	3N
52	6N	6N	6N

V. CONCLUSIONS

OCS generates face-valid, multiyear, and persistent basic course schedules typically in less than one minute on a PC. These schedules meet the DLI's preferences for section starts per week, maximize the number of pep sections scheduled, reduce year-end effects, and avoiding weekly changes to instructor levels.

OCS offers significant advantages over single-year manual scheduling. OCS schedules for the test courses start at least three sections per week and no more than six sections per week; they start at least as many pep sections as the DLI's manual schedule for the test courses. OCS generates multiyear schedules that reduce year-end effects and carryover sections encouraged by single-year schedules. OCS solves in less than one minute for each test course while manual scheduling typically takes days per schedule. The fast solve times and convenience of solving OCS on a PC offers the DLI scheduler a powerful and efficient tool for planning and conducting "what if" scenarios such as how many instructors are required to achieve 25 percent pep instruction. OCS also provides insight about the effects of these "what if" scenarios in future years.

OCS seeks to schedule section starts earlier in the schedule. This decreases the inefficiencies created by carryover sections allowing significantly more students to be trained in pep sections. We find OCS increases the number of students trained in pep sections by 27 percent in 2007 and 12 percent in 2008 for Arabic. Likewise, OCS increases the percentages in Chinese-Mandarin by 24 percent in 2007 and 6 percent in 2008; OCS increases the percentages in Persian-Farsi by 45 percent in 2006.

OCS₃ generates a revised schedule that is persistent but at a cost of pep sections scheduled in later years. Using OCS₁ and OCS₂ to generate a revised schedule increases the number of pep sections scheduled but at a cost of several scheduling changes. The DLI must weigh the cost of decreasing the number of students trained in pep sections against the benefit of a persistent schedule. For the hypothetical example we evaluate for Arabic, the scheduler must weigh the benefit of no additional scheduling changes in 2006 against the cost of losing an additional 6 percent of students trained in pep sections during 2007 with four scheduling changes in 2006.

OCS has proven beneficial already by helping to determine the number of instructors to hire for fiscal year 2006. The DLI's goal is to train at least 25 percent of all basic courses in pep sections. OCS will help the DLI significantly decrease the time to generate schedules and provide more insight into the long-term effects of policy and scheduling changes.

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