SEMI-AUTOMATED WELL INTERVENTIONS AND UNITS ALLOCATION SCHEDULER

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ตัวจัดตารางเวลาและจัดสรรอุปกรณ์ในการปฏิบัติงานกับหลุมผลิตแบบกึ่งอัตโนมัติ

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ปฏิบัติการที่เกี่ยวข้องกับหลุมผลิตน้ำมันและก๊าซธรรมชาติในอ่าวไทยจำต้องเพิ่มขึ้น เนื่องจากแหล่งผลิตที่เหลืออยู่มีขนาดเล็กลงในขณะที่เป้าปริมาณการผลิตยังเท่าเดิม ปิโตรเลียมในอ่าวไทยถูกกักเก็บอยู่ในชั้นกักเก็บที่เป็นกระเปาะขนาดเล็กจึงทำให้ต้องมีระดับกิจกรรมหน้าหลุมผลิตสูงกว่าปกติ เป็นผลให้การจัดตารางกิจกรรมเหล่านี้ใช้เวลานานและมีความซับซ้อน ในการศึกษานี้ทางออกที่เสนอคือการออกแบบกำหนดการเชิงเส้นเท่ีมีตัวแปรเลขฐานสองพื่อหาค่าที่เหมาะสมที่สุดด้วยโปรแกรม CPLEX เป้าหมายเพื่อสร้างแบบจำลองกำหนดการเชิงเส้นที่จะจัดลำดับการทำงานของชุดอุปกรณ์แบบกึ่งอัตโนมัติให้มีประสิทธิภาพ เพื่อนำผลที่ได้ไปใช้กับการจัดตารางเวลาและจัดสรรอุปกรณ์ในการปฏิบัติงานกับหลุมผลิตของแหล่งผลิตปิโตรเลียมในอ่าวไทย การศึกษานี้เกี่ยวข้องกับชุดอุปกรณ์ลวดนำไฟฟ้า, ชุดอุปกรณ์ลวดเรียบ และการปฏิบัติงานกับหลุมผลิตที่เกี่ยวข้อง ระยะเวลาในการปฏิบัติงานหน้าหลุมผลิตและระยะเวลาในการเคลื่อนย้ายยูนิตก็ถูกนำมาคำนวนในโปรแกรมด้วยเช่นกัน

ตัวแปรเลขฐานสองช่วยให้เกิดการสลับลำดับของชุดอุปกรณ์และงานหน้าหลุมผลิตภายในแบบจำลองเพื่อให้ได้คำตอบที่มีค่าต่ำที่สุดภายใต้ข้อจำกัดที่กำหนดไว้ ข้อมูลนำเข้าของแบบจำลองถูกเปลี่ยนแปลงเพื่อตรวจสอบการทำงานของแบบจำลอง การลดผลรวมของเวลาทั้งหมดที่ชุดอุปกรณ์ทำงานเสร็จรวมกับเวลาทั้งหมดที่ชุดอุปกรณ์ใช้ในการทำงานให้มีค่าต่ำสุดเป็นฟังก์ชันวัตถุประสงค์ที่เหมาะสมที่สุดของตัวจัดตารางเวลานี้ จำนวนของจุดเหตุการณ์และวันที่ครบกำหนดของงานต่างส่งผลกระทบต่อพื้นที่ค้นหาคำตอบของแบบจำลองซึ่งอาจทำให้มีการเปลี่ยนแปลงของคำตอบเกิดขึ้น ตัวจัดตารางเวลานี้ยังช่วยลดการใช้เวลาและความซับซ้อนที่เกิดขึ้นในการจัดลำดับการปฏิบัติงานกับหลุมผลิต เป็นผลให้การบริหารการใช้ชุดอุปกรณ์ต่างๆของแหล่งผลิตน้ำมันและก๊าซธรรมชาติมีประสิทธิภาพมากขึ้น แบบจำลองที่ผ่านการตรวจสอบแล้วได้ถูกนำไปใช้กับปัญหาการปฏิบัติงานกับหลุมผลิตของแหล่งผลิตจริง ตัวจัดตารางเวลานี้ได้ชี้ให้เห็นโอกาสในการเพิ่มประสิทธิภาพของลำดับการปฏิบัติงานกับหลุมผลิตของแหล่งผลิตจริง นอกจากนี้ยังได้มีการการวิเคราะห์ความไวในหลายกรณีของทางเลือกในการปฏิบัติงานและความไม่แน่นอนในการปฏิบัติงาน

ภาควิชา	วิศวกรรมเหมืองแร่และปิโตรเลียม	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมปิโตรเลียม	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
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KEYWORDS: WELL INTERVENTIONS / UNIT ALLOCATION / AUTOMATED SCHEDULER / OPTIMIZATION / BINARY VARIABLE / CONTINUOUS TIME REPRESENTATION

TANART WISIT: SEMI-AUTOMATED WELL INTERVENTIONS AND UNITS ALLOCATION SCHEDULER. ADVISOR: ASST. PROF. JIRAWAT CHEWAROUNGROAJ, Ph.D., 70 pp.

Oil and gas production operational activities are increasing due to number of smaller fields with same production target. In Gulf of Thailand, oil and gas formations are small pockets, thus the activity levels are relatively high leading to more time and complicated operation sequence scheduling. The proposed Linear programming (LP) optimization model with binary variable is constructed of CPLEX optimizer program. This study aims to develop LP model to optimize unit scheduling semi-automatically and apply it to well intervention and unit operation sequence optimization of an oil and gas production field in Thailand. Electric line unit, slick line unit and well interventions done by these units are involved. Well interventions duration and units mobilization time are also included.

Solving binary variable allows unit and job sequences shuffle to yield minimum solution which the model's constraints are satisfied. Multiple model inputs are changed to validate the model. Total unit utilization time and total finished time minimization are scheduler's most suitable objective function. Both number of event point and due date constraints affect model's search space which may change the solution of scheduler. The scheduler also reduces time usage and complexity resulting in more efficient and better management of units operation of oil and gas production field.The validated optimization model is applied to field well intervention operation case. The scheduler has identified optimization opportunity of selected field case. Furthermore, several sensitivity analysis cases of operational options and operation uncertainties are performed.

Department:	Mining and Petroleum Engineering	Student's Signature	______________
		Advisor's Signature	______________
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List of Abbreviations

GoT	Gulf of Thailand
LP	Linear programming
MILP	Mixed integer linear programming
GA	Genetic Algorithms
WHP	Well head platform
CBL	Cement bond log
MPLT	Memory production logging tool
SLU	Slick line unit
ELU	Electric line unit
BSLU	Braided line unit
BHP	Bottom hole pressure
MIT	Mechanical integrity test
GLV	Gas lift valve

Nomenclatures

P	Platforms
J	Jobs
U	Units
n	Event point, Time slot
J_P	Job requests of a platform
U_j	Unit that can perform a job
α_{pj}	Duration requirement of job j on platform p
β_{pp}	Mobilization time from platform p to platform
H	Sufficient time horizon
sDur	Sum of jobs duration in the time horizon
T^s	Start time
T^f	Finished Time
vp	Binary variable
TTf	Total finished time
mTTf	Total unit utilization time
Max Tf	Maximum finished time

Chapter1 Introduction

1.1 Background

Recently, activity levels of oil and gas production operation are increasing due to the smaller size of fields with the same production target to meet. Time spent to schedule the operational sequences tends to be more time taking process and has more complication. In Gulf of Thailand (GoT), oil and gas formations are small pockets which make the activity levels relatively high. However, well interventions sequences in GoT's field are scheduled manually. Linear programming (LP) is widely used to solve this scheduling problem in order to find an optimum solution with objective of maximizing production or minimizing total operation time. Semi-automated well interventions scheduler is the first automated scheduler in GoT operation which applies LP method to optimize the scheduling problems. The proposed mathematical optimization model of the scheduler is constructed by using CPLEX optimizer program. Semi-automated well intervention scheduler has objectives to optimize well intervention sequence and unit allocation and give quick operation schedule of field's well head platforms well work requests. Units involve with well intervention are such as electric line unit, slick line unit and coil tubing unit. The scheduler also helps reduce time usage and complexity of operation sequences arrangement. This will leads to better management and more efficient time spending of units operation of oil and gas production field.

1.2 Objectives

1. To develop mathematical optimization model to optimize unit allocation sequence semi-automatically
2. To apply developed semi-automated mathematical models in well intervention and unit operation sequence optimization of an oil and gas production field in Thailand.
3. To quantify impact from operation uncertainties of oil and gas production field by performing sensitivity analysis.

1.3 Outline of methodology

This thesis has five steps of methodology. Summary of methodology is shown in Figure 1.1.

1. Construct a motivating example which covers the most possible cases such as same unit can perform different tasks and different units can undertake similar tasks.
2. Formulate mathematical optimization models for motivating example without binary variables and with binary variables and event points using CPLEX optimizer program
3. Validate models with different input
    - Compare objective function
    - Add unit similarity
    - Increase number of event points
    - Add due date and earliest date constraints
4. Apply the mathematical optimization models to field case problem and compare with existing schedule
5. Perform sensitivity analysis: Quantify impact from the change in input
    - Operational options sensitivity
        - Unit's capabilities sensitivity
        - Number of units sensitivity
    - Operation uncertainties sensitivity
        - Number of job requests sensitivity
        - Job durations sensitivity

1.4 Outline of thesis

This thesis is divided into six chapters as shown in following outline.

Chapter 1 introduces background of well intervention and unit allocation on GoT, identifies objective and summarizes methodology of this study.

Chapter 2 reviews various literature related to study of mathematical optimization and model formulation techniques and scheduling optimization in oil and gas operation business.

Chapter 3 presents relevant theories of mathematical optimization modeling which are linear programming, mathematical optimization algorithm. Moreover, it introduces type of well interventions and well intervention's units.

Chapter 4 illustrates mathematical optimization model and formulation method of this study. It also provides model validation by varying model's input which are objective functions, unit similarity, number of event points and due date constraints. Moreover, result concluded from this chapter will be applied to oil and gas field scheduling optimization in chapter 5.

Chapter 5 illustrates application of the mathematical model in chapter 4 in GoT's oil and gas well intervention scheduling. It also present results and discussion of sensitivity analysis of well intervention schedule by varying unit abilities, number of units, number of job request and job duration.

Chapter 6 summarizes conclusion of this study and recommendation of field well intervention schedule.

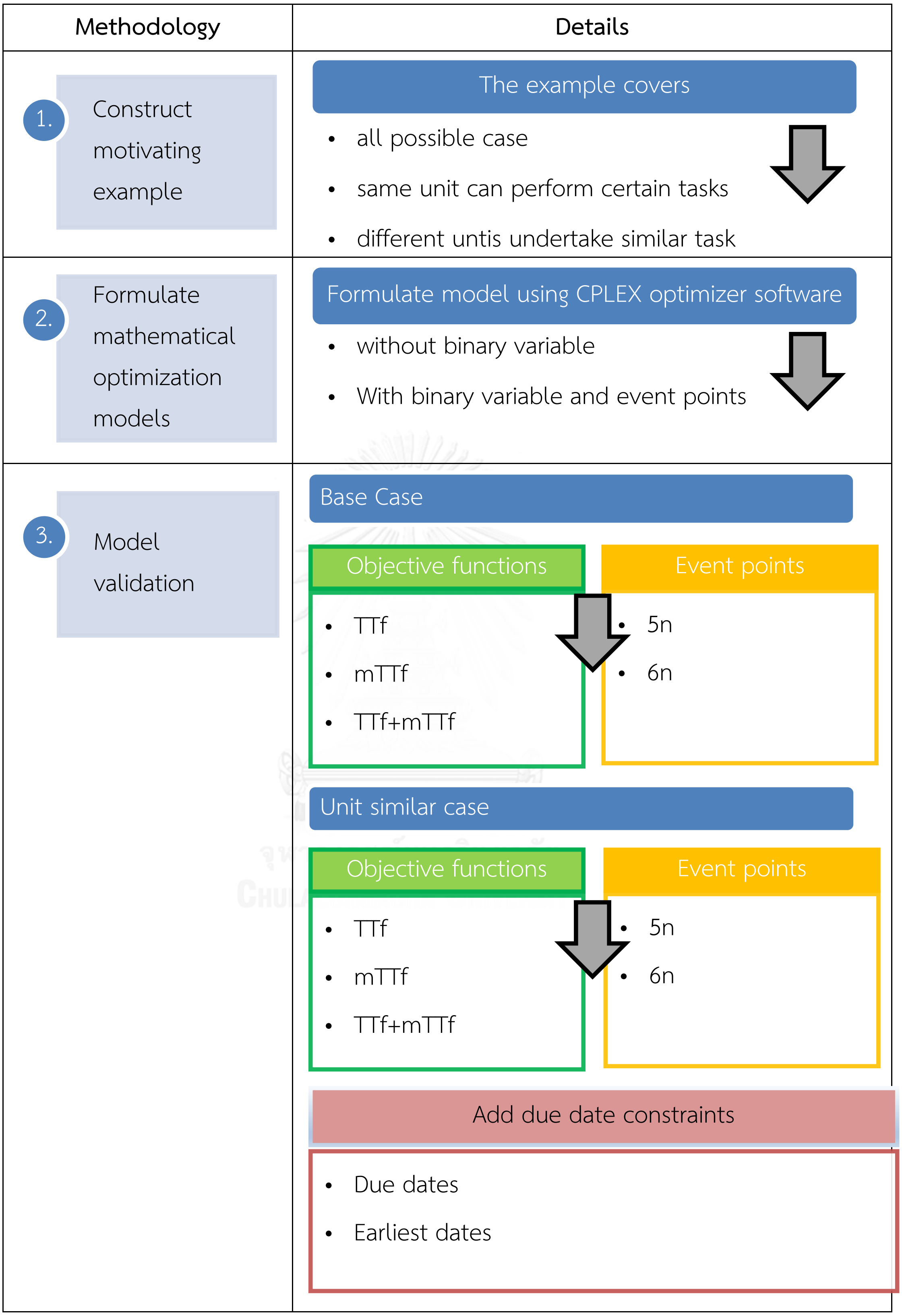

Figure 1.1 Summary of methodology

Methodology	Details
4. Apply to field case problem	Apply the validated model to field case and compare with existing schedule
5. Sensitivity analysis	Operational options **Number of units** • 4 units • 5 units • 6 units **Unit's capabilities** • Dedicate unit on a job • No dedicate unit Operation uncertainties **Number of jobs** • 12 job requests • 15 job requests • 17 job requests **Job durations** • Add 30% duration • reduce 30% duration
6. Conclusion	Conclude results of both optimization construction and application to field case

Figure 1.1 Summary of methodology (cont.)

Chapter2 Literature review

This chapter summarizes previous literatures of mathematical optimization model and model formulation techniques and scheduling optimization in oil and gas operation business.

2.1 Mathematical optimization model and model formulation technique.

This section reveals mathematical optimization model formulation method of short term scheduling problem and short term scheduling problem with intermediate due dates studied by various researches.

Pinto and Grossmann [1] proposed a mathematical optimization model formulation to solve the problem of minimizing the earliness of specific orders of multistage batch plants short term scheduling with due date constraints. Multistage batch plants usually contain units working in parallel. Minimized earliness of order forced each order to finished closed to due date so that inventory and intermediate storage requirements are minimized. This is typical idea for scheduling problem with due date constraints. There are two basic ideas in their proposed model, continuous time domain representation and time slots for the units. Their model was restricted to determining the sequence of orders to satisfy product demand without order prioritization. A mixed integer linear programming model was proposed that subjected to time matching constraints given parallel time coordinates for the units and the tasks and also unit utilization sequence constraints for each order. They also formulated the model with preordering constraints for units. Preordering constraints made some units to be utilized after only a specified unit. The result showed the significant reduction of model complexity and computational time. However, they did not consider raw materials limitation constraints and the batch sizes of each unit which effect processing times are assumed to be fixed parameters. The ultimate goal of their work is to establish a continuous time model that can solve large scale industrial problems.

Ierapetritou and Floudas [2] proposed mathematical optimization model formulation to solve the problem of maximizing revenue from product sales at the end of given time horizon for multipurpose batch processes. The main different key idea from Pinto and Grossmann model is that they decoupled task event from unit event by differentiate unit and task variables. They also considered processing time to be variable depending on amount of material being processed in the duration constraints. Their objective is to propose a new simple mathematical model for general short term scheduling problem of batch plants. The mixed integer linear programming (MILP) model was formulated with GAMS/CPLEX software. The computational results showed that mathematical models are in smaller size both in terms of continuous variables and constraints although more binary variables are addressed. Moreover, the objective values of models were able to easily optimize. However, there are limitations to apply the proposed formulation. The formulation required one to one task and unit events, some tasks can only perform by a specified unit, which increase the number of tasks and consequence constraints. This does not reflex the real situation in oil field well intervention scheduling application which operational units are able to do the same task on the same platform. Furthermore, number of event point or time slot needs to be determined by doing a few iterations prior to solve the problem model.

2.2 Scheduling optimization in oil and gas operation business

This section reveals mathematical modeling approach to optimize rig fleet and well intervention operation scheduling studied by various researches.

Irgens, et al. [3] illustrated the optimization of rig fleet management by applying Stochastic Local Search algorithms to solve rigs scheduling problem. Their proposed mathematical model has two objectives which are maximizing production and minimizing transportation cost. Start time of assigned rigs and drilling activities to be done by those rigs are variables in the model. This rigs schedule optimizer aimed to find good and workable fast rather than chasing the best solution in long computational run. This rigs schedule optimizer development objective was not only to optimize rigs utilization but also to support drilling project execution decision. Due to the fact that today's petroleum exploration and production business are being overloaded from information, more activities and complexity of operation to be done with limited resources. The optimizer could provide rigs schedules with different objectives and constraints such that decision analysis can be made with less time and fewer workforces.

Lasrado [4] illustrated work-over rig scheduling optimization using reservoir simulation. He proposed a prototype of rig scheduler software which aims to identify opportunities to improve planned work-over rig schedule. His scheduler considers minimization of work-over rig net distance travel while maintaining overall field oil production. Furthermore, the scheduler is also able to identify suitable number of rigs utilized in the field by sensitizing number of rig in the model. Reservoir simulation was used as a tool to assist this rig planning and scheduling. Oil production profiles and production potentials of each wells are generated through reservoir simulation runs. Production target of each wells are set to identify the need of work-over intervention when oil rate of the well fall below target. These production profiles, targets and potentials are as a constraint of maintaining overall field oil production put in the scheduler while minimizing net distances travel of rigs.

Zarei, Muradov, and Davies [5] illustrated work-over schedule optimization using Genetic Algorithms (GA). They incorporate both dynamics reservoir simulation and economics analysis into their proposed optimization model. Their model aims to create a proactive procedure of well intervention sequence in the field based on future event in order to maximize field revenue. Future event of the field is forecasted based on the most up to date reservoir simulation. GA typically has long calculation time and sometime also has convergence problems when large number of variable are being analyzed. Engineering knowledge of the field production condition can guide model and decrease the dimensionality of the search which lead to less number of iterations and calculation time. The model which was guided with guiding parameter called steered GA model. Guiding parameter is made from combination of reservoir permeability, thickness and oil saturation, which is $Log(k)hS_{oil}$. This parameter indicate reservoir quality of each individual zones. Permeability was subjected to logarithmic dampens to reduce effect of broader permeability values and allow others to have the same influence to the parameter. Their literature covers only well intervention that related to production zones opening or closing and costs of those interventions. Well intervention schedule result of steered GA showed signification added of field revenue compared with non-steered GA.

This thesis aims to propose a mathematical optimization approach addressing well intervention and unit allocation problem, especially in GoT. Well intervention operation in GoT normally involves with several types of well intervention, well intervention unit and various well head platform (WHP) in the same area. Well interventions for each WHP are requested through their responsible petroleum engineers. Some well interventions are not able to be predicted with reservoir simulation, such as scale removal and recovery of tools stuck in hole.

However, there is rarely study of well intervention scheduling on a group of unrelated wells and short term scheduling. Literatures above study longer term optimization on a single unit type and well intervention scheduling on group of wells penetrated through same reservoirs. This thesis does not cover only well intervention related to open and close of hydrocarbon zones. Furthermore, GoT formations are like small pockets which make most of the wells independent to each other.

This thesis aims to improve current well intervention operation scheduling to be more efficient with less man power by applying LP method. Pinto and Grossman and Ierapetritou and Floudas shown the effective way of short term scheduling formulation with Continuous time domain representation concept.

Chapter3 Relevant Theory

This chapter describes related theory of this literature. Linear programming (LP) and simplex algorithm are illustrated in section 3.1 and 3.2, respectively. LP is mathematical method widely used solving scheduling problem. Simplex algorithm is one of the most basic algorithm used solving LP problem. Section 3.3 illustrates binary variables application in LP model. Lastly, section 3.4 introduces well intervention and related units of oil and gas operation.

3.1 Linear programming

Linear programming (LP) or linear optimization is a mathematical method for determining the best solution, maximizing or minimizing an objective function, in the given linear relationship mathematical model. In various industries, linear programming can be applied to solve business problem such as shortest transportation route, maximum production under limited time frame, minimum time usage of operation sequence, etc. Mathematical model of linear programming can be expressed as follow

Objective function:

$$\text{Maximize } f(x_1, x_2) = c_1x_1 + c_2x_2$$

Subject to constraints:

$$a_{11}x_1 + a_{12}x_2 \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 \leq b_2$$

$$a_{31}x_3 + a_{32}x_3 \leq b_3$$

Boundaries of variables:

$$x_{1,}\ x_2 \geq 0$$

The problem is usually presented in matrix form as follow.

$$\text{Max } \{ c^T x \mid ax \leq b \wedge x \geq 0 \}$$

Where x represents vector of variables to be determined

And a, b and c represent vector of known coefficients

Below is an example of linear programming problem.

Objective function:

$$\text{Max} \quad z = x_1 + x_2$$

Subject to constraints:

$$2x_1 + x_2 \le 3$$

$$x_1 + 2x_2 \le 3$$

$$x_1 \ge 0, x_2 \ge 0$$

The optimum solution of this example can be determined by using graphical method which is shown in Figure 3.1. Area under constraints and above bound of zero is call feasible region. In order to maximize z, x_1 and x_2 need to be maximized, normally the solution is at the cross point of constraints (or bound of variables). Here the solution is at x_1, x_2 and objective value z are 1, 1 and 2, respectively.

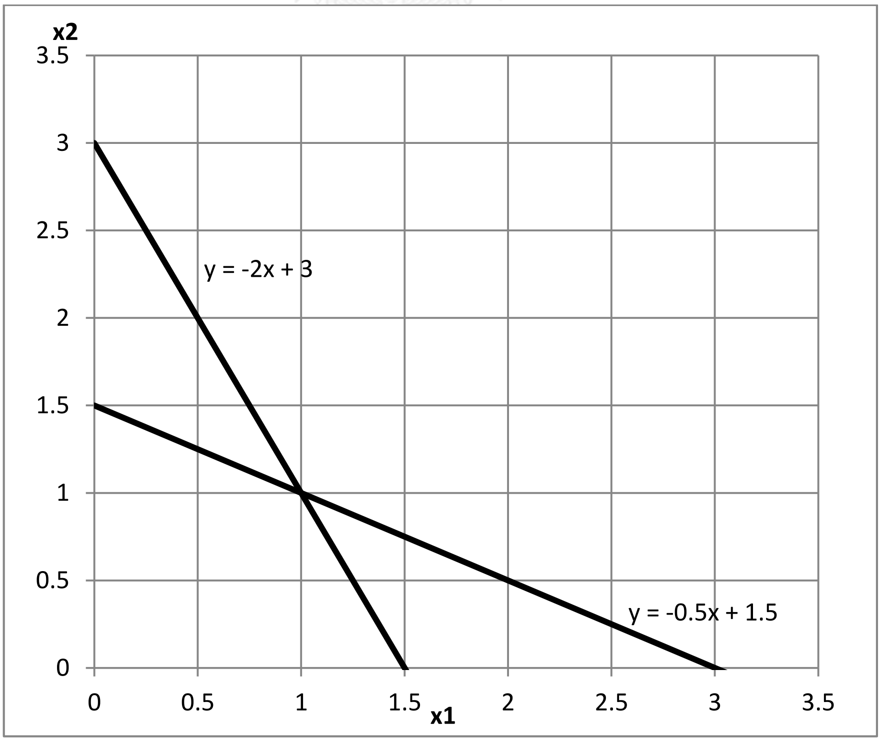

Figure 3.1 LP example graphical method

3.2 The Simplex Method

Simplex method or simplex algorithm is one of the methods that are used to solve linear programming problem. Simplex algorithm is a popular algorithm used in many solvers and other commercial linear programming software. CPLEX optimizer is one of these software. Simplex algorithm solves LP problem by constructing a feasible solution at a vertex of the polytope and then walking along a path on the edges of the polytope to vertices with non-decreasing values of the objective function until an optimum is reached (Castillo, E. et al.[6]). The polytope shape is defined by the constraints applied to the objective function. In order to apply simplex algorithm, LP problems need to be converted into standard form (augmented form). This form replaces inequalities with equalities constraints by introducing positive slack variables. LP example can be written in standard form as follow.

Recall LP example:

$$z - x_1 - x_2 = 0 \qquad \text{Row0}$$

$$2x_1 + x_2 + s_1 = 3 \qquad \text{Row1}$$

$$x_1 + 2x_2 + s_2 = 3 \qquad \text{Row2}$$

$$x_1 \geq 0,\ x_2 \geq 0,\ s_1 \geq 0,\ s_2 \geq 0$$

Where s1 and s2 are slack variables

In simplex algorithm, variables which appear in only one equation are called basic variables; here they are s1 and s2. A basic solution is obtained from these set of equation by setting non-basic variables, here they are x1 and x2, to zero. The basic solutions are shown below.

Basic solution $x_1 = x_2 = 0$, $s_1 = 3$, $s_2 = 3$ (point 1 in Figure 3.2)

Note that if all variables in the basic solution are more than zero (all required to be positive in this problem), the solution is feasible.

The goal of this equation system is to maximize z and if it can still be increased by increasing non-basic variables (x_1 and x_2), the solution is not an optimum solution. To increase value of z, x1 has to change, to increase value from zero, to basic variable by pivot process following Guass-Jordan procedure.

Pivot element in Row1:

$z - x_1 - x_2$	$= 0$	Row0
$\mathbf{2x_1} + x_2 + s_1$	$= 3$	Row1
$x_1 + 2x_2 + s_2$	$= 3$	Row2

Yields

$z \ - 1/2x_2 + 1/2s_1$	$= 3/2$	Row0
$x_1 + 1/2x_2 + 1/2s_1$	$= 3/2$	Row1
$3/2x_2 - 1/2s_1 + s_2$	$= 3/2$	Row2

Basic solution $x_1 = 3/2, x_2 = s_1 = 0, s_2 = 3/2, z = 3/2$ (point 2 in Figure 3.2)

Pivot element in Row2:

$z \ - 1/2x_2 + 1/2s_1$	$= 3/2$	Row0
$x_1 + 1/2x_2 + 1/2s_1$	$= 3/2$	Row1
$\mathbf{3/2x_2} - 1/2s_1 + s_2$	$= 3/2$	Row2

Yields

$z \ + 1/3s_1 + 1/3s_2$	$= 2$	Row0
$x_1 + 2/3s_1 - 1/3s_2$	$= 1$	Row1
$x_2 - 1/3s_1 + 2/3s_2$	$= 1$	Row2

Basic solution $x_1 = 1, x_2 = 1, s_1 = s_2 = 0, z = 2$ (point 3 in Figure 3.2)

After second pivot process, z has already reached maximum value with all constraints satisfied, so that pivot process stop.

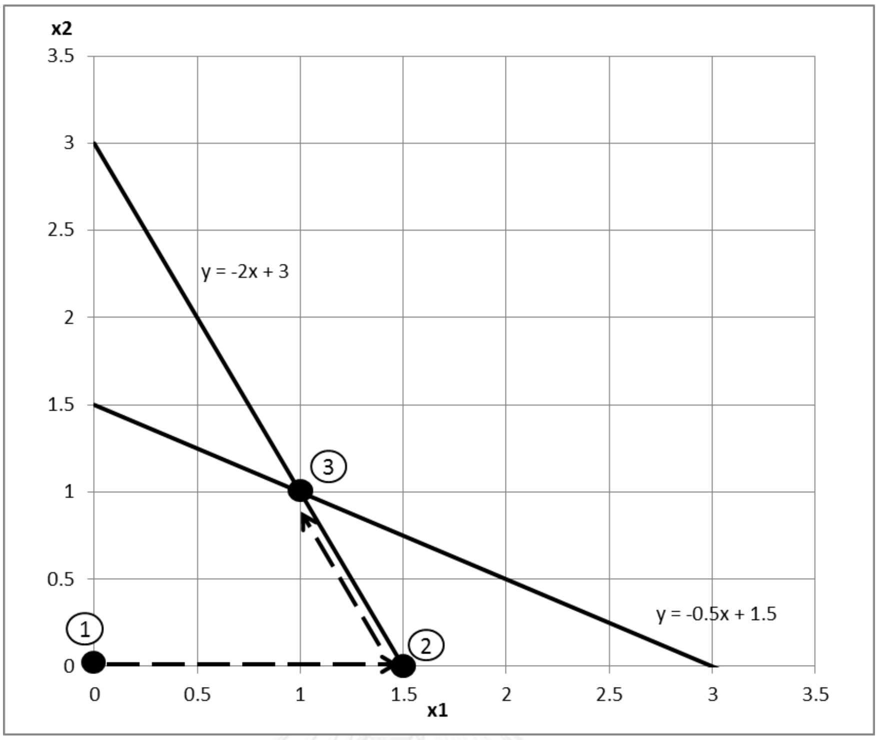

Figure 3.2 Simplex algorithm walk path for LP example

3.3 Binary variable

Binary variable is a special kind of integer variable. Binary variable can only takes the value 0 or 1. There are many practical uses of such variables. One of the example of binary variable usage is shown below. Binary variable is used to identify the minimum distances from starting point trough first, second and third places. Sets of x and n represent places and routes of this case, respectively. Table 3.1 shows distances from starting point to x_1 in the first row, and also x_1 to x_2 and x_2 to x_3. Three alternative routes are available between places to places. The constraints are only one route can be picked between each places and every place have to be visited.

Table 3.1 values of a(x,n)

a(x,n) km	n_1	n_2	n_3
x_1	1	2	4
x_2	5	2	8
x_3	7	4	6

Objective function:

$$\text{Minimize } z = b(x_1,n_1) + 2b(x_1,n_2) + 4b(x_1,n_3) + 5b(x_2,n_1) + 2b(x_2,n_2)$$

$$+ 8b(x_2,n_3) + 7b(x_3,n_1) + 4b(x_3,n_2) + 6b(x_3,n_3)$$

Where $b(x_i,n_i)$ represents binary variables to be determined

The objective function of this case is the summation of all distances multiply by their binary variables.

Subject to constraints:

$$b(x_1,n_1) + b(x_1,n_2) + b(x_1,n_3)= 1$$

$$b(x_2,n_1) + b(x_2,n_2) + b(x_2,n_3)= 1$$

$$b(x_3,n_1) + b(x_3,n_2) + b(x_3,n_3)= 1$$

Solution

Objective value z = 7 km

Table 3.2 values of b(x,n)

b(x,n)	n_1	n_2	n_3
x_1	1	0	0
x_2	0	1	0
x_3	0	1	0

According to objective function and constraints of this case, the objective value is 7 km which is the shortest distance from starting point to x_3. Table 3.2 shows the solutions of each binary variable. Route n1 is selected for traveling to x_1 and Route n_2 are selected for traveling to x_2 and also x_3. Binary variables act like switch button that identify the shortest route between places in this example.

3.4 Well Intervention

Well intervention, or generally call well work, is any operation working on oil and gas production wells. Well intervention operation is carried out with specific tools for each well work and cables which convey the tools into the wellbore. Well intervention involve with the wells since the well is initially completed until the end of its productive life. Well intervention is the operation which manages production of the well, alters state of the well and provides well diagnostics.

Typical oil and gas production well in GoT consist of many hydrocarbon zones. Bottom up perforation and comingle production from many hydrocarbon zone strategy is general practice to produce and deplete these wells. Well interventions are required since before initial perforation campaign. When the well production declining with time, well interventions are required again to perforate next hydrocarbon zone. However, fluids and particles from those wells may have form scale or any kind of wellbore restriction which needs to be cleared prior to perforation.

Another general practice of well intervention operation is grouping well works which require same type of unit to be a single well intervention campaign. This is an efficient way of utilizing units and reduce number of time that unit have to visit the platform.

3.4.1 Type of well works

Perforation is action of making holes on production tubing to establish flow path between interested formation and wellbore. Perforating involves with the well since initial completion to start oil and gas production. Batch perforation means a group of interested reservoirs inside the well are perforated to produce at the same time. This comingle production and batch perforation strategy is general practice in GoT operation. After first perforation batch deplete, well is perforated again on the next batch to maintain production and fully deplete the well. Figure 3.4 illustrates perforation in hydrocarbon wells.

Well logging is the practice of formation evaluation which evaluates physical properties of the formation and reservoir fluids. This logging normally conduct while the well was being drilled. Other than evaluation of physical properties of the formation, cement bond log (CBL) and production logging (MPLT) are the kind of logging well intervention that run after the well was completed and during production period, respectively.

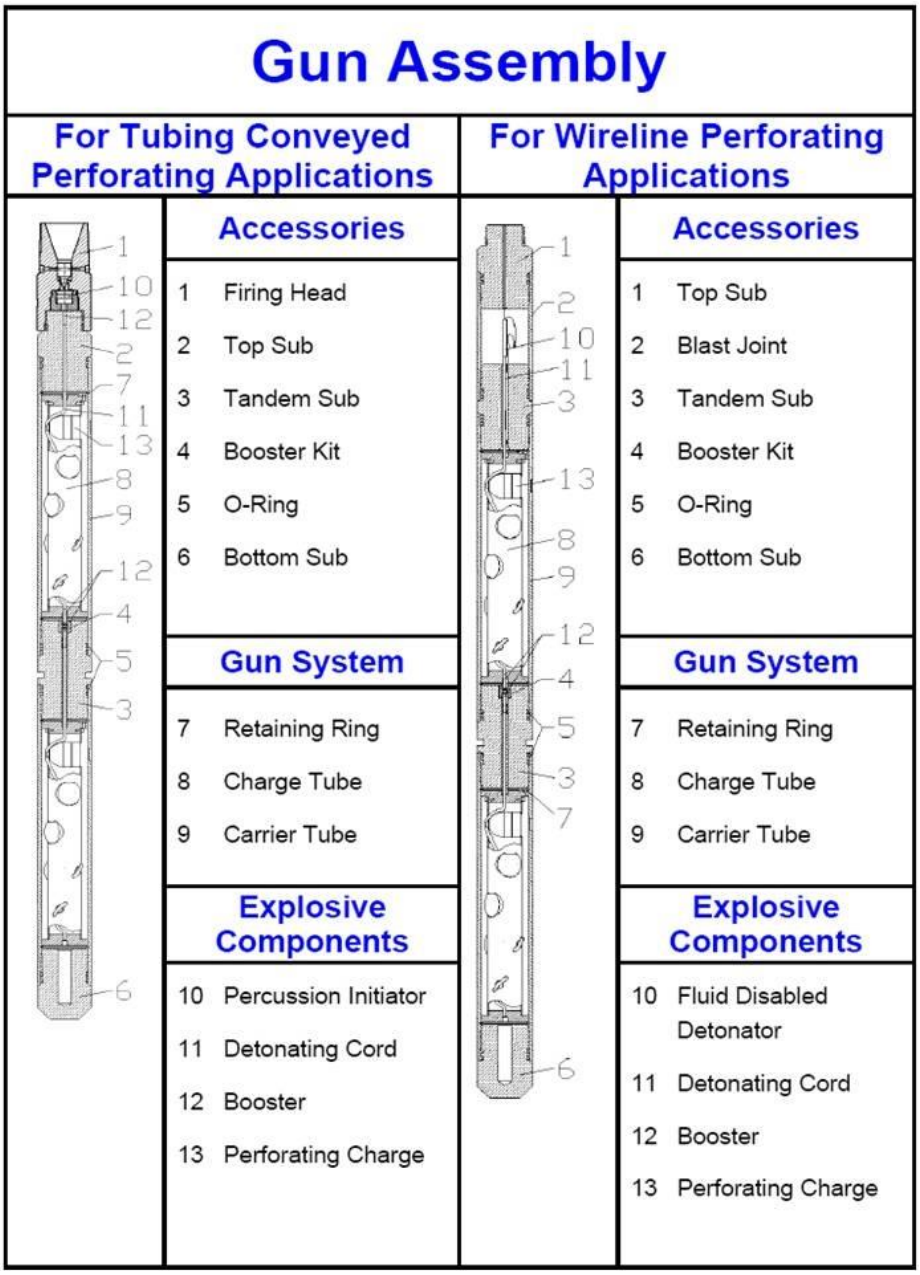

Figure 3.3 Perforation gun assembly [7]

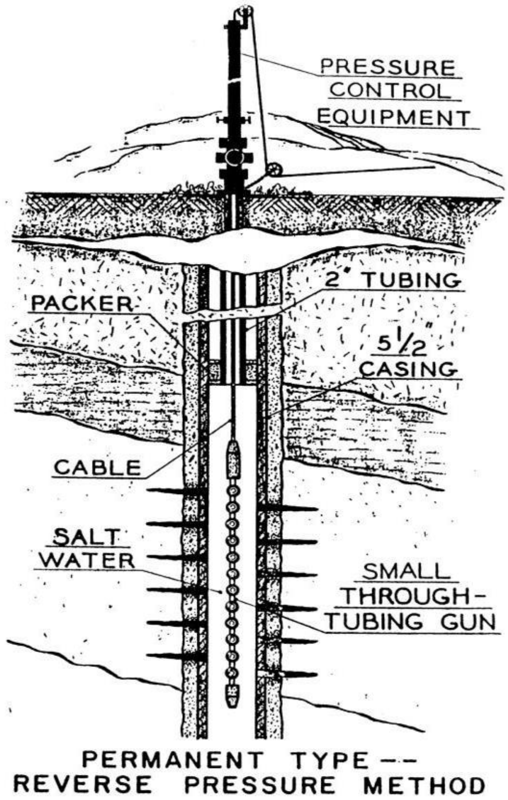

Figure 3.4 Through tubing perforation [8]

Cement bond log (CBL) is logging well work that evaluate cement bond quality. Since comingle production from many hydrocarbon zones and monobore completion is the general practice in GoT, quality of cement which indicate the quality of isolation between each sand throughout the well. The cement bond and sands isolation quality have highly impact to production management.

Production logging (MPLT) is logging well work that evaluate and identify the productivity of each perforated hydrocarbon zone during production period of well life. Typically, MPTL is used to identify water production zone in the well. That water production zone may be shut by using patches or plugs to reduce amount of water and maximize hydrocarbon production.

Patch and plug are kind of tools that are used to isolate part of the well. Usually, they are used to isolate water production zones which harm the productivity of the well. Patch is able to shut only a single formation. For example, a major water producing zone is above other hydrocarbon productive zones, patching water producing zone is a good solution for maximizing hydrocarbon production. On the other hand, plug is able to isolate all zones below the plug. It is also used to isolate bottom part of the well to prevent cross flow down to depleted zone as well.

Well preparation, or sometime specified as wellbore clean out, is the well work that is performed to identify wellbore restriction and clear those restriction out of the well. Wellbore restriction are as scale, sand and gun debris may have form during production period. These restriction restricts the well accessibility and need to be cleared prior to perforate or perform other well interventions.

3.4.2 Well intervention’s units

This literature consider three types of unit operating in GoT’s well intervention activity. These units are slick line unit, electric line unit and braided line slick line unit. They have different capabilities and suitability for well work as follow. All units come with cable and cable drum to convey tools in borehole. Generally, well works which require same type of unit are grouped to be done as a single well intervention campaign. For example, a SLU campaign on a platform may include well preparation, well bore clean out and equipment change out on many wells.

Slick line unit (SLU) is the unit with single-strand non-electric cables that can run tools in hole to perform wellbore drift run, wellbore clean out to prepare the well to be ready to start perforation. Moreover, SLU is also used for changing equipment down hole such as gas lift valves and subsurface safety valves, etc. and performing mechanical integrity test that identify casing and tubing communication. Figure 3.5 and Figure 3.6 show an example of slick line unit and slick line operation, respectively.

To recovery tools left in wellbore, well known as fishing job or fish in hole, it is required stronger units than normal SLU. Braided line slick line unit (BSLU) or fishing unit is the unit with braided non-electric cable which have enough strength to perform these fishing jobs. This BSLU is also able to perform SLU jobs as well.

Electric line units (ELU), on the other hand, are units with electric cables which normally convey perforation gun in hole to perforate the selected hydrocarbon zone.

ELU is also use running logging tools, MPLT, and pressure gauges for bottom hole pressure survey. However, both logging and BHP survey job can be run with both SLU and ELU.

Figure 3.5 Slick line unit [9]

Figure 3.6 Technician operates slink line unit [10]

Chapter 4 Mathematical optimization model

This chapter describe mathematical optimization model both with and without binary variables. The illustration of the models are shown in section 4.1 and 4.2 for without binary variables and with binary variables, respectively. In section 4.2 also shows the comparison of the result of models with difference objective functions. From section 4.3 onwards show model validation by adding unit capabilities, number of available time slots, and due date and earliest constraints. Nomenclature of the model are listed below.

Motivating example shows the simplest mathematical optimization model which has no binary variable in model. This example illustrates the basic idea of solving oil and gas operation scheduling problem by using mathematical optimization model. All units and jobs are required subjecting to preordered constraints so that the model yields smallest number of equations in the model.

Mathematical optimization model with binary variables allows unit and job sequences to shuffle in order to yield minimum solution which satisfied model's constraints. There are two types of constraint in the model which are binary variable constraints and continuous variable constraints. Binary constraints are the equation system whose objective is to solve time slot, n, for each job on a platform and a unit performing that job. Continuous variable constraints, on the other hand, are the equation system that aim to solve for time, Ts and Tf, for each job on a platform and a unit performing that job. The linkage of these constraints are binary variables which like on/off button for continuous variable constraints.

Indices

p = Platforms

j = Jobs

u = Units

n = Event points (Time slots)

Sets

P = set of platforms

J = set of jobs

U = set of units

J_p = Jobs request on a platform

U_j = Units which can perform a job

Parameters

α_{pj} = Duration requirement of job j on platform p

$\beta_{pp'}$ = Mobilization time from platform p to platform p'

H = Sufficient time horizon

sDur = Sum of jobs duration in the time horizon

Variables

$T^s(p,j,u,n)$ = Time start doing job j by unit u on platform p at event point n

$T^f(p,j,u,n)$ = Time finished job j by unit u on platform p at event point n

vp(p,j,u,n) = Binary variable that assign unit u perform job j on platform p at event point n

4.1 Motivating example and optimization model

This motivating example shows the simplest mathematical model in optimizing unit sequence schedule. This motivating example is conducted to illustrate the basic idea of mathematical optimization model in solving oil and gas operation scheduling problem. All units are subjected to preordered constraints so that the unit operation sequence is fixed and yields the smallest number of equation in the model.

Typical oil and gas production wells in GoT consist of many hydrocarbon zones. Bottom up and batch perforation strategy is general practice to produce and deplete the wells. Well interventions are required since initial perforation campaign and throughout well life. Well interventions or job requests are required for maintaining wells' conditions and perforating hydrocarbon zone to maintain their productions. Well interventions' units are the group of equipment and covey cable which are capable of performing those job requests. Units involve in this literature are slick line unit, electric line unit and braided slick line unit. These units' capabilities depend on what type of cables they have.

Slick line unit (SLU) is the unit with single-strand non-electric cables that can run tools or equipment in hole. SLU is mostly assigned to perform wellbore drift run, wellbore clean out to prepare the well to be ready to start perforation. SLU is also capable of changing equipment down hole such as gas lift valves and running memory gauges. Electric line unit (ELU) is unit with electric cable which normally convey perforation gun in hole to perforate the selected hydrocarbon zone. Braided slick line unit (BSLU) or fishing unit is the unit with braided non-electric cable which have enough strength to perform recovery of tool stuck in the well and also is able to perform normal SLU job as well.

The motivating example consists of eight types of job (j) on five well head platforms (P) which are performed by four units (u). Job requirements and sequences for each platform and jobs for each unit are shown in Table 4.1 and Table 4.2 respectively. Unit mobilization time, as shown in Table 4.3 are added when moving units from one WHP to another. Table 4.4 shows platforms and unit sequence for required job.

Table 4.1 shows job requests, sequences and durations of each platforms. P1 requests eight shifts of j1, six shifts of j3 and j4 and four shifts of j5. P2 requests eight shifts of j1, j2 and j3, and four shifts of j4, also P3 to P5. All jobs are sequential j1 to j8.Table 4.2 shows units' job capabilities. All four units have difference capabilities assigned to them. U1 can perform j1 and j5, u2 can perform j3 and j6, also u3 and u4.

Table 4.1 Job requests and sequences for each platform

Platforms	Jobs duration (shifts)							
	j1	j2	j3	j4	j5	j6	j7	j8
P1	8		6	6	4			
P2	8	8	8	4				
P3					4	1	2	
P4					6		8	
P5		6						8

Table 4.2 Units available for jobs

Units	Jobs	
u1	j1	j5
u2	j3	j6
u3	j2	j7
u4	J4	j8

Table 4.3 Mobilization time between platforms

$\beta_{pp'}$(shifts)	P1	P2	P3	P4	P5
P1		2	3	4	5
P2	2		1	2	3
P3	3	1		1	2
P4	4	2	1		1
P5	5	3	2	1	

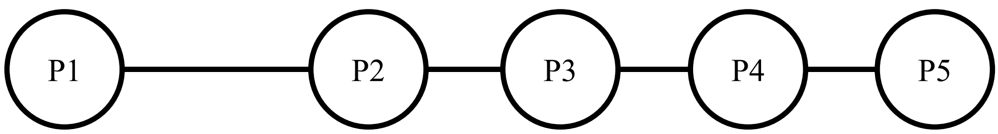

Figure 4.1 Platforms location

Table 4.3 shows unit mobilization times require of each platform to another platform. Based on platforms location shown in Figure 4.1, distances between P2 to P3, P3 to P4 and P4 to P5 are the same which require one shift to mobilize a unit. P1 is two steps away from P2, so it requires two shifts to move unit from P1 to P2, or vice versa.

Table 4.4 Unit sequence for the Motivating Example

Units	Platforms	Jobs	α_{pju}(shifts)
u1	P1	j1	4
	P2	j1	6
	P3	j5	4
	P4	j5	8
	P1	j5	8
u2	P1	j2	8
	P3	j6	1
	P2	j2	6
u3	P5	j4	8
	P2	j4	2
	P3	j7	8
	P4	j7	6
u4	P5	j8	4
	P1	j3	6
	P2	j3	8

All units are subjected to preordering WHP sequences. The sequences are ordered from top to bottom of each unit's row in Table 4.4. For example, unit u1 has to start working on WHP P1 first then move to P2 after that. Unit u2 also has to start work on job j2 on P1 first but j1 is require to be done by unit u1 prior to start j2, so u2 has to be on P1 after u1 left.

4.1.1 Constraints definition (without binary variables)

This section describes constraints definition using in optimization model. This optimization model involves only continuous variable, Ts and Tf for simplicity of solving motivating example model.

Duration constraints

This constraint is finished time equal to start time of each job on a platform by a unit added with job's duration.

$$T^f(p,j,u) = T^s(p,j,u) + \alpha_{pj} \; \forall p \in P, j \in J_p, u \in U_j$$

Sequence constraints

Sequence constraints can be splitted in to four type as shown below.

- Different tasks by the same unit on the same platform

$$T^s(p,j,u) \geq T^f(p,j',u)$$

For the same unit on the same platform, the later job, j, has to start after the earlier job, j', finished.

- Different tasks by different units on the same platform

$$T^s(p,j,u) \geq T^f(p,j',u')$$

For the same platform, the later job, j, with different unit, u, has to start after the earlier job, j', done by another unit, u'.

- Same task by the same unit on different platforms

$$T^s(p,j,u) \geq T^f(p',j,u) + \beta_{pp'}$$

For the unit, u, working on the same job, j, starting time on the next platform, p, has to be after job on previous platform, p', is done and added with mobilization time for unit movement.

- Different tasks by the same unit on different platforms

$$T^s(p,j,u) \geq T^f(p',j',u) + \beta_{pp'}$$

For the same unit, u, starting time on the next platform, p, for another job, j, has to be after job, j', on previous platform, p', is done. Mobilization time, $\beta_{pp'}$, is also add to the right side of equation to account unit's mobilization time.

Objective function

$$Minimize \sum T^f(p,j,u) = z$$

Objective function in solving this model is to minimize the sum of finished time of every job in each platform by a unit performing that job. The model is aiming to minimize the total unit utilization time and unit idle time with all job requests are done at soonest time available.

4.1.2 Optimization model's result and motivating example schedule

According to model's input and constraints mentioned above, Figure 4.2 shows the solution schedule of motivating example. All the job requests are done following the job and unit sequences in Table 4.1 and Table 4.4, respectively. The color is assigned to each unit for ease of visualization. Detail of start time and finished time are shown in Table 4.5. Sum of finished time are minimized as an objective function and its value is 365 shifts. Maximum finished time is 38 shifts which indicate time required to finish all job requests with these five available units.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p1	p1	p1	p1		p2	p2	p2	p2		p3	p3	p4	p4	p4			p1	p1							
	j1	j1	j1	j1		j1	j1	j1	j1		j5	j5	j5	j5	j5			j5	j5							
u2					p1	p1	p1						p3	p2	p2	p2	p2									
					j3	j3	j3						j6	j3	j3	j3	j3									
u3	p5	p5	p5							p2	p2	p2	p2		p3	p4	p4	p4	p4							
	j2	j2	j2							j2	j2	j2	j2		j7	j7	j7	j7	j7							
u4				p5	p5	p5	p5				p1	p1	p1					p2	p2							
				j8	j8	j8	j8				j4	j4	j4					j4	j4							

Figure 4.2 Motivating example solution

In Figure 4.2, the top row shows the timing of the schedule. In each unit's row, the first line shows WHP sequences and bottom line shows the jobs that the units are performing on each WHP. From the given sequences, P1 got the units and start the jobs earlier than other platforms. P4 requires only two units which are u1 and u2 got the units on platform later than others. This is because other WHPs have job requests that require u1 and u2 prior to perform next job with other units. While u1 and u2 are working on other WHP, u3 and u4 are available to perform their job requests on P5. According to preordered job and unit sequences, there is no further reduction in unit idle time can be done in the schedule.

Table 4.5 shows detail of motivating example result from the model. Unit and job sequences are the same as mention in Table 4.4. The additional to that is details of start time, Ts, and finished time, Tf of each job on the WHP. The objective value, TTf, is shown in the bottom of the table along with maximum finished time, computational time of CPLEX software and total unit utilization time. The total unit utilization time are sum of maximum finished time of each unit which indicate total time that units spent.

Table 4.5 Motivating Example result

Platforms	Jobs	Units	Dur	Ts	Tf
p1	j1	u1	8	0	8
	j3	u2	6	8	14
	j4	u4	6	19	25
	j5	u1	4	34	38
p2	j1	u1	8	10	18
	j2	u3	8	18	26
	j3	u2	8	26	34
	j4	u4	4	34	38
p3	j5	u1	4	19	23
	j6	u2	1	23	24
	j7	u3	2	27	29
p4	j5	u1	6	24	30
	j7	u3	8	30	38
p5	j2	u3	6	0	6
	j8	u4	8	6	14
TTf		365		Shifts	
Total units time		148		Shifts	
Max Tf		38		Shifts	
Run time		1.25		Sec	

4.2 Base case and optimization model with binary variables

This section describes optimization model with both continuous and binary variables and base case for further analysis. Base case shows optimized unit sequence schedule using the model with binary variables. All unit capabilities and job requests are from motivating example input. However, well head platform priority and unit sequences are not given to allow unit to shuffle in order to yield optimum sequences.

4.2.1 Optimization model's constraints definition

This section shows two types of constraints which are binary variable constraints and continuous variable constraints. Continuous variable constraints mostly are the same as describe in section 4.1.1 but adding binary variables which link two types of constraint to be single mathematical optimization model. To link these two types of constraints, all variables will depend on four parameters which are WHP(p), job(j), unit(u) and event point or time slot(n). Binary variable constraints is used to solve time slot, n, for each unit to perform a job on a platform. With these binary variables, the model allows unit and job sequences to shuffle in order to yield optimum solution.

Binary variable constraints

- A unit can only be at one WHP performing a job at any event point

$$\sum_{p \in P} \sum_{j \in j_p} vp(p,j,u,n) \leq 1, \forall u \in U, \forall n \in N$$

Every units can only be at one place and also only one job they can perform at a time. This constraint is the sum of binary variable of a unit performing jobs at every WHP that has to be less than 1 at any event point.

- Only one unit can be at a WHP performing a job at any event point

$$\sum_{u_j} \sum_{j_p} vp(p,j,u,n) \leq 1, \quad \forall p \in P, \forall n \in N$$

Only one unit can be on the WHP performing a job at a time. This constraint is the sum of binary variable of every unit on a WHP that has to be less than 1 at any event point.

- Job sequence constraint, a following job has to be done at later event point

$$vp(p,j,u,n) \leq \sum_{u'} \sum_{n'} vp(p,j',u',n'), \quad \forall P, \forall\, j,j' \in j_p, \forall\, u \in u_j, \forall\, u' \in u_{j'}, \forall\, n' < n$$

This constraint is prioritization of job sequence which makes lower priority job done later than the higher priority one. This constraint is the sum of binary variable of every lower priority jobs on a WHP that has to be less than binary variable of higher priority job.

- All jobs request need to be done by a unit at any event point

$$\sum_{u_j}\sum_{n} vp(p,j,u,n) = 1, \forall P, \forall j \in j_p$$

To make all the jobs request done within the interested time horizon, all jobs binary variables on every WHP have to be equal to 1 at any event point.

Continuous variable constraints

Continuous variable constraints and their definition are mostly the same as mention in section 4.1.1. The only difference is that binary variables are added to every constraints. This is the linkage between binary and continuous constraints. Binary variable acts like on/off switch for continuous constraints while solving for optimum solution.

Duration constraints

This constraint is finished time equal to start time of each job on a platform by a unit added with job's duration and binary variable term. Binary variable term consist of binary variable vp(p,j,u,n) deducted with 1 and multiply by value of time horizon, H. This binary variable term is used to control the value of finished time Tf. If the job j happened on WHP p by unit u on event point n, vp(p,j,u,n) will equal to 1. That will make binary term to be 0 and this duration constraint will be the same as mention in section 4.1.1. Oppositely, if vp(p,j,u,n) is equal to 0, binary term will be bigger than any start time Ts. As Tf is positive variable, this will make Tf to be zero instead of negative value.

$$T^f(p,j,u,n) = T^s(p,j,u,n) + \alpha_{pj} + H(vp(p,j,u,n) - 1), \qquad \forall p \in P, j \in J_p, u \in U_j$$

Sequence constraints

- Different jobs on the same platform

$$T^s(p,j',u',n') \geq T^s(p,j,u,n) + \alpha_{pj} + H(vp(p,j,u,n) - 1),$$
$$\forall p \in P, j, j' \in J_p, u \in U_j, u' \in U_j,$$

This constraint indicates that on same platform, the later job, j, has to start after the earlier job, j', finished. Units which can perform these jobs can be either be the same unit or different units.

- Same unit on different platforms

$$T^s(p',j',u,n') \geq T^s(p,j,u,n) + \alpha_{pj} + H(vp(p,j,u,n) - 1) + \beta_{pp'},$$
$$\forall p,p' \in P, j \in J_p, j' \in J_{p'}, u \in U_j, U_j,$$

For the same unit, starting time on the next platform, p, has to be after the job on previous platform, p', is done. Mobilization time, $\beta_{pp'}$, is also add to the right side of equation to account unit's mobilization time. Jobs which can be done with unit u on both WHPs can either be the same job or different jobs.

4.2.2 Objective functions

This section describes three different objective functions which will be used in the following section. The details of each objective functions are shown below. In the following section, objective functions will be varied and compare results to identify the most suitable objective function for field application. Conclusion of objective function are described in the end of this chapter.

- First objective function, TTf, is summation of finished time, Tf, of every jobs in time horizon. Minimizing this objective function yields the schedule that all the jobs start as soon as possible without unit being idle.

$$Minimize \sum_{p \in P} \sum_{j \in J_p} \sum_{u \in U_j} \sum_{n \in N} T^f(p,j,u,n) \quad = TTf$$

- Second objective function, mTTf, is summation of maximum finished time of each units in time horizon. This objective function yields the schedule that has minimum unit utilization time

$$Minimize \sum_{p \in P} \sum_{j \in J_p} \sum_{u \in U_j} \sum_{n \in N} Max(T^f(p,j,u,n)) \quad = mTTf$$

- The third objective function, TTf+mTTf, is the combination of the first two objective functions above. It has the two advantages that both starting jobs soonest possible while minimizing total unit time. However, because of the summation of two objective functions, the solution sometimes does not either yield the minimum of total unit utilization time or total time finished of all the jobs.

$$Minimize \sum_{p \in P} \sum_{j \in J_p} \sum_{u \in U_j} \sum_{n \in N} T^f(p,j,u,n) \; + \sum_{p \in P} \sum_{j \in J_p} \sum_{u \in U_j} \sum_{n \in N} Max(T^f(p,j,u,n))$$
$$= TTf + mTTf$$

4.2.3 Base case schedule

Base case shows the optimized unit sequence schedule solving by the optimization model with TTf as an objective function. Model's input are the same as motivating example but well head platform priority and unit sequences are not given to allow unit to shuffle in order to yield optimum sequences. Figure 4.3 shows the solution schedule of this case.

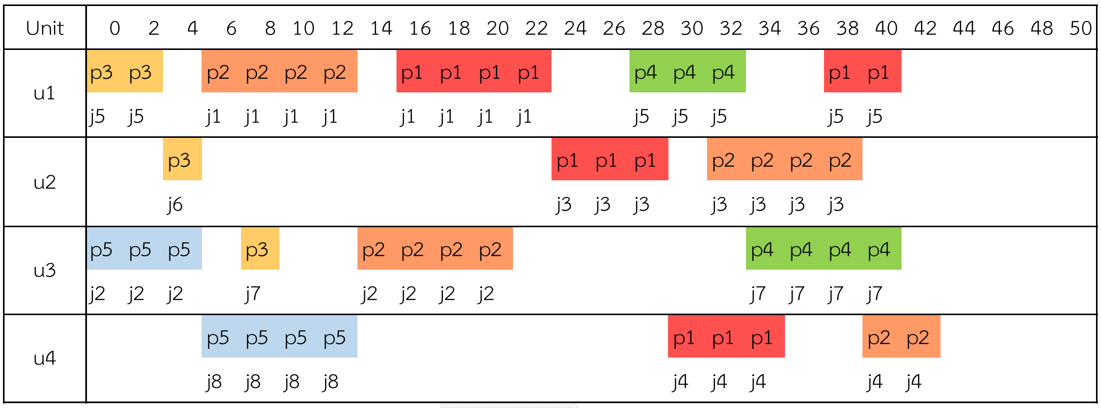

Figure 4.3 Base case solution schedule

This case result shows different solutions from motivating example because the unit sequence are not subjected to preordering constraints. Both binary variables and constraints allow units to shuffle their work sequences in order to yield the minimum solution of given objective function. Since TTf is an objective function, the solution is changed to the schedule that has minimum value of summation of all finished time which is 357 shifts and computational time is 1.5 seconds. Table 4.6 shows detail results, start time (Ts) and finished time (Tf), of base case schedule.

With the effect of summation of objective function, shorter jobs are moved to the front of the schedule. Job requests in p3 has been suggested to start first. Units u3 and u4 which are available start doing jobs on P5 first same as pervious schedule. Other jobs are placed on the later part of the schedule. However, if performing small jobs first is not preferred, making every job durations to be relatively the same magnitude or adding due date constraints will help reduce this summation effect.

Table 4.6 Base case result

Platforms	Jobs	Units	Dur	Ts	Tf
p1	j1	u1	8	15	23
	j3	u2	6	23	29
	j4	u4	6	29	35
	j5	u1	4	37	41
p2	j1	u1	8	5	13
	j2	u3	8	13	21
	j3	u2	8	31	39
	j4	u4	4	39	43
p3	j5	u1	4	0	4
	j6	u2	1	4	5
	j7	u3	2	8	10
p4	j5	u1	6	27	33
	j7	u3	8	33	41
p5	j2	u3	6	0	6
	j8	u4	8	6	14
TTf		357		Shifts	
Total units time		164		Shifts	
Max Tf		43		Shifts	
Run time		1.51		Sec	

4.2.4 Base case with different objective functions

This section shows the comparison of model results with different objective functions. The objective of this variation is to identify the most suitable objective function which will be used in the field application chapter, Chapter 5. In order to identify the most suitable one, objective functions are varied with other model's input in the following section as well.

With second and third objective functions which are mTTf and TTf+mTTf, the solution schedules are exactly the same. The solution schedule is shown in Figure 4.4. As objective function changed, objective values are now change to total unit time and the sum of TTF and total unit time which are column 6 and sum of column 4 and 6 in Table 4.7, respectively. The sum of unit time are changed to minimum value to satisfy new objective functions. However, computational time is increase to 2.5 seconds with the third objection as shown in the last column of Table 4.7.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p1	p1	p1	p1		p2	p2	p2	p2		p3	p3	p4	p4	p4			p1	p1							
	j1	j1	j1	j1		j1	j1	j1	j1		j5	j5	j5	j5	j5			j5	j5							
u2					p1	p1	p1						p3	p2	p2	p2	p2									
					j3	j3	j3						j6	j3	j3	j3	j3									
u3	p5	p5	p5							p2	p2	p2	p2		p3	p4	p4	p4	p4							
	j2	j2	j2							j2	j2	j2	j2		j7	j7	j7	j7	j7							
u4				p5	p5	p5	p5				p1	p1	p1					p2	p2							
				j8	j8	j8	j8				j4	j4	j4					j4	j4							

Figure 4.4 Base case with third objective function solution schedule

Table 4.7 shows the comparison summary of different objective functions of base case. The table consist of seven column which are comparison cases, number of event point used in the model, value of TTf, maximum finished time, total unit utilization time and computational time of CPLEX software. As objective function changed objective value changed and also the solution schedules. TTf in column 4 of Table 4.7 is the objective value of the first objective function which has value of 357 shifts for base case. After change objective function to mTTf, objective value changed to total unit time in column 6 of the same table which is 148 shifts compare to 168 shifts in the first case. This also happened to the model with the third objective function, TTf+mTTf, as well. Objective value of this case is the sum of column 4 and 6 in the table which is 513 shifts compare to 521 shifts in the first case.

Table 4.7 Result summary of Base case with difference object functions

Cases	Objective function	N	TTF (Shifts)	Max Tf (Shifts)	Total unit time (Shifts)	Run time (seconds)
Base case	TTf	5	357	43	164	1.51
Base case	mTTf	5	365	38	148	1.56
Base case	TTf+mTTf	5	365	38	148	2.59

4.3 Units similarity

This section, units' capabilities are added and makes u1, u2 and u3, u4 to be able to do the same jobs. The added units' capabilities are shown in the Table 4.8. As mention previously, oil and gas production field typically has many well intervention units running well intervention operations. Units' capabilities are indicator of the unit type. Adding units' capabilities make the model more realistic and applicable for field schedule optimization. Furthermore, this added units' capabilities also emphasize the identification of suitable objective function.

As units are similar, different units with the same capabilities are able to perform the same job request. This leads the duplication of the possible solution from the model. Binary variables which acting like switch buttons are playing major role of optimizing the schedule. The following section illustrate and compare the result of the model with different objective functions after units' capabilities added.

Table 4.8 Units capabilities

Units	Jobs			
u1	j1	j3	j5	j6
u2	j1	j3	j5	j6
u3	j2	j4	j7	j8
u4	j2	j4	j7	j8

4.3.1 Base case with units similar

According to base case in section 4.2, TTf is the objective function, more units' capabilities are added to model which resulted in reduction of total unit operation time and jobs request can be done in shorter period. The solution schedule of this case is shown in Figure 4.5. Computational time increases to 5 minutes because of wider model's search space from unit similarity. Unit similarity widen the model's search space from the duplication of the solution due to different units are able to do the same job at the same time and still yields the same outcome. The detail results and comparison of different objective function cases are in Table 4.9.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p2	p2	p2	p2		p1	p1	p1	p1	p1	p1	p1				p1	p1									
	j1	j1	j1	j1		j1	j1	j1	j1	j3	j3	j3				j5	j5									
u2	p3	p3	p3	p4	p4	p4			p2	p2	p2	p2														
	j5	j5	j6	j5	j5	j5			j3	j3	j3	j3														
u3				p3	p2	p2	p2	p2					p1	p1	p1											
				j7	j2	j2	j2	j2					j4	j4	j4											
u4	p5	p5	p5	p5	p5	p5	p5		p4	p4	p4	p4		p2	p2											
	j2	j2	j2	j8	j8	j8	j8		j7	j7	j7	j7		j4	j4											

Figure 4.5 Base case with unit similar schedule

4.3.2 Second objective function with units similar

The second objective function, mTTf, guides the model to minimize total unit operation time which is objective value in this case. Total unit operation time is changed to the minimum value which is 107 shifts compare to 117 shifts in section 4.3.1. Objective value of this case is shown in Table 4.9. However, the solution schedule has significantly changed to unrealistic solution. This is because objective function only guide the model to minimize the summation of last finished time of each unit regardless of unit release date. Objective value of this case is 107 shifts which are from summation of 5 shifts, 48 shifts, 47 shifts and 7 shifts for unit1, unit2, unit3, and unit4, respectively.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3 j5	p3 j5	p3 j6																							
u2	p4 j5	p4 j5	p4 j5		p2 j1	p2 j1	p2 j1	p2 j1		p1 j1	p1 j1	p1 j1	p1 j1	p1 j3	p1 j3	p1 j3		p2 j3	p2 j3	p2 j3	p2 j3		p1 j5	p1 j5		
u3	p5 j2	p5 j2	p5 j2	p5 j8	p5 j8	p5 j8	p5 j8		p4 j7	p4 j7	p4 j7	p4 j7		p2 j2	p2 j2	p2 j2	p2 j2		p1 j4	p1 j4	p1 j4		p2 j4	p2 j4		
u4				p3 j7																						

Figure 4.6 Units similar with mTTf objective function

Figure 4.6 shows the result in this case, u1 and u3 are released at the 5th shift and left only two units perform the rest of job requests. Consequently, all job requests are done with longer period, maximum Tf increases to 48 shifts. Moreover, the platforms owner want their jobs request to be done at the soonest possible. Accordingly, the result is invalid even though the objective function is satisfied.

4.3.3 Third objective function with units similar

With the third objective function, TTf+mTTf, all the job requests are done at soonest possible and slightly faster than with first objective function in section 4.3.1. Total unit operation time is slightly reduced compare to the first case. However, computational time is significantly increases to 17 minutes due to more complication of objective function calculation. Figure 4.7 shows the solution schedule of section 4.3.3.

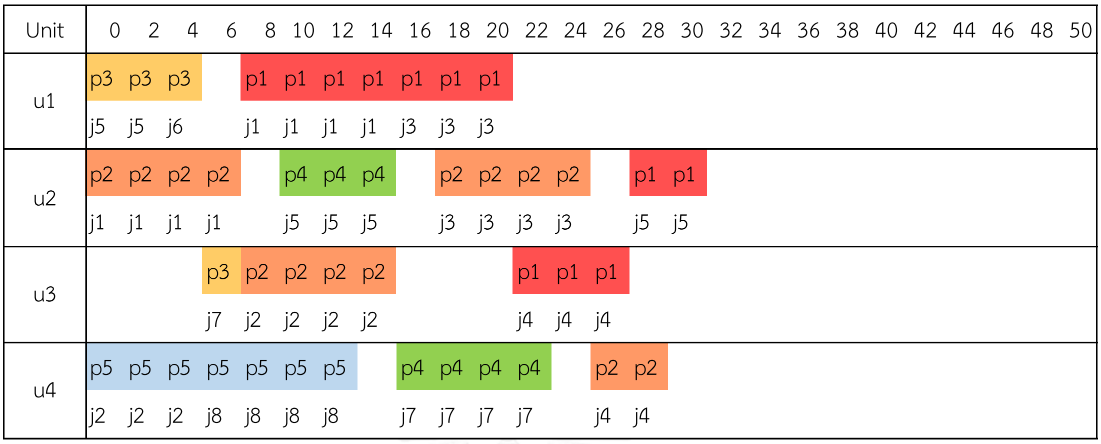

Figure 4.7 Units similar with third objective function

Table 4.9 Unit similar cases result summary

Cases	Objective function	n	TTf (Shifts)	Max Tf (Shifts)	Total unit time (Shifts)	Run time (minutes)
Unit similar	TTf	5	254	34	117	5.33
Unit similar	mTTf	5	350	48	107	15.07
Unit similar	TTf+mTTf	5	254	32	112	17.03

Table 4.9 shows the comparison of unit similar cases with different objective functions. Unit similar case with the third objective function, TTf+mTTf, has minimized the summation of total finished time, TTf, and total unit time which is 366 shifts in this case. The result has the minimum value of TTf at 254 shifts and also reduce total unit time to 112 shifts compare to 117 shifts from first objective function.

4.4 Number event points

This section illustrates how the number of event points affect the model and result. Event point or time slot, n, is an unknown input of the mathematical optimization model of this literature. It is required a few iteration in order to get an appropriate number of event points.

CPLEX optimizer software is able to automatically relax constraints when the number of event points are not enough to satisfy all model's constraints but it will lead to invalid result. From this reason, the model is required to increase number of event points. The solution will be valid when all the constraints are satisfied.

With more event points, the model is allowed to find new minimum solution from wider search space. However, the wider search space increases computational time significantly. In some cases, this leads to the computer's memory run out before reaching the solution. The following sections vary number of event point of cases in section 4.2 and 4.3.

4.4.1 Base case with 6n

When increasing more event points to Base case from 5n to 6n, results show the same solution schedule as in section 4.2 for all three cases. The results in Base case, even with three difference objective functions, are already at global minimum of the search space of each case. However, computational times are increased in every cases especially the model with the third objective function as shown in Table 4.10.

Table 4.10 Base case with 6n result summary

Cases	Objective function	n	TTF (Shifts)	Max Tf (Shifts)	Total unit time (Shifts)	Run time (minutes)
Base case	TTf	6	357	43	164	6.75
Base case	mTTf	6	378	38	148	4.64
Base case	TTf+mTTf	6	365	38	148	12.64

Table 4.10 shows detail result of base case with added event point and different objective functions. The results are the same as shown in Table 4.7 but all computational times are increased.

4.4.2 Base case with unit similar and more event points

The search space of Base case with units similar in section 4.3.1 is increased with added event point from 5n to 6n and 7n. Figure 4.8 shows the solution schedule of model with first objective function, TTf, and added event points. The results from both cases show the same solution schedule which have changed to the next minimum point of model's search space. However, the objective value remains the same as 5n case. Moreover, computational time is increased significantly from 5 minutes to 45 minutes for 6n case and over 4 hours for 7n case compare to 5n case as shown in Table 4.11.

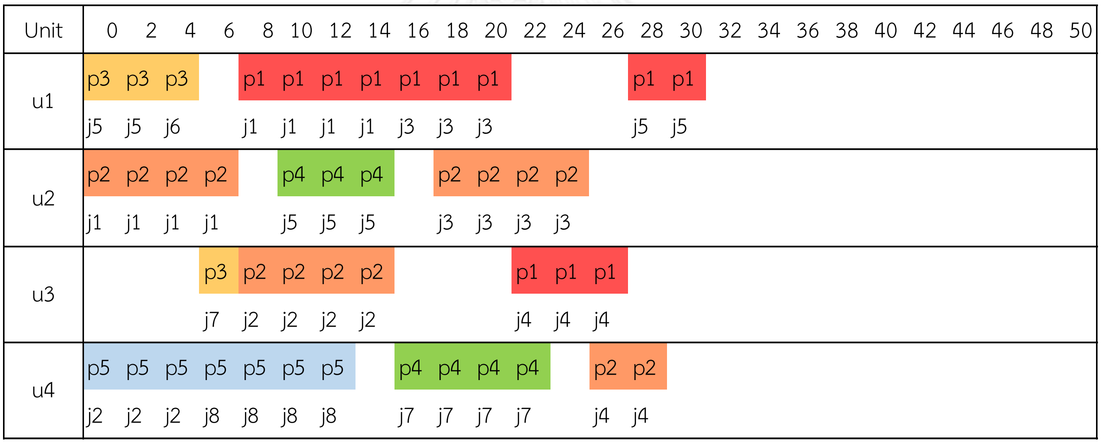

Figure 4.8 Units similar with TTf and 6n solution schedule

Solution schedule in Figure 4.8 is slightly different in from Figure 4.5. Unit u1 is assigned to start performing job requests on p3 first. Unit u2 is assigned to perform job on p2 first. Consequently, jobs on p1 is accelerated and job in p4 is delayed.

Table 4.11 Units similar with 6n and 7n result summary

Cases	Objective function	n	TTf (Shifts)	Max Tf (Shifts)	Total unit time (Shifts)	Run time (minutes)
Unit similar	TTf	6	254	32	116	45
Unit similar	TTf	7	254	32	116	251

Unit	0	1	2	3	4	5
u1	p2 j1		p1 j1	p1 j3		p1 j5
u2	p3 j5	p3 j6		p4 j5	p2 j3	
u3			p3 j7	p2 j2	p1 j4	
u4	p5 j2		p5 j8		p4 j7	p2 j4

Unit	0	1	2	3	4	5	6
u1	p3 j5	p3 j6	p1 j1		p1 j3		p1 j5
u2	p2 j1		p4 j5			p2 j3	
u3			p3 j7		p2 j2	p1 j4	
u4	p5 j2	p5 j8		p4 j7			p2 j4

Unit	0	1	2	3	4	5	6	7
u1	p3 j5	p3 j6	p1 j1			p1 j3		p1 j5
u2	p2 j1	p4 j5				p2 j3		
u3			p3 j7	p2 j2			p1 j4	
u4	p5 j2	p5 j8				p4 j7		p2 j4

Figure 4.9 Unit's jobs in each time slot for 5n (left), 6n (middle) and 7n (right)

Figure 4.9 illustrates how added event points change the solution schedule of the model in section 4.3.1. It shows time slots that each unit are assigned to perform jobs. On the top of Figure 4.9 is the event point slots. More event points mean units have more time slots available for mobilizing units. As shown in Figure 4.9, u1 do five jobs with 6n compare to four jobs with 5n, which lead to new solution. Assigned time slots for some jobs are changed after increasing another event points to 7n but job sequences remain the same. However, job sequences remain the same which yield the same solution as 6n case. Moreover, the objective value, TTf, remains the same at 254 shifts for all cases. This means the model is already at global minimum since with 5n event points.

4.5 Due date and earliest constraints

Two equations below are due date and earliest constraints of each platform which represent platform priority. All of the job requests on each platform are not allowed to start before platform earliest and required to finish before due date. These two constraints reflect reality of oil and gas operations. Some of well work requests are required to have fixed due date such as jobs with safety concern and gas production related. Earliest date constraint reflects platform readiness and availability. Sometime the platform is not ready for well intervention operation due to conflict with another field operation and will be ready after a specific date.

$$T^f(p,j,u,n) \geq Due(p), \qquad \forall p, \in P, j \in J_p, u \in U_j$$

$$T^s(p,j,u,n) \geq Earliest(p), \qquad \forall p, \in P, j \in J_p, u \in U_j$$

Due date constraint is used to ensure all jobs on each WHP are done before their due dates. Earliest constraint is used to ensure all jobs on any WHP start later than the earliest date of the platform. These constraints also restrict the search space of the optimization model such that the run time is less with the same amount of job requests. Furthermore, cases that computer's memory run out before model reaches the solution, such as available time slots increase case, also reduce compare to the cases without these constraints. From these restricted search space, the solutions will not change significantly when the number of event points change

4.5.1. Base case with unit similar and due date constraints

Due date and earliest constraint in the Table 4.12 below are applied in the models in section 4.3. By varying objective functions and numbers of event point, the results are shown in Table 4.13.

Due date constraint reduces the variation of the solution schedule, first and third objective function give the same solution. Moreover, less deviation of solution with second objective function is observed compare with the cases without due date constraints. The solution schedules of these cases are shown in Figure 4.10 and Figure 4.11, respectively. Model computational time also decreases from the smaller search space.

Table 4.12 Due date and earliest constraints

	P1	P2	P3	P4	P5
Due date (Shifts)	25	30	100	100	100
Earliest (Shifts)	0	0	0	0	0

Moreover, these constraints also reduce the variation in solution schedule when the numbers of event points increase. All of objective function cases with 6n yield the same solution schedule as with 5n as shown in summary Table 4.13.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p2	p2	p2	p2		p3	p3		p2	p2	p2	p2		p4	p4	p4										
	j1	j1	j1	j1		j5	j5		j3	j3	j3	j3		j5	j5	j5										
u2	p1	p1	p1	p1	p1	p1	p1				p1	p1														
	j1	j1	j1	j1	j3	j3	j3				j5	j5														
u3	p5	p5	p5					p1	p1	p1			p2	p2												
	j2	j2	j2					j4	j4	j4			j4	j4												
u4					p2	p2	p2	p2		p3		p5	p5	p5	p5		p4	p4	p4	p4						
					j2	j2	j2	j2		j7		j8	j8	j8	j8		j7	j7	j7	j7						

Figure 4.10 Units similar with TTf and due date constraint solution schedule.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p2	p2	p2	p2		p4	p4	p4			p1	p1														
	j1	j1	j1	j1		j5	j5	j5			j5	j5														
u2	p1	p1	p1	p1	p1	p1	p1		p2	p2	p2	p2		p3	p3											
	j1	j1	j1	j1	j3	j3	j3		j3	j3	j3	j3		j5	j5											
u3	p5	p5	p5					p1	p1	p1			p2	p2		p3										
	j2	j2	j2					j4	j4	j4			j4	j4		j7										
u4					p2	p2	p2	p2		p4	p4	p4	p4		p5	p5	p5	p5								
					j2	j2	j2	j2		j7	j7	j7	j7		j8	j8	j8	j8								

Figure 4.11 Units similar with mTTf and due date solution schedule

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p2	p2	p2	p2		p4	p4	p4			p1	p1														
	j1	j1	j1	j1		j5	j5	j5			j5	j5														
u2	p1	p1	p1	p1	p1	p1	p1		p2	p2	p2	p2		p3	p3											
	j1	j1	j1	j1	j3	j3	j3		j3	j3	j3	j3		j5	j5											
u3	p5	p5	p5					p1	p1	p1			p2	p2												
	j2	j2	j2					j4	j4	j4			j4	j4												
u4					p2	p2	p2	p2		p4	p4	p4	p4		p5	p5	p5	p5		p3						
					j2	j2	j2	j2		j7	j7	j7	j7		j8	j8	j8	j8		j7						

Figure 4.12 Units similar with mTTf , 6n and due date solution schedule

Table 4.13 Due date and earliest constraints cases result summary

Cases	Objective function	n	TTf (Shifts)	Max Tf (Shifts)	Total unit time (Shifts)	Run time (min : sec)
Unit same, due date	TTf	5	295	40	124	0 : 0.41
Unit same, due date	mTTf	5	316	35	121	0 : 1.07
Unit same, due date	TTf+mTTf	5	295	40	124	0 : 1.12
Unit same, due date	TTf	6	295	40	124	21 : 56
Unit same, due date	mTTf	6	323	39	121	13 : 07
Unit same, due date	TTf+mTTf	6	295	40	124	36 : 31

Table 4.13 shows the comparison of unit similar cases with different objective functions, number of event points and include due date constraints. As mention previously in section 4.4, adding more event point may result in further optimization due to wider search space. However, there is no further optimization with added event points in any of these cases above. Even though the cases with mTTf have some slightly different, the objective values are still at the minimum point, 121 shifts of total unit operation time. As mention in section 4.3.2, there is no unit release date constraint to control unit release date in the model. Both Figure 4.11 and Figure 4.12 show solution schedule which are able to achieve 121 shifts of total unit operational time.

4.6 Mathematical optimization model summary

This section summarizes model validation by changing objective functions, unit capabilities, number of event point and due date constraints mentioned in previous sections.

First objective function, TTf, is summation of time finish of every jobs in time horizon. Minimizing this objective function yields the schedule that all the jobs start as soon as possible without unit idle if the platform is available. However, the minimization of sum may not give the minimum total unit utilization time and the may give different solution when event points changed, as shown in section 4.4.2.

Second objective function, mTTf, is summation of maximum time finish of each platforms in time horizon. This objective function yields the schedule that has minimum unit utilization time and the solution does not vary much with event point changes. However, there is a chance that unit is left idle even platform is available because the objective function does not make all the jobs start at the soonest possible, as shown in section 4.3.2.

Last objective function, TTf+mTTf, is the combination of the first two. This objective function yields the schedule that is in between those two objective functions. It has taken the two advantages of starting jobs soonest possible while minimizing the total unit time. However, because of the summation of two objective functions, the solution sometimes does not either yield the minimum of total unit utilization time or total finished time of all the jobs.

To be more into real oil and gas field operations, unit capabilities were added to assign unit 1 and 2 to be similar unit type and unit 3 and 4 to be another type of units. By adding more similarity to units resulted in computational time increased. Due to the fact that possible outcome of the model increased from these additional unit capabilities.

The event point is the time slot that the model allows units to move to match the jobs required on platform. Increasing number of event points expands the search space of the model and makes the computational time increase significantly. Moreover, solution may change to next minimum point from the wider search space.

Due date and earliest constraints are the constraints that restrict the search and reduce the variation of solution when the input, objective function and number of event points, are changed. With the restricted search space, computational time is reduced compare to the case with same input but does not have these constraints. However, the solution may change according to these constraints.

Chapter 5 Field case and sensitivity analysis

Typical oil and gas production wells in GoT consist of many hydrocarbon zones. Bottom up and batch perforation strategy is general practice to produce and deplete these wells. Well interventions are required since before initial perforation campaign. When the well production declining with time, well interventions are required again to perforate next hydrocarbon zone. However, fluids from those wells may have form scale or any kind of wellbore restriction which needs to be cleared prior to perforation. This thesis involves with three types of well intervention units which are slick line units, electric line units and braided slick line units. Well intervention types and units are described in chapter 3.

This chapter shows the application of the mathematical optimization model described in chapter 4 to oil and gas production field case in GoT. The third objective function, TTf+mTTf, is the only objective function in the field mathematical optimization model. The smallest number of event point will be used throughout the sensitivity analysis. Sensitivity analysis is performed from section 5.2 onwards to quantify impact of unit abilities, number of units, due date constraints and jobs duration to field unit operation sequences.

5.1 Field case and optimization model input

This section illustrates example of field case of oil and gas production field in Gulf of Thailand. Field case covers 45 days of well intervention operations and consists of eight WHPs, two SLUs, a braided line SLU and two ELUs. All job requests are categorized into five types as shown in Table 5.1. In field optimization model, only j5 which is ELU’s job that require j4 which is SLU’s job to prepare the well prior to ELU start the job, other jobs are allow to shuffle without dependent job.

Table 5.1 Field jobs definition and job model number

#j	Job definition
j1	Fishing
j2	Safety, Mechanical integrity test (MIT), subsurface safety valve change out
j3	Perforation, MPLT logging, set plug/patch, BHP survey, without SLU well preparation
j4	Well preparation, pull/set plug, wellbore clean out, GLV change out
j5	Perforation, MPLT logging, set plug/patch, BHP survey, require SLU well preparation

Table 5.2 shows unit types and their abilities to perform job requests. Table 5.3 shows platforms' job request and job durations. Unit mobilization time is assumed to be 1 day for every unit movement as shown in Table 5.4.

Table 5.2 Field units and abilities

#u	Unit	Jobs		
u1	SLU	j2	j4	
u2	SLU	j2	j4	
u3	BSLU	j1	j2	j4
u4	ELU	j3	j5	
u5	ELU	j3	j5	

Table 5.3 shows job requests and duration of each platforms in this interested 45 days period. P1 requests 8 days of perforation campaign which required well preparation jobs 13 days prior to perforation. P2 has ELU working on perforation and MPLT which need another 14 days to finish the campaign. P2 also has been scheduled fishing campaign for 7 days to remove the tool stuck in hole. P3 has same requests as P1 but with shorter time. P4 has BSLU working on fishing job on the last well which need another 4 days. P4 also requests another 3 jobs which are 6 days of perforation,

6 days of well preparation and 12 days of MIT job. P5 requests 9 days of perforation and 5 days of MPLT survey. P6 has SLU working on well preparation for another 14 days prior to start 14 days of perforation campaign. P7 requests 25 days of well preparation. P8 requests fishing campaign for 2 wells using 10 days period.

Table 5.3 Field jobs request for each platform

Platforms	Jobs duration (days)				
	j1	j2	j3	j4	j5
P1				13	8
P2	7		14		
P3				7	8
P4	4	12		6	6
P5			14		
P6				14	14
P7				25	
P8	10				

Table 5.4 Field unit mobilization time between platforms

$\beta_{pp'}$(days)	P1	P2	P3	P4	P5	P6	P7	P8
P1		1	1	1	1	1	1	1
P2	1		1	1	1	1	1	1
P3	1	1		1	1	1	1	1
P4	1	1	1		1	1	1	1
P5	1	1	1	1		1	1	1
P6	1	1	1	1	1		1	1
P7	1	1	1	1	1	1		1
P8	1	1	1	1	1	1	1	

Unit mobilization time are 1 days for every unit movement based on an assumption that boats are available within this interested 45 days period, as shown in Table 5.4.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3	p3	p3	p3	p1	p1	p1	p1	p1	p1	p1															
	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4															
u2	p6	p6	p6	p6	p6	p6	p6		p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7						
	j4	j4	j4	j4	j4	j4	j4		j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4						
u3	p4	p4	p4	p4	p4		p8	p8	p8	p8	p8	p2	p2	p2	p2		p4	p4	p4	p4	p4	p4				
	j1	j1	j4	j4	j4		j1	j1	j1	j1	j1	j1	j1	j1	j1		j2	j2	j2	j2	j2	j2				
u4	p2	p2	p2	p2	p2	p2	p2		p3	p3	p3	p3	p4	p4	p4		p1	p1	p1	p1						
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5		j5	j5	j5	j5						
u5	p5	p5	p5	p5	p5	p5	p5		p6	p6	p6	p6	p6	p6	p6											
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5											

Figure 5.1 Field case unit sequence schedule

Figure 5.1 shows field unit sequence schedule. There are three units that have not completed their job from previous periods. Those jobs are fishing, j1, at p4, perforation, j3, at p2 and well preparation, j4, at p6 which are require to be done by unit 3, unit4 and unit2, respectively, before units released from these WHPs. Moreover, unit1 and unit5 have been scheduled to be maintenance on day 35th of this 45 days period. BSLU, unit3, campaign at p4 was split into two due to the requirement of perforation, j5, on p4 within this 45 days period which make the MIT job, j2, done by unit3 later. Jobs which were not mention can be done without any specific constraints.

5.2 Optimize field case with math model without any due date constraints

This section, field case has been put into optimization model to identify field unit sequence optimization opportunities. Figure 5.2 shows result of field case from the model.

The schedule from model are mostly the same as field schedule. Three jobs that have not finished from previous are planned to continue with the same units. Main difference is MIT job on p4 is moved to be done with u1, then u1 will be released from the field for maintenance. Model suggests to continue well preparation jobs on p4 after fishing job done. Moreover perforation job, j5, on p4 was accelerated by 8 days. P6 perforation was deferred to be done with u4 because u5 has maintenance schedule on 35th day.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3	p3	p3	p3	p1	p1	p1	p1	p1	p1	p1	p4	p4	p4	p4	p4	p4									
	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j2	j2	j2	j2	j2	j2									
u2	p6	p6	p6	p6	p6	p6	p6		p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7						
	j4	j4	j4	j4	j4	j4	j4		j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4						
u3	p4	p4	p4	p4	p4		p8	p8	p8	p8	p8	p2	p2	p2	p2											
	j1	j1	j4	j4	j4		j1	j1	j1	j1	j1	j1	j1	j1	j1											
u4	p2	p2	p2	p2	p2	p2	p2		p3	p3	p3	p3	p6	p6	p6	p6	p6	p6	p6							
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5	j5	j5	j5	j5							
u5	p5	p5	p5	p5	p5	p5	p5		p4	p4	p4	p1	p1	p1	p1											
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5											

Figure 5.2 Field schedule from optimization model

Table 5.5 Field case from optimization model result summary

Cases	#P	#J	#U	#n	Total duration (Days)	TTF (Days)	Max Tf (Days)	Total unit time (Days)
Field case	8	15	5	-	162	392	43	172
Field case from model	8	15	5	4	162	320	40	171

Total unit time and maximum time finish are reduced to 171 days and 40 days from 172 and 43 days, respectively. Table 5.5 shows summary of field case and field case from the model. From the constraints and requirement, the model has shown a little more optimization opportunity of field unit sequence schedule.

5.3 Sensitivity analysis

This section illustrates sensitivity analysis of operational options and operation uncertainties effect to unit sequence schedule. Operational options sensitivity covers unit abilities and number of units which are shown in section 5.3.1 and 5.3.2. Operation uncertainties sensitivity covers jobs duration and number of job requests which are shown in section 5.3.3 and 5.3.4.

5.3.1 Unit abilities sensitivity

BSLU or commonly named as fishing unit is normally preferred to be used on fishing jobs only. It is still preferred to do this even though using it to perform SLU jobs, such as well preparation, will result in less unit movement. This section shows impact of using BSLU on only fishing jobs to unit sequence schedule and unit usage time. Table 5.6 shows units' abilities input of this sensitivity case compare to field case input, changed input are highlighted in yellow. BSLU capabilities is reduced from three jobs to only one job in this sensitivity case.

Table 5.6 Unit abilities input comparison of unit abilities sensitivity

Cases		Field case			Unit abilities	
#u	Unit	Jobs				
u1	SLU	j2	j4		j2	j4
u2	SLU	j2	j4		j2	j4
u3	BSLU	j1	j2	j4	j1	
u4	ELU	j3	j5		j3	j5
u5	ELU	j3	j5		j3	j5

Table 5.7 Field case with BSLU perform only fishing job summary table.

Cases	#P	#J	#U	#n	Total duration (Days)	TTF (Days)	Max Tf (Days)	Total unit time (Days)
Field case from model	8	15	5	4	162	320	40	171
BSLU fishing only	8	15	5	4	162	335	54	173

Figure 5.3 shows schedule of this case. BSLU, u3, has perform only fishing jobs, thus well preparation and MIT jobs on p4 was moved to be done with SLU, u1. SLU, u2, also have more work from the same reason which make its works done on 54^{th} day. Total unit time has slightly increased from previous case, 171 to 173 days as shown in Table 5.7. Well preparation jobs on p7 is delays by almost 2 weeks which

may also delay upcoming perforation jobs in the next period. However, this is also an opportunity to accelerate other fishing jobs from next period which may be as much production as perforation on p7 that has been delayed.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3	p3	p3	p3	p4	p4	p4	p4	p4	p4	p4	p4	p4													
	j4	j4	j4	j4	j4	j4	j4	j2	j2	j2	j2	j2	j2													
u2	p6	p6	p6	p6	p6	p6	p6		p1	p1	p1	p1	p1	p1		p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7
	j4	j4	j4	j4	j4	j4	j4		j4	j4	j4	j4	j4	j4		j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4
u3	p4	p4		p8	p8	p8	p8	p8	p2	p2	p2	p2														
	j1	j1		j1	j1	j1	j1	j1	j1	j1	j1	j1														
u4	p2	p2	p2	p2	p2	p2	p2		p6	p6	p6	p6	p6	p6	p6	p1	p1	p1	p1							
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5	j5	j5	j5	j5							
u5	p5	p5	p5	p5	p5	p5	p5		p3	p3	p3	p3		p4	p4	p4										
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5		j5	j5	j5										

Figure 5.3 Field unit schedule with BSLU perform only fishing job

5.3.2 Number of unit sensitivity

According to limited resources across GoT, there is always a consideration of number of units working in the field. Number of units working in the field depends on well intervention job requests of each field. If there are many job requests with time constraint to be done in a particular period, the field may consider to have more units. On the other hand, field may consider releasing units to others when job requests are less. However, final decision will be made based on unit availability and work requests across GoT. This optimization scheduler can quantify impact of number of units in different scenario to support the decision.

This section shows the impact of number of units to unit sequence schedule. Typically, SLU jobs are always bottle neck of well intervention operation. As oil and gas field ages through time, wells become older carrying more issues such as scale formed and sand filled. These kind of wells require SLU to clean and prepare the well for further jobs. Thus, twos cases are considered which are an additional SLU, u6, and a SLU reduction, u1 early released for maintenance to help making decision of number of units in the field. Table 5.8 shows input comparison between these two cases and field case input.

Table 5.8 units' abilities input comparison of number of unit sensitivity

Cases		Field case			Add SLU			Reduce SLU		
#u	Unit	Jobs			Jobs			Jobs		
u1	SLU	j2	j4		j2	j4				
u2	SLU	j2	j4		j2	j4		j2	j4	
u3	BSLU	j1	j2	j4	j1	j2	j4	j1	j2	j4
u4	ELU	j3	j5		j3	j5		j3	j5	
u5	ELU	j3	j5		j3	j5		j3	j5	
u6	SLU				j2	j4				

In additional unit case, SLU, u6, has been added to unit sequence schedule. Maximum time finished has shifted up to 38 days. Total unit utilization time also reduce to 158 days. The unit sequence schedule of this case is shown in Figure 5.4. As more SLU working in the field, both MIT on p4 and well preparations on p7 are accelerated. Perforation jobs on p4 is planned to be done after MIT jobs finish. An additional SLU, u6, is assigned to only one job which shows an opportunity to accelerate more SLU work from next period.

Table 5.9 Number of units sensitivity result summary

Cases	#P	#J	#U	#n	Total duration (Days)	TTF (Days)	Max Tf (Days)	Total unit time (Days)
Field case from model	8	15	5	4	162	320	40	171
Added SLU	8	15	6	4	162	301	38	158
Reduced SLU	8	15	4	4	162	392	62	177

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3	p3	p3	p3	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7									
	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4									
u2	p6	p6	p6	p6	p6	p6	p6		p4	p4	p4	p4	p4	p4												
	j4	j4	j4	j4	j4	j4	j4		j2	j2	j2	j2	j2	j2												
u3	p4	p4	p4	p4	p4		p8	p8	p8	p8	p8	p2	p2	p2	p2											
	j1	j1	j4	j4	j4		j1	j1	j1	j1	j1	j1	j1	j1	j1											
u4	p2	p2	p2	p2	p2	p2	p2		p3	p3	p3	p3	p6	p6	p6	p6	p6	p6	p6							
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5	j5	j5	j5	j5							
u5	p5	p5	p5	p5	p5	p5	p5		p1	p1	p1	p1			p4	p4	p4									
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5			j5	j5	j5									
u6	p1	p1	p1	p1	p1	p1	p1																			
	j4	j4	j4	j4	j4	j4	j4																			

Figure 5.4 field case with an additional SLU

In reduction of number of units case, SLU, u1, has been send on planned maintenance earlier. Maximum time finish has shifted to 62 days. The results summary and schedule are shown in Table 5.9 and Figure 5.5. Unit stand by is obviously seen on ELU, u5, which is waiting to be moved to p1 after SLU, u2, finished well preparation jobs. Even though number of units is reduced, total unit utilization time does not necessary to be less. As shown in this case that total unit utilization time is increase to 177 days because of more unit idle time. Well preparation jobs on p3 are also delay to be done by SLU, u2, so dose related perforation jobs, j5. Perforation jobs on p6 is required to fill the gap on ELU, u4, due to p1 and p3 are not ready for ELU jobs yet. The MIT jobs on p4 is now suggested to be done by BSLU, u3, instead of waiting for SLU to do it.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1																										
u2	p6	p6	p6	p6	p6	p6	p6		p3	p3	p3		p1	p1	p1	p1	p1	p1		p7	p7	p7	p7	p7	p7	p7
	j4	j4	j4	j4	j4	j4	j4		j4	j4	j4		j4	j4	j4	j4	j4	j4		j4	j4	j4	j4	j4	j4	j4
u3	p4	p4	p4	p4	p4		p8	p8	p8	p8	p8	p2	p2	p2	p2	p4	p4	p4	p4	p4	p4					
	j1	j1	j4	j4	j4		j1	j1	j1	j1	j1	j1	j1	j1	j1	j2	j2	j2	j2	j2	j2					
u4	p2	p2	p2	p2	p2	p2	p2		p6	p6	p6	p6	p6	p6	p6											
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5											
u5	p5	p5	p5	p5	p5	p5	p5		p4	p4	p4	p3	p3	p3	p3				p1	p1	p1	p1				
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5				j5	j5	j5	j5				

Figure 5.5 field case with a reduction SLU

According to sensitivity result above, adding one more SLU is preferred option of this 45 days period. One more SLU help reduce total unit utilization time which will result in cost reduction. On the other hand, reducing SLU leads to more unit utilization time resulting in higher cost with the same amount of job requests which is not preferred option. However, final number of units will depend on unit availability across GoT.

5.3.3 Number of job requests sensitivity

As oil and gas operations always have uncertainties, so unplanned activities are always happened. Example of uncertainties are surface equipment maintenance delay, shortage of gas production to meet nomination, logistic uncertainties, safety concern and weather. These uncertainties affect unit sequence schedule either urgently adding or reducing job requests. This section shows impact of unplanned adding and reducing jobs request on a platform. As shown in Table 5.10, p9 has added two job requests which are j2 and j3 in unplanned additional job requests case. On the other hand, three jobs are postponed from p4 in reduce job requests case. Table 5.10 and Table 5.11 show input comparison between this sensitivity cases and field and the results summary of these cases, respectively.

Table 5.10 Job requests of number of job requests sensitivity cases

Cases	Field case					Adding P9					Cut job P4				
Platforms	Jobs duration (days)														
	j1	j2	j3	j4	j5	j1	j2	j3	j4	j5	j1	j2	j3	j4	j5
P1				13	8				13	8				13	8
P2	7		14			7		14			7		14		
P3				7	8				7	8				7	8
P4	4	12		6	6	4	12		6	6	4				
P5			14					14					14		
P6				14	14				14	14				14	14
P7				25					25					25	
P8	10					10					10				
P9							7	8							

In unplanned jobs added case, p9 has been added into model with two job requests which are perforation, j3, and MIT, j2. These jobs are urgently added in schedule due to gas shortage and well integrity concern. Due dates of these jobs are day 30th and 35th according to their concerns. Furthermore, any change of the plan will require an approval process and documentation. To avoid this unnecessary issue, unit sequence schedule will keep the first platform for each unit to be the same as schedule in Figure 5.2 and vary the sequence after that. The unit sequence schedule of this case is shown in Figure 5.6.

Table 5.11 Unplanned job requested added and reduced result summary

Cases	#P	#J	#U	#n	Total duration (Days)	TTF (Days)	Max Tf (Days)	Total unit time (Days)
Field case from model	8	15	5	4	162	320	40	171
Adding p9	9	17	5	4	176	375	45	187
Cut job on p4	8	12	5	4	138	236	40	130

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3	p3	p3	p3	p1	p1	p1	p1	p1	p1	p1	p4	p4	p4	p4	p4	p4									
	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j2	j2	j2	j2	j2	j2									
u2	p6	p6	p6	p6	p6	p6	p6		p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7						
	j4	j4	j4	j4	j4	j4	j4		j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4						
u3	p4	p4	p4	p4	p4		p9	p9	p9		p2	p2	p2		p8	p8	p8	p8	p8							
	j1	j1	j4	j4	j4		j2	j2	j2		j1	j1	j1		j1	j1	j1	j1	j1							
u4	p2	p2	p2	p2	p2	p2	p2		p4	p4	p4	p9	p9	p9	p9		p6	p6	p6	p6	p6	p6	p6			
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5			
u5	p5	p5	p5	p5	p5	p5	p5		p3	p3	p3	p3	p1	p1	p1	p1										
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5	j5										

Figure 5.6 Field case with uplanned job requests added

Regarding job requests concern on p9, the jobs are added in the middle of the previous schedule. MIT job, j2, on p9 is planned to start after BSLU, u3, finished work on p4. Fishing jobs on both p2 and p8 are defered. Perforation job, j3, on p9 is added in front of p6. Other jobs in the schedule are mostly the same as section 5.2. Maximum time finish and total unit uitilization time are increase as number of job requests increase, as shown in Table 5.11.

In unplanned jobs reducing case, p4 perforation, j5, related well preparation jobs, j4, and MIT, j2, are postponed to be done in the next periods. The only job left on p4 is fishing job, j1. As a result, fishing jobs on both p2 and p8 are accelerated 6 days. Perforation jobs on p6 are also accelerated to fill gab on ELU, u5, as shown in Figure 5.7. Other than these are mostly the same as schedule in section 5.2. Maximum time finish is still the same as section 5.2 at 40 days with less number of jobs. However, total unit utilization time is definitely reduce, as shown in Table 5.11.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3	p3	p3	p3	p1	p1	p1	p1	p1	p1	p1															
	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4															
u2	p6	p6	p6	p6	p6	p6	p6		p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7	p7						
	j4	j4	j4	j4	j4	j4	j4		j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4						
u3	p4	p4		p8	p8	p8	p8	p8	p2	p2	p2	p2														
	j1	j1		j1	j1	j1	j1	j1	j1	j1	j1	j1														
u4	p2	p2	p2	p2	p2	p2	p2		p3	p3	p3	p3	p1	p1	p1	p1										
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5	j5										
u5	p5	p5	p5	p5	p5	p5	p5		p6	p6	p6	p6	p6	p6	p6											
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5											

Figure 5.7 Field case with unplanned job requests reduced

5.3.4 Jobs duration sensitivity

SLU jobs, especially fishing and MIT, are difficult to estimate jobs duration estimation. Fishing jobs duration are vary from 1 days to 2 weeks per well depend on what stuck in hole. MIT always has more than 1 week for estimated duration which actual duration also vary like fishing jobs. This section shows impact of SLU jobs duration to unit sequence schedule by assuming 30% more and less to all SLU jobs which are j2 and j4. Table 5.2 shows input comparison between this sensitivity cases and field case which SLU’s job duration are added and reduced by 30%. Table 5.13 shows results summary of these cases.

Table 5.12 Job requests of number of job duration sensitivity cases

Cases	Field case					Add 30% duration					Reduce 30% duration				
Platforms	Jobs duration (days)														
	j1	j2	j3	j4	j5	j1	j2	j3	j4	j5	j1	j2	j3	j4	j5
P1				13	8				17	8				9	8
P2	7		14			9		14			5		14		
P3				7	8				9	8				5	8
P4	4	12		6	6	5	12		8	6	3	12		4	6
P5			14					14					14		
P6				14	14				18	14				10	14
P7				25					33					18	
P8	10					13					7				

Table 5.13 Field case with added and reduced job durations result summary

Cases	#P	#J	#U	#n	Total duration (Days)	TTF (Days)	Max Tf (Days)	Total unit time (Days)
Field case from model	8	15	5	4	162	320	40	171
Added 30% duration	8	15	5	4	188	376	52	200
Reduced 30% duration	8	15	5	4	137	275	38	146

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3 j4	p3 j4	p3 j4	p3 j4	p3 j4	p1 j4	p1 j4	p1 j4	p1 j4	p1 j4	p1 j4	p1 j4	p1 j4	p1 j4												
u2	p6 j4	p6 j4	p6 j4	p6 j4	p6 j4	p6 j4	p6 j4	p6 j4	p6 j4		p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4	p7 j4
u3	p4 j1	p4 j1	p4 j1	p4 j4	p4 j4	p4 j4	p4 j4	p2 j1	p2 j1	p2 j1	p2 j1	p2 j1	p4 j2	p4 j2	p4 j2	p4 j2	p4 j2	p4 j2		p8 j1	p8 j1	p8 j1	p8 j1	p8 j1	p8 j1	
u4	p2 j3	p2 j3	p2 j3	p2 j3	p2 j3	p2 j3	p2 j3		p4 j5	p4 j5	p4 j5	p6 j5	p6 j5	p6 j5	p6 j5	p6 j5	p6 j5	p6 j5								
u5	p5 j3	p5 j3	p5 j3	p5 j3	p5 j3	p5 j3	p5 j3		p3 j5	p3 j5	p3 j5	p3 j5			p1 j5	p1 j5	p1 j5	p1 j5								

Figure 5.8 Field case with increased 30% SLU job durations

As more time requires to finish all the jobs, maximum time finish is certainly increased to 54 days with added 30% duration of all SLU jobs. Unit sequence schedule is shown in Figure 5.8. BSLU, u3, has the biggest change as both p2 and p8 are available for fishing jobs after well preparation jobs on p4 are done. MIT jobs on p4 have to be done with u3 instead of u1 as shown in previous section. It also start after perforation jobs done by u4 to reduce ELUs idle time due to p6 is not ready for perforation. However, MIT jobs on p4 and fishing jobs on p8 can be switched with each other and still yield the same objective value. SLU, u1, is able to do jobs only on 2 platforms and then released for maintenance. ELU, u5, is idle for 4 days after finished perforation on p3 due to p1 is not ready yet.

As less time requires to finish all the jobs, maximum time finish is certainly reduced to 38 days with 30% less duration of all SLU jobs. Unit sequence schedule is shown in Figure 5.9. Unit sequence are mostly the same as section 5.3.2. Only p4 jobs sequence has significant change that perforation jobs have been move to be done after MIT finished. This is because SLU, u2, is available after well preparations on p6 are done. Furthermore, to avoid ELU, u5, unit stand by, p7 well preparations are move to be done with SLU, u1.

Unit	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
u1	p3	p3	p3	p1	p1	p1	p1	p1	p7	p7	p7	p7	p7	p7	p7	p7	p7									
	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4	j4									
u2	p6	p6	p6	p6	p6		p4	p4	p4	p4	p4	p4														
	j4	j4	j4	j4	j4		j2	j2	j2	j2	j2	j2														
u3	p4	p4	p4	p4	p8	p8	p8	p8	p2	p2	p2															
	j1	j1	j4	j4	j1	j1	j1	j1	j1	j1	j1															
u4	p2	p2	p2	p2	p2	p2	p2		p1	p1	p1	p1	p6	p6	p6	p6	p6	p6	p6							
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5	j5	j5	j5	j5							
u5	p5	p5	p5	p5	p5	p5	p5		p3	p3	p3	p3	p4	p4	p4											
	j3	j3	j3	j3	j3	j3	j3		j5	j5	j5	j5	j5	j5	j5											

Figure 5.9 Field case with reduced 30% SLU job durations

According to the duration uncertainty, additional job requests would be suggested plan. The variation in job durations is the cause of unit idle times in 30% more duration case. BSLU, u3, and SLU, u2, have done assigned job by 24th day which make them idle if no jobs request ready to add in this 45 days period. Due dates of job with safety concern and gas rate related should be put in the model so that the impact of jobs delay to the operation are minimized.

5.4 Field case and sensitivity analysis summary

This section summarize field application and sensitivity analysis of the semi-automated well intervention scheduler. Sensitivity analysis covers operational options and operation uncertainties.

According to field case input to the scheduler, the scheduler has identified the optimization opportunity of selected field case. Furthermore, it is also able to perform sensitivity analysis to compare possible scenario and quantify impact of uncertainty. This helps support decision of operational option.

Based on selected field case and operational option analysis, BSLU is preferred to do fishing and SLU jobs if there is no requirement of fishing jobs acceleration. The request of an additional SLU should be proposed. It will help reducing total unit utilization time which will lead to cost reduction. However, this depends on unit availability across GoT.

From operation uncertainty analysis, back-up job requests should be ready to fill any gaps in the schedule. The variation in number of job requests and job durations are the cause of unit idle times. Additional job requests should fill those gaps which will lead to more efficiency in unit utilization. Both more jobs requests and durations cause the delay of the schedule. Adding due dates for the jobs with safety concern and gas rate related to the model is suggested so that jobs delay impact to operation are minimized.

Chapter 6 Conclusion and Recommendation

This chapter concludes the results of optimization model validation and the application of optimization model on field case problem. Moreover, recommendations for further application and improvement are also provided

6.1 Conclusions

The mathematical optimization model was successfully developed and validated by changing objective functions, unit capabilities, number of event points and due date constraints. The conclusions are shown as follows.

1. First objective function, TTf, is summation of finished time which yields the schedule that all the jobs start as soon as possible. However, it may give different solution when event points changed. Second objective function, mTTf, is summation of maximum finished time which yields the schedule that has minimum unit utilization time. However, there is a chance that unit is left idle because it does not make all the jobs start at the soonest possible. Third objective function, TTf+mTTf, which is the combination of the first two was found to be the best for the scheduler. It has taken the two advantages of starting jobs soonest possible while minimizing the total unit time.
2. As more available time slots, n, units are allowed to shuffle which may yield the next minimum solution. However, it expanded the search space of the model and made the computational time increase significantly.
3. Due date and earliest constraints help restrict the search and reduce the variation of solution when the inputs change.

The scheduler has identified the optimization opportunity of selected field case. Furthermore, it is also able to perform sensitivity analysis to compare possible scenario and quantify impact of uncertainty. The conclusion are shown as follows

1. According to operational option analysis results, BSLU is preferred to do both fishing and SLU's jobs if there is no requirement of fishing jobs acceleration.
2. The request of an additional SLU should be proposed which will help reducing total unit utilization time.
3. From operation uncertainty analysis results, additional job requests is suggested to be planned and ready to fill gaps in the schedule as the uncertainties are the cause of unit idle times.
4. Due dates constraints are suggested to apply with the jobs with safety concern and gas rate related to minimize impacts to operation from those uncertainties.

6.2 Recommendations

There are recommendations for further study to improve the optimization model and field application.

1. This thesis assumed job duration uncertainty range which is vary from field to field. Detail study on this range of uncertainty of a specific field should be conducted, then incorporate the range to the scheduler. This will help generate more stable schedule for field operation as well as minimizing extra planning works.
2. Implementation of the scheduler in bigger field scope which unit mobilization time is a significant factor impacting the schedule. This will illustrate the influence of unit mobilization time to the schedule. However, this may requires simplification of inputs and optimization model in order to handle bigger number of variables
3. This thesis assumed every unit have the same utilization cost so that minimizing total unit utilization time is the same as minimizing total unit utilization cost. However, cost of each unit types are not the same. Actual

cost of each units should be considered in the scheduler. The objective function should be adjusted in order to optimize total cost of unit utilization.

4. The scheduler can be further improved in order to encounter with dynamic situation regarding operation uncertainties such as cancelling of certain upcoming jobs or delaying of current jobs. Mathematical optimization model can be modified to be able to identify job sequences in early period which does not get impact from uncertainty and should be excluded from the calculation. Then, the model should rerun only the later period of the schedule to handle the impact from any uncertainty.

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APPENDIX

APPENDIX I: Motivating example constraints and objective function

Duration constraints

Platform1

$$T^{f}(p1,j1,u1) = T^{s}(p1,j1,u1) + 8$$
$$T^{f}(p1,j3,u2) = T^{s}(p1,j3,u2) + 6$$
$$T^{f}(p1,j4,u4) = T^{s}(p1,j4,u4) + 6$$
$$T^{f}(p1,j5,u1) = T^{s}(p1,j5,u1) + 4$$

Platform2

$$T^{f}(p2,j1,u1) = T^{s}(p2,j1,u1) + 8$$
$$T^{f}(p2,j2,u3) = T^{s}(p2,j2,u3) + 8$$
$$T^{f}(p2,j3,u2) = T^{s}(p2,j3,u2) + 8$$
$$T^{f}(p2,j4,u4) = T^{s}(p2,j4,u4) + 4$$

Platform3

$$T^{f}(p3,j5,u1) = T^{s}(p3,j5,u1) + 4$$
$$T^{f}(p3,j6,u2) = T^{s}(p3,j2,u2) + 1$$
$$T^{f}(p3,j7,u3) = T^{s}(p3,j7,u3) + 2$$

Platform4

$$T^{f}(p4,j5,u1) = T^{s}(p4,j5,u1) + 6$$
$$T^{f}(p4,j7,u3) = T^{s}(p4,j7,u3) + 8$$

Platform5

$$T^{f}(p5,j2,u3) = T^{s}(p5,j2,u3) + 6$$
$$T^{f}(p5,j8,u4) = T^{s}(p5,j8,u4) + 8$$

Sequence constraints

- Different tasks by different units on the same platform

Platform1

$$T^{s}(p1,j3,u2) \geq T^{f}(p1,j1,u1)$$
$$T^{s}(p1,j4,u4) \geq T^{f}(p1,j3,u2)$$
$$T^{s}(p1,j5,u1) \geq T^{f}(p1,j4,u4)$$

Platform2

$$T^s(p2, j2, u3) \geq T^f(p2, j1, u1)$$
$$T^s(p2, j3, u2) \geq T^f(p2, j2, u3)$$
$$T^s(p2, j4, u4) \geq T^f(p2, j3, u2)$$

Platform3

$$T^s(p3, j6, u2) \geq T^f(p3, j5, u1)$$
$$T^s(p3, j7, u3) \geq T^f(p3, j6, u2)$$

Platform4

$$T^s(p4, j7, u3) \geq T^f(p4, j5, u1)$$

Platform5

$$T^s(p5, j8, u4) \geq T^f(p5, j2, u3)$$

- Same task by the same unit on different platforms

Unit1

$$T^s(p2, j1, j1) \geq T^f(p1, j1, u1) + 2$$
$$T^s(p4, j5, u1) \geq T^f(p3, j5, u1) + 4$$
$$T^s(p1, j5, u1) \geq T^f(p4, j5, u1) + 6$$

Unit3

$$T^s(p2, j2, u3) \geq T^f(p5, j2, u3) + 3$$
$$T^s(p4, j7, u3) \geq T^f(p3, j7, u3) + 1$$

Unit4

$$T^s(p2, j4, u4) \geq T^f(p1, j4, u4) + 2$$

- Different tasks by the same unit on different platforms

Unit1

$$T^s(p3, j5, u1) \geq T^f(p2, j1, u1) + 1$$

Unit2

$$T^s(p3, j6, u2) \geq T^f(p1, j3, u2) + 3$$
$$T^s(p2, j3, u2) \geq T^f(p3, j6, u2) + 1$$

Unit3

$$T^s(p3, j7, u3) \geq T^f(p2, j2, u3) + 1$$

Unit4

$$T^s(p1, j4, u4) \geq T^s(p5, j8, u4) + 5$$

Objective function

$$\begin{aligned} Minimize\ \ z = {} & T^f(p1, j1, u1) + T^f(p1, j3, u2) + T^f(p1, j4, u4) + T^f(p1, j5, u1) \\ & + T^f(p2, j1, u1) + T^f(p2, j2, u3) + T^f(p2, j3, u2) + T^f(p2, j4, u4) \\ & + T^f(p3, j5, u1) + T^f(p3, j6, u2) + T^f(p3, j7, u3) + T^f(p4, j5, u1) \\ & + T^f(p4, j7, u3) + T^f(p5, j2, u3) + T^f(p5, j8, u4) \end{aligned}$$

VITA

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