

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

RESOURCE LEVELING IN LINE-OF-BALANCE SCHEDULING

Ph.D. THESIS

Atila DAMCI

Department of Civil Engineering

Structure Engineering Programme

MAY 2012

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

RESOURCE LEVELING IN LINE-OF-BALANCE SCHEDULING

Ph.D. THESIS

Atilla DAMCI
(501062002)

Department of Civil Engineering

Structure Engineering Programme

Thesis Advisor: Assoc. Prof. Dr. Gül POLAT

MAY 2012

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**DENGE DİYAGRAMI YÖNTEMİNDE
KAYNAK DENGELEMESİ İÇİN
BİR MODEL ÖNERİSİ**

DOKTORA TEZİ

**Atilla DAMCI
(501062002)**

İnşaat Mühendisliği Anabilim Dalı

Yapı Mühendisliği Programı

Tez Danışmanı: Doç. Dr. Gül POLAT

MAYIS 2012

Atila DAMCI, a **Ph.D.** student of **ITU Graduate School of Science and Technology** student ID **501062002**, successfully defended the **dissertation** entitled “**Resource Leveling in Line-of-Balance Scheduling**”, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Dr. Gül POLAT**
İstanbul Technical University

Jury Members : **Prof. Dr. David ARDITI**
Illinois Institute of Technology

Assoc. Prof. Dr. Murat ÇIRACI
İstanbul Technical University

Assoc. Prof. Dr. Uğur MÜNGEN
İstanbul Technical University

Asst. Prof. Dr. Almula KÖKSAL
Yıldız Technical University

Date of Submission : 26 March 2012

Date of Defense : 10 May 2012

To my mother,

FOREWORD

The use of alternative scheduling methods that are known under the generic term “linear scheduling methods” has gained increasing attention due to the shortcomings of conventional scheduling methods used in the construction industry. In the past years, several studies have been conducted in order to improve the standard features of the linear scheduling methods. Resource management is one of these features. The linear scheduling methods, by their very nature, deal with resource allocation. However, the distribution of resources could be further improved by resource leveling. This research was initiated in response to the absence of a resource leveling model for line-of-balance schedules and was intended to be useful for construction professionals.

It was my honor to conduct this research under the guidance of my advisor Assoc. Prof. Dr. Gül POLAT. She encouraged and supported me whenever I found myself in a tight spot. I have achieved so much in so little time with her support, for which I am very grateful.

Most of all, I am deeply grateful to Prof. Dr. David ARDITI. He is the best mentor that I have ever met. He spent extra hours to help me whenever I needed. Without his positive attitude and support, I do not think I could have completed this research as successfully. Each of our “line-of-balance” discussions allowed me to take one more step forward in my studies. I also have to express my appreciation to him and his wife for their hospitality during the time I conducted a part of my research in Chicago.

I would like to express my appreciation to the members of my committee, Assoc. Prof. Dr. Murat ÇIRACI, Assoc. Prof. Dr. Uğur MÜNGEN and Asst. Prof. Dr. Almula KÖKSAL, for their valuable suggestions, to Tolga ÖZÜDOĞRU, for his invaluable help in computer and software related problems, to Can Ersen FIRAT, for providing inspiration in the beginning of this research.

Finally, I would like to thank my whole family for their continued support and motivation. Especially, my wife always kept me motivated whenever I faced a challenge during this research. I cannot thank her enough for her patience and tolerance.

May 2012

Atilla DAMCI

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	ix
TABLE OF CONTENTS	xi
ABBREVIATIONS	xiii
LIST OF TABLES	xv
LIST OF FIGURES	xvii
SUMMARY	xix
ÖZET	xxi
1. INTRODUCTION	1
1.1 Problem Statement	1
1.2 Objectives of the Research	4
1.3 Research Methodology	5
1.4 Research Scope	5
2. REVIEW OF PREVIOUS STUDIES ON RESOURCE MANAGEMENT IN LINEAR SCHEDULES	7
3. RESEARCH METHODOLOGY	13
3.1 Line-of-balance Scheduling	13
3.2 Genetic Algorithms	17
3.3 Evolutionary Solver	19
4. RESOURCE LEVELING IN LINE-OF-BALANCE METHODOLOGY	21
4.1 The Principle of “Natural Rhythm”	24
4.2 Example Pipeline Project	32
4.3 Discussion of the Results	42
5. MULTI-RESOURCE LEVELING IN LINE-OF-BALANCE	49
5.1 Example: Pipeline Project	52
6. CONCLUSION AND RECOMMENDATIONS	63
REFERENCES	69
APPENDICES	75
CURRICULUM VITAE	125

ABBREVIATIONS

CPM	: Critical Path Method
PERT	: Program Evaluation and Review Technique
LOB	: Line-of-Balance

LIST OF TABLES

	<u>Page</u>
Table 4.1 : Objective Functions for Resource Leveling.....	25
Table 4.2 : Information about activities	33
Table 4.3 : Objective Functions for Resource Leveling.....	40
Table 4.4 : Results after Resource Leveling	42
Table 5.1 : Information about activities	52

LIST OF FIGURES

	<u>Page</u>
Figure 3.1 : Relationship between LOB quantities and time (Lumsden 1968).....	15
Figure 3.2 : Exmple of an LOB diagram.	16
Figure 3.3 : Crossover process.	18
Figure 3.4 : Mutation process.	18
Figure 3.5 : Example for an operational flow of a genetic algorithm.	19
Figure 3.6 : Screenshot of Evolutionary Solver.	20
Figure 4.1 : Relationship between required worker-hours and crew size.	26
Figure 4.2 : Examples of LOB diagram.	27
Figure 4.3 : Examples of LOB diagrams before using the principle of “natural rhythm” for resource leveling.	29
Figure 4.4 : Examples of LOB diagrams after using the principle of “natural rhythm” for resource leveling.	31
Figure 4.5 : The LOB schedule before resource leveling for Scenario 1.....	35
Figure 4.6 : The LOB schedule before resource leveling for Scenario 2.....	36
Figure 4.7 : Resource histogram before resource leveling for Scenario 1.	37
Figure 4.8 : Resource histogram before resource leveling for Scenario 2.	38
Figure 4.9 : Schedule after Resource Leveling for Scenario 1.	43
Figure 4.10 : Schedule after Resource Leveling for Scenario 2.	44
Figure 4.11 : Resource Histogram after Resource Leveling for Scenario 1.	45
Figure 4.12 : Resource Histogram after Resource Leveling for Scenario 2.	46
Figure 5.1 : Examples of LOB diagrams with multiple resources.	51
Figure 5.2 : The LOB schedule before resource leveling.	54
Figure 5.3 : Combined histogram of weighted resource usage before resource leveling.....	55
Figure 5.4 : The LOB schedule after resource leveling.	57
Figure 5.5 : Resource histogram before resource leveling for Resource 1.	58
Figure 5.6 : Resource histogram after resource leveling for Resource 1.	59
Figure 5.7 : Resource histogram before leveling for Resource 2.....	60
Figure 5.8 : Resource histograms after resource leveling for Resource 2.	61

RESOURCE LEVELING IN LINE-OF-BALANCE SCHEDULING

SUMMARY

Line-of-balance (LOB) methodology produces a work schedule where resource allocation is automatically performed to provide a continuous and uninterrupted use of resources, but the distribution of resources could be further improved by resource leveling even if multiple resources are involved. Resource leveling involves minimizing fluctuations, peaks and valleys in resource utilization without changing the completion time of a construction project. It assumes that there are sufficient resources available, but that the project duration is fixed. Even though LOB is a resource-based scheduling system that is used in projects that exhibit repetitive characteristics, it does not deal with resource leveling. The objective of this research is to develop a genetic algorithm-based model for both single resource leveling and multi-resource leveling model for LOB schedules. The resource leveling model presented in this paper is based on the principle of “natural rhythm” that assumes that the highest productivity can be achieved as long as an activity is performed in a unit of production by a crew of optimum size. Therefore, one needs to change the number of crews employed to shift the start times of an activity forwards or backwards at different units of production. The total project duration, the duration of an activity in any unit and the precedence relationships between activities remain the same during this procedure. The impacts of using different objective functions in leveling resources in schedules established by using LOB methodology is also investigated in this study. Two LOB schedules that are established for two different resource scenarios of a pipeline project are used to illustrate the performance of these objective functions. It is observed that the objective functions may or may not provide the same optimal resource distribution depending on the number activities and their float distribution. The same pipeline project is used to perform multi-resource leveling. For demonstration purposes, two different resources are used to complete the project, and are considered in establishing the LOB schedule. The proposed model postulates that the production rate and duration of an activity are governed by the resource that requires the longest duration in completing a unit. After resource leveling, it is observed that the proposed multi-resource leveling model provides a smoother resource utilization histogram while maintaining optimum productivity.

DENGE DİYAGRAMI YÖNTEMİNDE KAYNAK DENGELEMESİ İÇİN BİR MODEL ÖNERİSİ

ÖZET

Bir inşaat projesinde, inşaat yönetimi (yapı işletmesi) süreci ile temel olarak yerine getirilmeye çalışılan amaç, projeyi istenilen kalite gereksinimlerini sağlayarak, güvenli bir şekilde, bütçeyi aşmadan ve zamanında tamamlamaktır. İnşaat projelerinin iş programının hazırlanması bu amaca ulaşmak için gerekli olan ana faktörlerden biridir. Bu bağlamda, inşaat projesinin içerdiği faaliyetler için planlanan başlama ve bitiş zamanlarını gösteren iş programının hazırlanmasında kullanılan yöntemler büyük önem taşımaktadır. İnşaat sektöründe kullanılan iş programı hazırlama yöntemleri, ağ diyagramı tabanlı ve mahal tabanlı olmak üzere iki ana gruba ayrılabilir. Tekrar arz eden aktivitelerden oluşan inşaat projelerinde (karayolu, boru hattı projeleri vb.) iş programının hazırlanması için ağ diyagramı tabanlı yöntemlerden biri kullanıldığında, projenin tamamı için oluşturulacak ağ diyagramının hazırlanması, gösterimi ve anlaşılması oldukça zor olabilir. Bu durum, mahal tabanlı iş programı hazırlama yöntemleri adı altında alternatif iş programı hazırlama yöntemlerinin geliştirilmesine neden olmuştur.

Mahal tabanlı iş programı hazırlama yöntemlerinin temeli denge diyagramı yöntemine dayanmaktadır. Denge diyagramı yöntemi ile iş programının oluşturulması için ilk aşamada bir ünitenin (bir kilometre yol, yüksek katlı bir binanın bir katı, vb.) yapımı için gerekli olan adam-saat değeri, bir ekip için en uygun (optimum) kişi sayısı ve günlük çalışma süresi gereklidir. Söz konusu bilgiler elde edildikten sonra bir ünitenin üretimi için gerekli olan süre hesaplanabilir. Hesaplanan bu süre ekip için en uygun kişi sayısı değiştirilmediği sürece her zaman sabit kalacaktır. En uygun kişi sayısına sahip bir ekibin, aktivitenin bir ünitesi için sahip olduğu üretim oranına “doğal ritim” adı verilmiştir. Doğal ritim korunduğu sürece çalışan ekip ya da ekipler için, öngörülemeyen bir durum haricinde herhangi bir bekleme süresi olmayacaktır. İkinci aşamada, aktivitenin her bir ünite için başlama ve bitiş zamanları hesaplanır.

Söz konusu mahal tabanlı iş programı hazırlama yöntemlerinin mevcut özelliklerini geliştirmek amacıyla çeşitli çalışmalar yürütülmüştür. Geliştirilmeye çalışılan özelliklerden biri de kaynak yönetimidir. Kaynak yönetimi için kullanılan yaklaşımlar arasında bulunan kaynak dengelemesinin amacı gerekli olan proje süresini değiştirmeden kaynak kullanımındaki dalgalanmaları en aza indirmeye çalışmaktır. Kaynak dengelemesinde ihtiyaç duyulan kaynakların hepsinin yeterli derecede bulunduğu ve proje süresinin kısıtlı olduğu kabul edilir. Yapılan literatür araştırması sonucunda hem ağ tabanlı hem de mahal tabanlı iş programı hazırlama yöntemlerinde kaynak dengelemesinde kullanılan dokuz adet farklı amaç fonksiyonu belirlenmiştir: (1) belirli bir zaman aralığı için (gün,hafta vb.) kaynak ihtiyacındaki farkın mutlak değerleri toplamının en küçüklemesi, (2) belirli bir zaman aralığı için (gün,hafta vb.) kaynak ihtiyacındaki artışların toplamının en küçüklemesi, (3) belirli

bir zaman aralığı için (gün,hafta vb.) kaynak ihtiyacı ile ortalama kaynak ihtiyacı arasındaki farkların mutlak değerleri toplamının en küçükleme, (4) belirli bir zaman aralığı için (gün,hafta vb.) en büyük kaynak ihtiyacı değerinin en küçükleme, (5) belirli bir zaman aralığı için (gün,hafta vb.) en büyük kaynak ihtiyacı farkının en küçükleme, (6) belirli bir zaman aralığı için (gün,hafta vb.) en büyük kaynak ihtiyacı ile ortalama kaynak ihtiyacı arasındaki farkın mutlak değerinin en küçükleme, (7) belirli bir zaman aralığı için (gün,hafta vb.) kaynak ihtiyacı değerlerinin karelerinin toplamının en küçükleme, (8) belirli bir zaman aralığı için (gün,hafta vb.) kaynak ihtiyacındaki farkın karelerinin toplamının en küçükleme, (9) belirli bir zaman aralığı için (gün,hafta vb.) kaynak ihtiyacı ile ortalama kaynak ihtiyacı arasındaki farkların karelerinin toplamının en küçükleme. Ancak, literatürde mahal tabanlı iş programı hazırlama yöntemlerinin temelini oluşturan denge diyagramı yöntemiyle hazırlanan iş programlarında kaynak dengelemesi için geliştirilmiş ve dokuz amaç fonksiyonunun etkilerini araştıran bir modele rastlanmamıştır. Bu çalışmada, tekrar arz eden aktivitelerden oluşan inşaat projelerinin denge diyagramı ile hazırlanan iş programlarında kaynak dengelemesi için kullanılacak bir model geliştirilmiştir.

Literatür araştırmasında incelenen kaynak dengeleme çalışmalarında kullanılan yöntemler üç gruba ayrılabilir: (1) analitik yöntemler, (2) bulgusal yöntemler, (3) meta-bulgusal yöntemler. Analitik yöntemlerle (tamsayı ile doğrusal programlama, vb.) geliştirilen modeller küçük ölçekli problemlerde uygun çözümleri vermesine rağmen büyük ölçekli problemlerde yetersiz kalmaktadır. Bulgusal yöntemlerle geliştirilen yöntemler basit biçimleri nedeniyle uygulamada başarılıdır. Ancak, probleme bağlı doğaları nedeniyle farklı türde problemlerde en iyi sonucu veremeyebilir. Meta-bulgusal yöntemler (genetik algoritma, vb.) ise diğer yöntemler yardımıyla çözülemeyen problemlerde kullanılmaktadır. Bu çalışmada kaynak dengelemede kullanılmak üzere meta-bulgusal yöntemlerden biri olan ve diğer yöntemlerin yetersiz kaldığı noktaları belirli ölçüde gideren genetik algoritma kullanılmıştır. Kaynak dengeleme problemini genetik algoritma ile çözmek için “Microsoft Excel” programında ek yazılım olarak çalışan “Risk Solver Platform” kullanılmıştır.

Tekrar arz eden aktivitelerden oluşan inşaat projelerinin denge diyagramı ile hazırlanan iş programlarında kaynak dengelemesi için geliştirilen model esas olarak denge diyagramı yönteminde geçerli olan “doğal ritim” prensibine dayanmaktadır. “Doğal ritim” prensibinde, aktivitelerin farklı üniteler için başlangıç zamanları ileriye veya geriye ötelenabilir. Bu işlem aktivitenin bir ünitesi için gerekli olan yapım süresini değiştirmeden, kullanılan ekip sayısı değiştirilerek yapılmaktadır. Ayrıca, aktiviteler arasındaki ilişkiler ve projenin toplam tamamlanma süresi değişmemektedir.

Kaynak dengelemesi için genetik algoritma modelinin oluşturulması sürecinde ilk adım olarak genlerden oluşan kromozomun gösteriminin nasıl olacağının belirlenmiştir. Bu çalışmada, bir kromozomun genleri aktivitenin farklı ünitelerde sahip olduğu ekip sayılarını temsil etmektedir. Bir kromozomu oluşturan genlerin toplam sayısı tamamlanacak olan ünitelerin toplam sayısına eşittir. İkinci adım, kromozomların uygunluğunu değerlendirmek için kullanılacak olan amaç fonksiyonunun belirlenmesidir. Bu çalışmada kaynak dengelemesi probleminin çözümü için dokuz farklı amaç fonksiyonu kullanılmıştır. “Risk Solver Platform” programında amaç fonksiyonunu temsil eden bir “Microsoft Excel” hücresi tanımlanmıştır.

Genetik algoritma modelinin oluşturulmasında bir sonraki adım model için kısıtların tanımlanmasıdır. Genetik algoritma modeli, kısıtları sağlamayan çözümleri popülasyona dahil etmemektedir. Kısıtlardan biri aktivitelerin ekip sayıları için alabileceği en küçük ve en yüksek değerleri belirlemektedir. Dördüncü adım, popülasyon büyüklüğünün, çaprazlama ve mutasyon oranının belirlenmesidir. Gerekli olan tüm adımların tamamlanmasının ardından, model için bir “Microsoft Excel” sayfası oluşturulmuştur.

Kaynak dengelemesi için gerekli olan bilgiler (ünite sayıları, aktivitelerin her bir ünite için başlangıç zamanları, aktivitelerin her bir ünite için bitiş zamanları, ekip sayıları, eğim değerleri, aktivitelerin her bir ünite için tamamlanma süreleri, aktivitelerin bir ünitesinin tamamlanması için gerekli olan adam saat değerleri, bir ekip için en uygun kişi sayısı, günlük çalışma saati, günlük ihtiyaç duyulan kaynak miktarları) oluşturulan “Microsoft Excel” sayfasındaki kolonlarda gösterilmiştir. Aktivite isimleri de satırlarda gösterilmiştir. Oluşturulan “Microsoft Excel” sayfasında bir aktivite için belirli bir günde ihtiyaç duyulan kaynak miktarı, aktivitenin ünite başlangıç zamanları “doğal ritim” prensibine göre değiştirildiğinde, otomatik olarak değişmektedir. Böylece, model kaynak kullanımının dengelenmesi için en uygun ya da en uyguna en yakın sonucu bulabilmektedir.

Söz konusu modelin geliştirilmesinin ardından, kaynak dengelemesinde kullanılan farklı amaç fonksiyonlarının denge diyagramı yöntemiyle oluşturulan iş programlarının kaynak histogramları üzerindeki etkisi incelenmiştir. Tekrar arz eden aktivitelerden oluşan bir boru hattı projesinde kaynak tahsisi için yaratılmış iki farklı senaryo ile oluşturulan iki farklı iş programının kaynak histogramları, amaç fonksiyonlarının etkisinin incelenmesi için örnek olarak kullanılmıştır. Tüm girdiler belirlendikten sonra kaynak dengelemesi probleminin çözümü için oluşturulan genetik algoritma modeli dokuz amaç fonksiyonu için ayrı ayrı çalıştırılmıştır. Dokuz amaç fonksiyonunun kullanılan örnek için aynı iş programını ve kaynak histogramını verdiği tespit edilmiştir. Elde edilen kaynak histogramı dengelemeden önceki histograma göre daha verimli bir kaynak dağılımı sağlamıştır. Farklı amaç fonksiyonlarının kaynak dengelemesi sonrasında aynı iş programını oluşturmaları şu şekilde açıklanabilir; (1) denge diyagramı ile hazırlanan iş programlarında kaynak dengelemesinde kullanılabilecek kritik olmayan aktivitelerin sayısı oldukça azdır (2) kritik olmayan aktivitelerin bolluklarının kullanımı, denge diyagramı yönteminde ekiplerin en verimli şekilde bekleme yapmadan çalışmalarını sağlayan “doğal ritim” prensibi nedeniyle kısıtlanmaktadır. Farklı amaç fonksiyonlarının kaynak dağılımı üzerindeki etkisinin kullanılan projenin kritik olmayan aktivitelerinin sayısına ve bolluklarına bağlı olarak değişebileceği tespit edilmiştir.

Aynı örnek proje birden fazla kaynak kullanıldığı durumda da kaynak dengelemesi için kullanılmıştır. Geliştirilen model, bir aktivitenin üretim oranının ve süresinin bir ünitenin üretimi için en uzun süreyi veren kaynak tarafından belirlendiğini kabul etmektedir. Üretim oranını ve süresini belirleyen kaynak, baskın kaynak olarak adlandırılmıştır. Birden fazla kaynak kullanımı için kaynak dengelemesi sonrasında elde edilen kaynak histogramı dengelemeden önceki histograma göre daha verimli bir kaynak dağılımı sağlamıştır. Ancak, bir ünitenin üretimi için en uzun süreyi veren baskın kaynağın diğer kaynaklar için üretim oranını ve süresini belirlemesi, baskın kaynak dışındaki kaynakların “doğal ritim” prensibinden taviz vermelerine neden olmaktadır.

1. INTRODUCTION

1.1 Problem Statement

The development of reliable schedules is one of the key factors in achieving project goals. The use of an inappropriate scheduling method can easily result in failure of achieving project goals. Several studies reveal that network-based scheduling methods such as the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) are inadequate for linear construction projects (e.g., highways, tunnels, pipelines, high-rise buildings, railways, etc.) which exhibit repetitive characteristics where the same basic unit is repeated several times. The shortcomings of network-based scheduling methods in linear construction projects are (Hegazy et al. 1993, Mattila 1997, Arditi et al. 2002a):

- Difficulties in visualization of a large network that consists of repetitive activities,
- The focus on minimizing project duration rather than dealing with time/space conflicts and resource constraints,
- Not clearly showing activities' rates of progress relative to the units to be constructed.

The bar chart (Gantt chart) is another scheduling method that is preferred in construction projects as it is simple and has universal appeal. Nevertheless, bar charts do not show interrelationships between activities, which in turn causes difficulties in modifying and updating the schedule (Arditi et al. 2002a). Due to these shortcomings, alternative methodologies that are known under the generic term "linear scheduling methods" have been developed in the last 40 years (Hegazy et al. 1993, Mattila 1997, Arditi et al. 2002a, Arditi et al. 2002b). However, the use of linear scheduling methods is not enough to complete a linear construction project without a failure. The process of planning or management of resources is as important as using an appropriate scheduling method (Popescu 1976, Mattila and

Abraham 1998). The steps for the process described by Battersby (1970) include the following:

- Defining the objectives of a project and the resources for the accomplishment of project objectives.
- Determining the available resources and quantities.
- Constructing an initial schedule in order to confirm that the resources available are enough to accomplish the project objectives.
- Reviewing the project objectives and modifying them if the resources available are not enough to accomplish the project objectives or acquiring the required resources.
- Examining other projects that may need similar resources and determining the priority.

There are two common approaches for management of resources; (1) resource allocation, and (2) resource leveling. Resource allocation or resource-constrained scheduling, assumes that there are limitations on resources. The main objective of this approach is to minimize project duration according to the constraints on resources (Senouci and Adeli 2001). The linear scheduling methods, by their very nature, do exactly the same. But linear scheduling methods do not deal with resource leveling or resource smoothing. Resource leveling assumes that there are sufficient resources available, but that, the project duration is fixed. The goal of resource leveling is to minimize fluctuations, peaks and valleys in resource utilization without changing the project duration (Son and Skibniewski 1999, Leu et al. 2000, Hegazy and Ersahin 2001, Senouci and Adeli 2001, Doulabi et al. 2010, Hariga and El-Sayegh 2010). Some research has been conducted into resource leveling in linear schedules (Dubey 1993, Elwany et al. 1998, Mattila and Abraham 1998, Yen 2005, Georgy 2008, Lucko 2010), but none of them dealt with using different objective functions for resource leveling in schedules established by using line-of-balance (LOB) methodology that is a linear scheduling method. Nine different objective functions were determined with the review of the literature about resource leveling in network-based schedules and linear schedules, namely:

- Minimization of the sum of the absolute deviations in resource usage for a determined time interval (day, week etc.).
- Minimization of the sum of the only increases in resource usage for a determined time interval (day, week etc.).
- Minimization of the sum of the absolute deviations between resource usage for a determined time interval (day, week etc.) and the average resource usage.
- Minimization of the maximum resource usage for a determined time interval (day, week etc.).
- Minimization of the maximum deviation in resource usage for a determined time interval (day, week etc.).
- Minimization of the maximum absolute deviation between resource usage for a determined time interval (day, week etc.) and the average resource usage.
- Minimization of the sum of the square of resource usage for a determined time interval (day, week etc.).
- Minimization of the sum of the square of the deviations in resource usage for a determined time interval (day, week etc.).
- Minimization of the sum of the square of the deviations between resource usage for a determined time interval (day, week etc.) and the average resource usage.

The methods used in studies on resource management in linear schedules can be categorized into three categories: (1) analytical methods, (2) heuristic methods and (3) metaheuristic methods. In analytical methods, the solution converges to the optimum iteratively or in a finite number of steps (e.g., linear programming, branch and bound algorithms). These methods can be useful for finding the optimum solution on small-scale problems; however, they can be inefficient on large-scale problems, because they may consume too much time in order to find the optimal solution. Heuristic methods (e.g., using a rules of thumb) can considerably speed up the process of finding a solution on large-scale problems, but they do not guarantee an optimal solution. Analytical and heuristic methods may fail to solve complex

optimization problems. Metaheuristics (e.g., genetic algorithms, tabu search, simulated annealing) can be used in order to solve complex optimization problems (Leu et al. 2000, Osman and Laporte 1996, Senouci and Eldin 2004, Taha 1995). Osman and Laporte (1996) defined metaheuristics “ as an iterative generation process which guides a subordinate heuristic by combining intelligently different concepts for exploring and exploiting the search space, learning strategies are used to structure information in order to find efficiently near-optimal solutions”. Resource leveling in real-life schedules is large-scale and complex problems since there are a great number of activities and dependencies among these activities. Therefore, it is commonly acknowledged that heuristic methods or metaheuristics may simply and fast solve resource leveling problem, but may not give the best solution in all cases (Leu et al. 2000, Senouci and Eldin 2004). This was the motivation for using the genetic algorithms in this study and other studies conducted by Hegazy (1999), and Senouci and Eldin (2004). The objective of this study is to investigate the impacts of using different objective functions in leveling resources in LOB schedules through a genetic algorithm-based model that uses the principles of “optimum crew size” and “natural rhythm” in adjusting the production rates of the activities.

The leveling was achieved by adjusting the production rates of “eligible” activities while implementing the principles of “optimum crew size” and “natural rhythm”. The basic principles of LOB, the meaning of “eligible” activities, the principles of “optimum crew size” and “natural rhythm”, and information about genetic algorithms and multi-resource leveling are presented in succeeding sections. The model was demonstrated on an illustrative pipeline project by setting up an LOB schedule and its resource utilization histogram, calculating the total project duration, the start/finish times of activities through basic LOB procedures, determining the particular activities that are eligible for resource leveling, running the genetic algorithm-based model, and generating and comparing the resource utilization histograms for nine different objective functions before and after resource leveling.

1.2 Objectives of the Research

This research is based on leveling the resources of a LOB schedule. The main objectives of this study are presented as follows:

1. Developing a model for single resource management and multi-resource leveling for schedules that are established by the LOB methodology,
2. Investigating the impacts of using different objective functions in leveling resources in LOB schedules through a genetic algorithm-based model that uses the principles of “optimum crew size” and “natural rhythm” to adjust the production rates of the activities.

1.3 Research Methodology

The following tasks were performed in this study:

1. Reviewing the literature on resource leveling in linear scheduling methods
2. Determining the objective functions that are used in leveling resources in network-based and linear schedules by reviewing the literature
3. Setting up an LOB schedule and its resource utilization histogram before resource leveling for an illustrative pipeline project
4. Determining the particular activities that are eligible for resource leveling according to their floats
5. Developing and running a genetic algorithm-based model for single resource leveling and multi-resource leveling in LOB schedules by using the illustrative schedule of a pipeline project
6. Generating and comparing the resource utilization histograms before and after performing resource leveling.

1.4 Research Scope

This thesis proposes a genetic algorithm-based model for leveling resources in LOB schedules. The outline of the thesis is described below.

This chapter presents the problem statement, the objectives of the research, and the research methodology.

In Chapter 2, an overview of previous studies focusing on resource leveling in linear schedules is presented.

Chapter 3 provides information about LOB and genetic algorithms. The basic principles of LOB, crossover process, the mutation process, the evaluation process, and the selection process are described thoroughly in this chapter.

In Chapter 4, the definition of resource leveling, the objective functions for resource leveling, the principles of “optimum crew size” and “natural rhythm”, the meaning of “eligible” activities for resource leveling, and an example pipeline project that is used for illustration of single resource leveling in LOB schedules are presented. An example pipeline project that is used as a demonstration of the resource leveling model is also introduced. The results that are obtained after resource leveling of the example pipeline project are discussed.

The definition of the “dominant” resource, the principles of multi-resource leveling in LOB schedules, an example pipeline project that is used for demonstration of multi-resource leveling in LOB schedules, and the discussion of the results of resource leveling are presented in Chapter 5.

Chapter 6 summarizes the results of the study and provides recommendations for future studies.

2. REVIEW OF PREVIOUS STUDIES ON RESOURCE MANAGEMENT IN LINEAR SCHEDULES

Resources are vitally important in linear scheduling methods as it is a resource driven scheduling methodology. However, researches in the area of resource leveling of linear schedules are limited. An overview of previous studies focusing on resource leveling in linear schedules is presented below:

Perera (1983) developed a method, which uses linear programming to determine the resource requirements in various activities, for resource allocation by considering resource-hour unit. Besides, the method also enables users to determine whether it is more economical to use additional resources. Perera (1983) applied the method to four activities in a housing unit in order to validate and test it. The method provides the opportunity for sharing resources, which are available in limited quantities, as an advantage. However, the method is not taking into account all resource constraints.

Dubey (1993) modified the minimum moment algorithm which is a resource leveling procedure for linear schedules formerly developed by Harris (1978). The new model is named as “modified minimum moment algorithm”. Some of the important modifications made include: (1) new rules were added to consider multiple location and variable resource usage for activities, and (2) some heuristic rules were modified in order to increase the computational efficiency. The modified algorithm was applied to eleven examples in order to validate and test the algorithm. Exploring alternative priority rules in selection of an activity for shifting on large-sized projects involving activities with significant amounts of float are recommended as a future study by Dubey (1993).

Elwany et al. (1998) developed a linear programming model for a single resource allocation and smoothening in repetitive construction projects. There are two objectives that the proposed model is based on, which are: (1) following a desirable resource histogram, and (2) minimizing the number of changes in resource requirements. The major limitations of the model are inability to consider variable resource requirements and the activities which are not continuous.

Mattila and Abraham (1998) presented a model for resource leveling of a linear construction schedule by using integer linear programming. The linear scheduling method—developed by Harmelink (1998)—is used as it provides an algorithm to determine the controlling activity path which consists of controlling activities. The production rate floats of activities which are used in shifting of non-controlling activities in order to level the resources, are identified by the controlling activity path. The proposed model intends to achieve two objective functions without changing the total project duration: (1) minimize the absolute sum of deviations from a desired resource rate, (2) minimize the absolute sum of day-to-day change in resource use. The proposed model was implemented on an actual highway construction project in order to validate and test the model. The most important advantage of the model is its ability to level multiple resources. Mattila and Abraham (1998) recommended the automation of the procedure and the use of stochastic production rates for future work.

Liu (1999) proposed an approach which consists of two heuristic models aim to minimize the project duration of linear construction projects under resource constraints. The first is a rule-of-thumb heuristic model which integrates the network technique features of critical path method (activity precedence relationship and float analysis) and controlling activity path concept –developed by Harmelink (1998)—for resolving resource conflicts within reasonable project duration. The feasible solution, which includes activity duration and resource assignment, is used as the input for the second optimization-based model called Heuristic Linear Scheduling (HLS). The HLS is a meta-heuristic model which seeks a near-optimal solution for linear construction project duration through Tabu Search algorithms. The proposed model was implemented on a highway and a housing project, in order to validate and test the model. Liu (1999) mentioned that the proposed model provided a 10% reduction in the total project duration. The most important limitation of the proposed model is not considering the interruptions of resource assignments and the corresponding resource requirements due to different crew sizes. Besides, Liu (1999) recommended evaluating the possibility of using simulated annealing and genetic algorithms on the proposed model and the extension of computerized efforts in order to provide automation.

Leu and Hwang (2001) proposed a genetic algorithm-based model for optimal repetitive scheduling under resource constraints via consideration of integrating resource allocation and resource sharing. Genetic algorithm was used to provide more flexibility for solving complex repetitive scheduling problems and explore several near-optimal solutions. Precast production is used in order to validate and test the effectiveness of the proposed model. The model effectively provided near-optimal set of production durations and resource amounts. Use of stochastic activity durations and learning curve effects were recommended in the study by Leu and Hwang (2001).

El-Rayes and Moselhi (2001) presented an automated and dynamic programming-based model for optimizing resource utilization for repetitive construction projects. Dynamic programming formulation intends to minimize the total duration of repetitive construction projects through the identification of an optimum crew formation and interruption option for each activity. Besides, the proposed model integrates a scheduling algorithm and an interruption algorithm in order to automate the generation of interruptions during scheduling. A validation and test of the model was done by a concrete bridge example which was previously presented in the literature. The proposed model provided a reduction in project duration, less total interruption days and earlier start dates which are considered as the advantages of the model.

Yen (2005) developed a model that handles both resource allocation and leveling simultaneously, in order to schedule linear construction projects with multiple resource constraints by improving the model developed by Liu (1999). Essentially, the model intends to achieve the goal of minimizing the project duration and the fluctuation in resource usage by a simulated annealing search algorithm. The proposed model was implemented on an artificial housing and highway pavement project in order to validate and test the model. The proposed model provided a reduction in the project duration of both projects. The most important contribution of the model is the use of different activity production rates at different locations which gives more flexibility in the resource assignments. However, Yen (2005) mentioned that this flexibility also can increase the computation time required to find a solution when the model is implemented in large construction projects with too many

decision variables. Furthermore, Yen (2005) recommended using a hybrid heuristic algorithm that overcomes the limitations of the proposed model.

Liu and Wang (2006) presented a constraint programming-based model which optimizes the allocation of resources required by linear construction projects. The model intends to minimize the total project duration or total cost for linear construction projects by considering the temporary addition of resources required to shorten the duration of specific activities which is called outsourcing resources. The proposed model was applied to a bridge construction example, which was originally introduced by El-Rayes and Moselhi (2001), in order to validate and assess the model. Besides, two different scenarios are conducted for the demonstration of the proposed model's capability. According to scenario analysis and example results, Liu and Wang (2006) mentioned that the consideration of outsourcing resources for linear construction projects creates a positive influence on the optimum solution.

Georgy (2008) presented a model which automates resource leveling procedure of linear construction projects under the linear scheduling model scheme—developed by Harmelink (1995)—via integration of genetic algorithms and AutoLISP programming language under AutoCAD. Genetic algorithm was used due to its ability to overcome the primary drawbacks of mathematical solutions, such as, inability to solve more complicated problems. Besides, AutoLISP was chosen because of its graphical-oriented capabilities and efficiency in handling the complex mathematical solutions of the genetic algorithms. Resource leveling procedure was performed by minimizing either day-to-day fluctuations in resource usage or daily deviations from the average resource usage throughout the linear construction project. A validation and comparison of the proposed automated model was done via a case study of an actual highway project which previously presented by Mattila and Abraham (1998). Georgy (2008) mentioned that the proposed model provided an improvement on resource leveling process in comparison with the previous study conducted by Mattila and Abraham (1998). However, the model cannot handle the varying resource utilization rates and multiple-resource leveling.

Hsie et al. (2009) developed a new optimization model, which considers limited availability of resources for linear construction projects. The proposed model minimizes the project duration by automatically selecting the optimal set of production rates for activities in terms of crew composition and size in different time

periods. An evolutionary strategies algorithm is used in order to solve the combinatorial optimization problem, due to its easiness in programming and short execution time. A real-life ditch upgrade project is used to validate and test the proposed model. The most important advantage of the proposed model is the ability to handle real life situations, such as: (1) ability to use variable production rates in different locations, (2) crews may start and finish at different locations and skip certain portions of the project; and (3) an activity may have multiple predecessors and successors.

Lucko (2010) proposed a model for resource leveling of linear schedules by using singularity functions which include all possible permutations from shifting activities or changing their resource rates. The model also provides a basis for subsequent optimization via a genetic algorithm. A validation of the proposed model was done via a case study of an actual highway project which was previously presented by Mattila and Abraham (1998) and performed comparably well. The proposed model has a number of advantages in comparison to previous studies, such as: (1) reduces the required number of variables and constraints significantly, (2) efficiently models even large resource loaded linear schedules, (3) its singularity functions are flexible to make the proposed approach extensible. Nevertheless, the model cannot handle multiple parallel resource types and probabilistic durations.

3. RESEARCH METHODOLOGY

The literature review points out that there is a need for investigating the impacts of using different objective functions in leveling resources in LOB schedules. A genetic algorithm-based model that uses the principles of “optimum crew size” and “natural rhythm” in adjusting the production rates of the activities was developed in order to investigate those impacts. This chapter explains the methods and programs that were used during the development of the model, namely, line-of-balance scheduling, genetic algorithms and Evolutionary Solver.

3.1 Line-of-balance Scheduling

The U.S. Navy Department initiated the development process of the Line-of-Balance (LOB) methodology as a response to the need for improving the planning and control of manufacturing processes in 1942. The Goodyear Company also used the LOB methodology in the early 1950s and made significant contributions to its development. (Johnston 1981, Arditi and Albulak 1986, Mattila and Abraham 1998, Arditi et al. 2001a, Arditi et al. 2001b, Arditi et al. 2002a, Arditi et al. 2002b, Tokdemir et al. 2006) Construction researchers and professionals adopted LOB as soon as they became aware that it might be useful in scheduling linear construction projects, because the repetitive sequences of activities in linear construction projects are similar to industrial manufacturing processes (Arditi and Albulak 1986, Arditi et al. 2002, Tokdemir et al. 2006). Many researchers have made modification to the LOB methodology and expanded its features into different methods such as, velocity diagrams (Roeh 1972), construction planning technique (Peer and Selinger 1973), vertical production method (O’Brein 1975), linear scheduling model (Johnston 1981), time space scheduling method (Stradal and Cacha 1982), repetitive project model (Reda 1990). However, all of these variations are essentially traced back to the LOB methodology (Lumsden 1968).

The LOB schedule of a linear construction project can provide much more information than a schedule constructed for the same linear construction project by a

network-based scheduling method. For example, the construction of 200 houses that have the same design would result in a network of some 6,000 to 12,000 activities if the schedule is constructed by a network-based scheduling method. The presentation of the network, the collection of the progress data, and the update of the network will be very difficult because due to this large network. It is possible to eliminate these problems with a schedule that is constructed by using the LOB methodology (Lumsden 1968). The advantages that make LOB methodology a better scheduling technique for a project composed of repetitive activities than any other scheduling technique are stated below (Arditi and Albulak 1986, Tokdemir et al. 2006):

- The production rate and duration information can be interpreted easily through a LOB schedule. The ability to quickly establish the current state of the project provides an opportunity for effective decision making and performance measurements.
- The scheduler can easily determine which activity is falling behind and what is wrong with the progress of an activity.
- The LOB methodology allows adjusting the activities' rates of production. The rate of production of an activity that is falling behind can be accelerated in order to complete the activity in time.

The information required for each activity to set up an LOB schedule is composed of the following:

1. The required worker-hours for the production of a unit,
2. The optimum crew size, and
3. The daily working hours.

The duration of an activity in a unit can be computed by dividing its required worker-hours by the optimum crew size and daily working hours. The duration of an activity in a unit is constant for each activity as long as the optimum crew size is preserved in each activity. The calculation of the start and the finish times of an activity at each unit is the final step before plotting the LOB diagram. The relationship between the number of units produced and time is similar to the equation of a line (Figure 3.1).

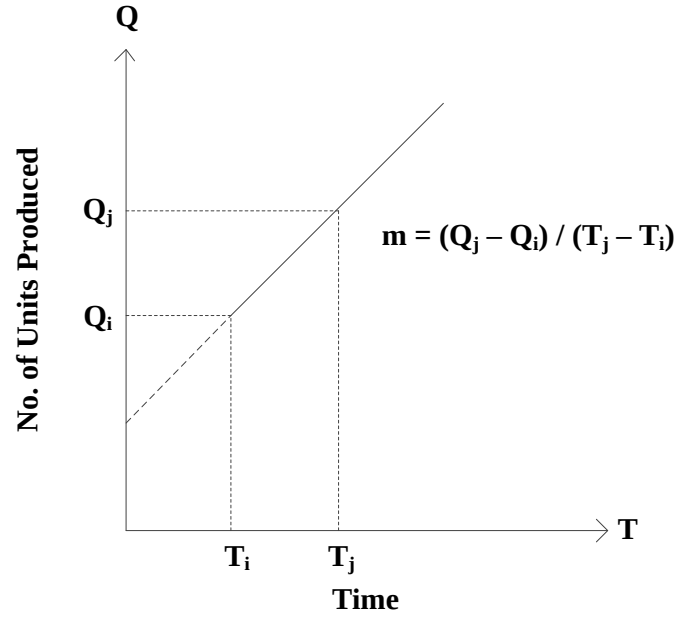


Figure 3.1 : Relationship between LOB quantities and time (Lumsden 1968).

The slope of the line joining the start (or finish) times of the repetitive activity in each unit is calculated as follows (Arditi and Albulak 1986, Arditi et al. 2002a):

$$m = \frac{Q_j - Q_i}{T_j - T_i} \quad (3.1)$$

where m = the slope of the line; Q_j and Q_i = number of units; T_j and T_i = time elapsed between the start of the project and the start of the i^{th} and j^{th} units, respectively.

It is possible to calculate the time for how long the target number of units should be achieved with the Equation 1. For example, if the first unit is to be completed at day 10, at what time will the 40th unit be completed if a start-to-start (or finish-to-finish) production rate of 2 per day is achieved.

$$Q_1 = 2 \text{ units}$$

$$t_1 = 10 \text{ days}$$

$$Q_2 = 40 \text{ units}$$

$$m = 2 \text{ units/day}$$

$$t_2 = t_1 + \frac{Q_2 - Q_1}{m} \text{ derived from Equation 1.}$$

$$t_2 = 10 \text{ days} + \frac{40 \text{ units} - 1 \text{ unit}}{2 \text{ units/day}}$$

$$t_2 = 10 \text{ days} + 19.5 \text{ days}$$

$$t_2 = 29.5 \text{ days}$$

In an LOB diagram, the start and finish times of an activity at each unit are represented by two oblique and parallel lines where the x-axis and the y-axis show the time and the number of units to be produced, respectively (Figure 3.2). The slope (m) of these two oblique and parallel lines represents the start-to-start (or finish-to-finish) production rate (Lumsden 1968). For example, in Figure 3.2 where only one crew is used on an activity, moving from one unit to the next, the start-to-start (or finish-to-finish) production rate (m) is calculated as: $(5-1) / (4-0) = 1 \text{ unit/day}$.

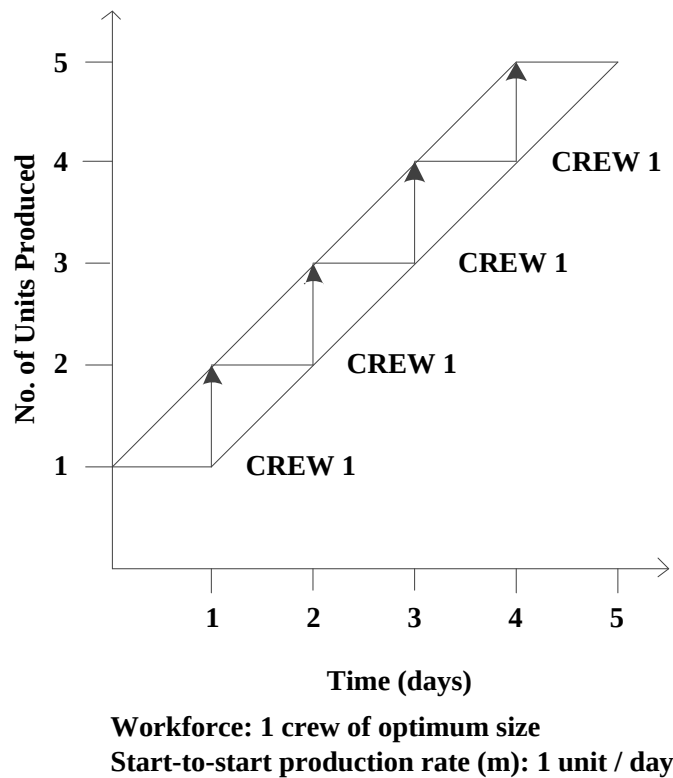


Figure 3.2 : Exmple of an LOB diagram.

Throughout the text, the use of the LOB methodology is explained with a calculation of the start and finish times of activities and representing them in a graphical form. However, dealing only with the start and finish times of activities is not enough to construct a reliable schedule. The management of resources also has a crucial effect on the construction of schedules that is explained in the following chapter.

3.2 Genetic Algorithms

Genetic algorithms are metaheuristic methods that simulate the natural selection process in order to locate the global optimum or near-optimum solution for a particular problem. Essentially, the stronger individuals of a population stay alive in the natural selection process (Leu et al. 2000, Hegazy 1999, Senouci and Eldin 2004). The attempts to use genetic algorithms in locating the global optimum or near-optimum solution for engineering problems have been initiated in the late 1980s (Goldberg 1989). Genetic algorithms are different from traditional optimization methods. These differences might be considered as advantages, such as: (1) using a coding set of variables instead of variables themselves, (2) searching for a population of solutions for the problem in preference to improving a single solution (Goldberg 1989, Senouci and Eldin 2004). Moreover, there is a mounting interest for using genetic algorithms as an alternative to existing optimization models, because genetic algorithms are efficient in finding optimal solutions for large and complex problems (Hegazy 1999, Senouci and Eldin 2004).

In genetic algorithms, the feasible solutions for a problem are shown as chromosomes. In other words, the candidate solution of a problem is represented in a population of chromosomes (Hegazy 1999, Leu and Hung 2002). Each chromosome consists of a series of genes that represent the value of a variable for a particular problem. Binary or real numbers can be used to represent the values of the variables according to the nature of the problem or the preference of the user (Al-Tabtabai and Alex 1999, Hegazy 1999, Leu and Yang 1999b, Leu and Hung 2002).

The genetic algorithm manipulates reproduction, crossover and mutation to generate a population that consists of chromosomes representing the feasible solutions of a problem (Goldberg 1989, Senouci and Eldin 2004). The chromosomes evolve through a reproduction process among the population members. Crossover and mutation are required operations for the reproduction process that produces offsprings that might take part in the population as an alternative solution for the problem.

In the crossover operation, two randomly selected parent chromosomes merge by exchanging their information, in order to produce a pair of offspring that takes part in

the population as an alternative solution for the problem (Figure 3.3). In other words, a particular parent chromosome is fragmented into parts through a pre-determined crossover rate in order to exchange its parts with the corresponding parts of another parent chromosome (Senouci and Eldin 2004). Crossover rate is the parameter that affects the probability at which the crossover operator is applied. The crossover rate is usually high as it introduces new strings more quickly into the population. On the other hand, while too high crossover rate may cause high performance strings to be eliminated faster than selection can produce improvements, too low crossover rate may cause stagnation due to the lower exploration rate.

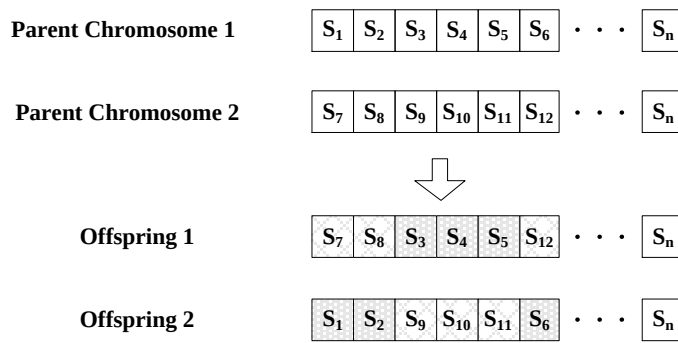


Figure 3.3 : Crossover process.

In mutation, contrary to crossover, only one randomly selected parent chromosome produces a new chromosome by changing its own genes through a pre-determined mutation rate (Figure 3.4). In other words, a chromosome is modified with a pre-determined mutation rate in order to produce an offspring that is nonexistent in the population. Mutation rate is the parameter that determines the probability that mutation will occur. The mutation rate is usually set low as a very high mutation rate may result in primitive random search. The mutation process provides candidate solutions that may never be explored without this process. Also, it has a natural advantage in that it can break any stagnation in the evolutionary process (Senouci and Eldin 2004, Hegazy and Kassab 2003).

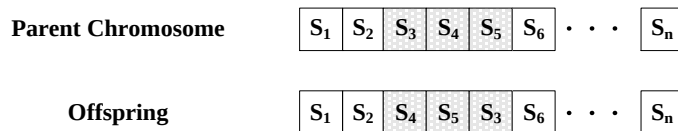


Figure 3.4 : Mutation process.

The chromosomes produced after the crossover and the mutation operations are evaluated by an fitness function. A fitness function ($F(x)$) is derived from the

objective function ($f(x)$) of a minimization or maximization problem. The fitness function can be the same as the objective function where a maximization problem is considered, because chromosomes that will survive are determined by maximizing the fitness function. Nevertheless, the objective function of a minimization problem has to be transformed to a fitness function that deals with a maximization problem (Equation 3.1). Only the chromosomes that fit the objective function better than others in the population survive in order to produce new chromosomes (Hegazy 1999, Leu and Hung 2002, Prashant and Ganguli 2011, Senouci and Eldin 2004, Wenyan 2011).

$$F(x) = 1 / (1 + f(x)) \quad (3.1)$$

This process seen in Figure 3.5 ends after the generation of a chromosome that represents the optimum or near-optimum solution for a particular problem (Hegazy 1999, Leu et al. 2000, Senouci and Eldin 2004).

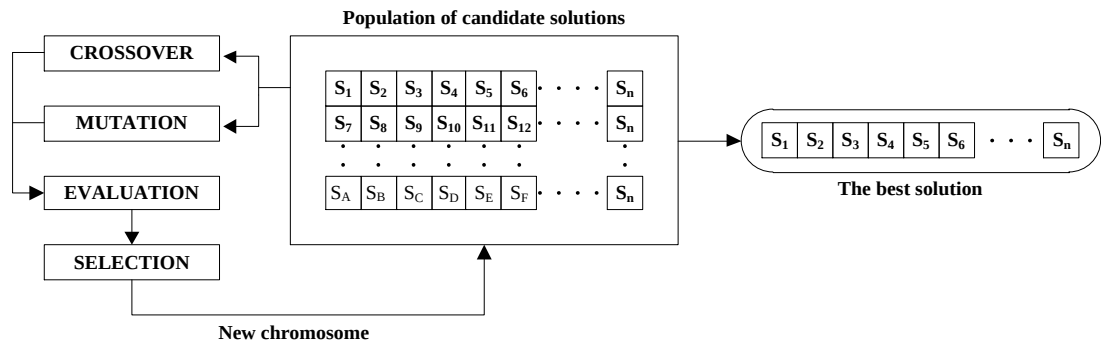


Figure 3.5 : Example for an operational flow of a genetic algorithm.

3.3 Evolutionary Solver

This study utilizes the Evolutionary Solver that is an add-in program for MS Excel. It deals with optimization problems through genetic algorithms. In other words, the Evolutionary Solver inspired by the natural selection process in order to locate the global optimum or near-optimum solution for a particular problem. The settings of Evolutionary Solver that the user is allowed to modify can be seen in Figure 3.6. Carter and Ragsdale (2002), Lee, Heaney and Lai (2005), Sample and Heaney (2006), Wright, Heaney and Dent (2006), Kim and Kim (2010), and Kim and Hong (2012) were also used Evolutionary Solver in their studies.

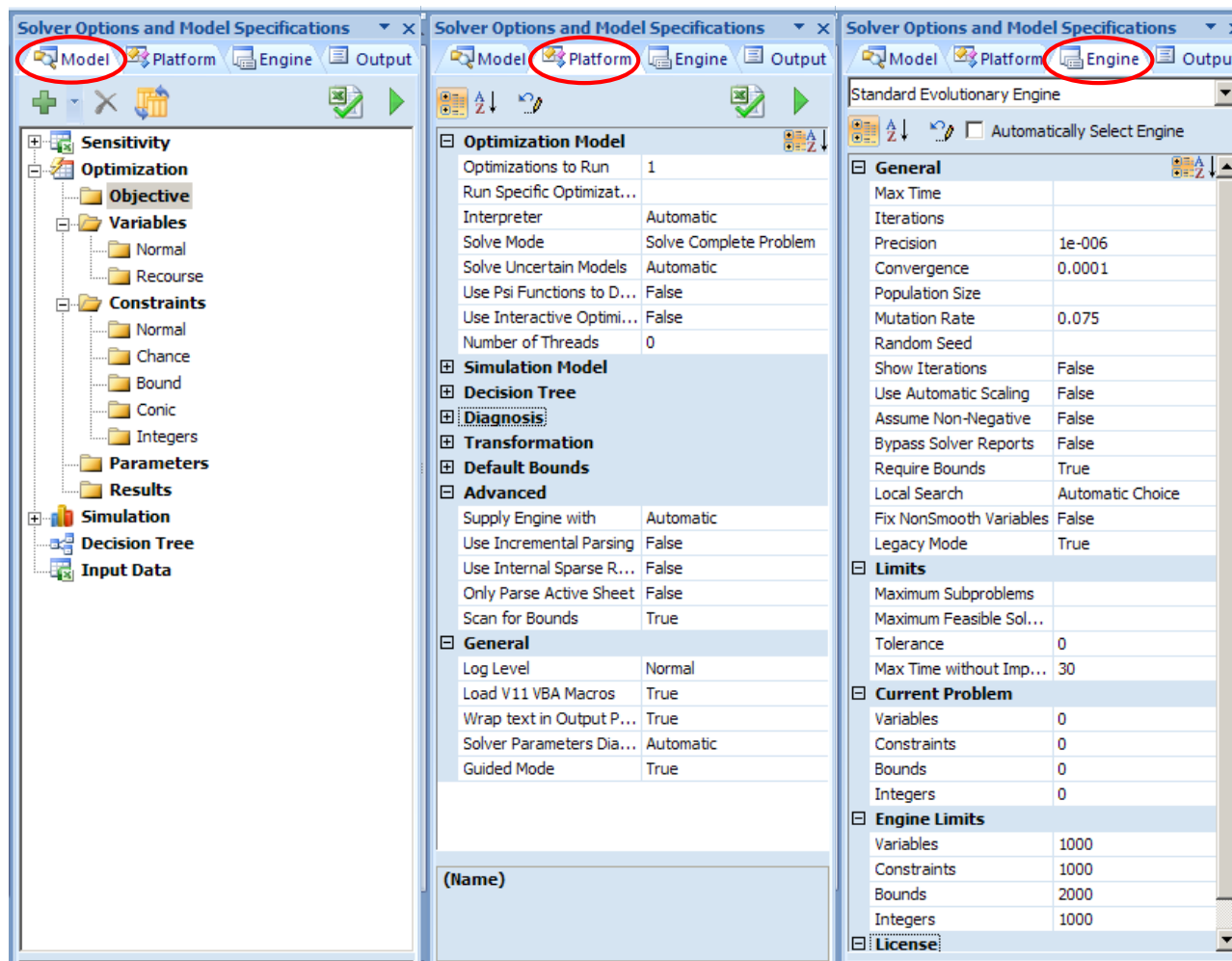


Figure 3.6 : Screenshot of Evolutionary Solver.

4. RESOURCE LEVELING IN LINE-OF-BALANCE METHODOLOGY

The development of reliable schedules is one of the key factors for achieving project goals. Reliable schedules can be constructed not only with an appropriate scheduling method but also by the efficient management of resources; because the duration of an activity depends on the required and available resources (Hinze 2008). Pierce (1998) defines resource management as follows: "Resource management is the decision-making process in which activities are prioritized and scheduled so that the expenditure of labor and/or equipment occurs in a desirable way."

There are two common approaches for the management of resources:

- Resource allocation.
- Resource leveling.

A common mistake that scheduler make is to assume that there is an unlimited supply of resources. The real-world situation is usually different for construction projects. Resource allocation or resource-constrained scheduling, assumes that there are limitations on the availability of resources. For example, one may need a single crane for two different tasks at the same time; or a painting crew may not be allowed to work alongside the electrician in a particular location (Naylor 1995). An adequate amount of resources must be supplied in a timely manner in order to prevent delays in activities and in order to complete the project as fast as possible (Pierce 1998). The main objective of this approach is to minimize project duration while attempting to ensure that a sufficient amount of the required resource is available at the right time (Pierce 1998, Senouci and Adeli 2001). LOB methodology, by its very nature, does exactly the same. But LOB methodology does not deal with resource leveling.

Resource leveling aims to ensure that the resources are used efficiently (Pierce 1998). Fluctuations in resource utilization could occur if the resource usage over a determined time period (day, week, month, etc.) is not constant (Naylor 1995). The goal of resource leveling is to minimize those fluctuations, peaks and valleys in resource utilization without changing the project duration. Resource leveling

assumes that there are sufficient resources available to complete the tasks, but that, the project duration is fixed unlike in resource allocation (Wiest and Levy 1977, Callahan et al. 1992, Son and Skibniewski 1999, Leu et al. 2000, Hegazy and Ersahin 2001, Senouci and Adeli 2001, Doulabi et al. 2010, Hariga and El-Sayegh 2010). Resource leveling may be desirable for several reasons presented below (Horowitz 1980, Stevens 1990, Pierce 1998):

- Minimizing the fluctuations in resource utilization: It is not desirable to have sharp fluctuations in resource requirements. For example, a schedule that requires 1 day of work, then being idle for 2 days, and another 2 days of work for craftspeople is an unsatisfactory situation because that kind of fluctuation has a negative effect on efficiency and productivity. When craftspeople are once hired, they cannot always be laid off and rehired. Besides, if it is not possible to rehire the same employees, and the process of recruiting, hiring, and training of new employees is costly, time-consuming and inefficient. It is desirable to keep the workers fully employed as much of the time as possible.
- The need of fixed resource demand for a determined time interval (i.e., day): It is commonly desirable to have a fixed number of resources to complete a project. For example, employing 40 workers on a day that 20 workers are required is not efficient. It is an unsatisfactory situation if there is a need for more workers per day than are available or if there are more workers per day than are needed.

Resource leveling can be performed through the steps that are stated below after constructing the initial schedule (Naylor 1995, Hinze 2008):

- Plotting a resource histogram (profile): The resource histogram is a time-based graph showing the number of resources needed on each day of the project where the x-axis and the y-axis show the time and the number of resources, respectively. The number of a resource required on each day is represented by a bar, in a resource histogram. The number of a resource required on a day is determined by the sum of the number of that resource being used for the completion of activities that are in progress on that day.
- Determining the total usage of a resource over the duration of a project: The sum of the areas of the bars represents the total number of resources required

for the project. For example, an activity that has a duration of 3 days needs 4 workers on each day. The total number of workers required for that activity is calculated by multiplying the duration of that activity and the number of workers (3 days x 4 workers = 12 worker-days). The total number of a resource can be calculated by executing this calculation for every activity of the project.

- Shifting the activities for leveling a resource: In this step, the start and finish times of activities are changed in a manner that the resource requirements will be more uniform. The principles that are used in order to determine the activities that are eligible for shifting can differ according to the linear scheduling method that is used for scheduling. These activities have a float that provides flexibility in the start and finish times. After shifting the eligible activities, it must be ensured that the total project duration, the precedence relationships between activities, and the total number of resource remain unchanged after resource leveling.
- Plotting the new resource histogram: The initial resource histogram will change after re-scheduling. The scheduler can plot the new resource histogram in order to provide the new resource demand on each day.

The aforementioned steps can be accommodated for a single resource or multiple resources. Harris (1978) states that when one resource is leveled, other resources tend to be leveled as well due to the fact that most of the resources are related to each other in construction projects. Nevertheless, there can be some situations where the scheduler may prefer to consider multiple resources for resource leveling. There are two common procedures for multiple resource leveling, namely:

- Resource leveling in series: Resources are leveled one by one in this procedure. Let's suppose that a scheduler considered two resources called Resource A and Resource B. The scheduler decided that Resource A has priority over Resource B. Resource leveling is first performed for Resource A. The position of each and every activity after the leveling of Resource A represents the schedule that will be used in the leveling of Resource B. The leveling procedure is repeated for Resource B. The resource histogram that is obtained for Resource A after the first leveling may change after the leveling

process for Resource B is performed. In this situation, both resources may be compromised when the final resource histograms are obtained.

- Resource leveling with combined resources: In this approach, resources are leveled in four steps, namely: (1) determine the weight of each resource according to a criterion that is determined by the scheduler; (2) plot a combined resource histogram by using the sum of the different resources after treating them with the weights determined in the previous step; (3) level the combined resource histogram; and (4) separate the resources and plot their respective histograms. Resource leveling with a combined resource histogram provides a significant time saving compared to the resource leveling in series. The time for leveling resources in series will be much longer as the number of resources increase.

The efficiency of resource leveling can depend on the objective function that is used for leveling the resources. The review of the studies on resource leveling of network-based scheduling methods and linear scheduling methods revealed that nine different objective functions had been used in resource leveling models (Table 4.1).

All of the studies presented in Table 4.1 have dealt with various aspects of resource leveling in schedules developed by network-based and linear scheduling methods. It was observed that no attempt was made to study the impacts of using different objective functions on resource leveling in schedules established by using the LOB methodology. The resource leveling model for LOB schedules that is presented in this study is based on the principles of “natural rhythm” and “optimum crew size.”

4.1 The Principle of “Natural Rhythm”

In LOB, the principle of “optimum crew size” assumes that the highest productivity can be achieved as long as an activity is performed in a unit of production by a crew of optimum size. Any crew that is composed of fewer or more workers is bound to result in lower productivity (Figure 4.1). It is therefore essential that optimal size crews be used in activities.

Table 4.1 : Objective Functions for Resource Leveling.

Objective Function No	Optimization Criteria	Source(s) for resource leveling in network-based scheduling methods	Source(s) for resource leveling in linear scheduling methods
1	Minimization of the sum of the absolute deviations in resource usage for a determined time interval (day, week etc.)	Wagner et al. (1964), Ahuja (1976), Easa (1989)	Mattila and Abraham (1998), Yen (2005), Georgy (2008)
2	Minimization of the sum of the only increases in resource usage for a determined time interval (day, week etc.)	Wagner et al. (1964)	-
3	Minimization of the sum of the absolute deviations between resource usage for a determined time interval (day, week etc.) and the average resource usage	Wagner et al. (1964), Easa (1989), Leu et al. (2000), Doulabi et al. (2010)	Elwany et al. (1998), Mattila and Abraham (1998), Georgy (2008)
4	Minimization of the maximum resource usage for a determined time interval (day, week etc.)	Wagner et al. (1964)	-
5	Minimization of the maximum deviation in resource usage for a determined time interval (day, week etc.)	Wagner et al. (1964)	-
6	Minimization of the maximum absolute deviation between resource usage for a determined time interval (day, week etc.) and the average resource usage	Popescu (1976)	-
7	Minimization of the sum of the square of resource usage for a determined time interval (day, week etc.)	Burgess and Killebrew (1962), Ahuja (1976), Harris (1978), Harris (1990), Son and Skibniewski (1999), Hiyassat [24], Hegazy and Ersahin [10], Hiyassat (2000,2001), Christodoulou et al. (2000)	Dubey (1993), Lucko (2011)
8	Minimization of the sum of the square of the deviations in resource usage for a determined time interval (day, week etc.)	Popescu (1976)	-
9	Minimization of the sum of the square of the deviations between resource usage for a determined time interval (day, week etc.) and the average resource usage	Popescu (1976)	-

The slope of the production line (start-to-start or finish-to-finish) of an activity is dependent on the number of crews. For example, if one crew is used, the crew will have to finish work in one unit before it can move to the next unit. If two crews are used, the slope of the production lines will be steeper. Slopes that are steeper than a one-crew production and less steep than a two-crew production are not acceptable as they will create a situation that will create idle times for crews. In other words, the

principle of “natural rhythm” implies that to increase the production rate of an activity, multiple crews of optimum size have to be used such that no idle time occurs when crews move from unit to unit.

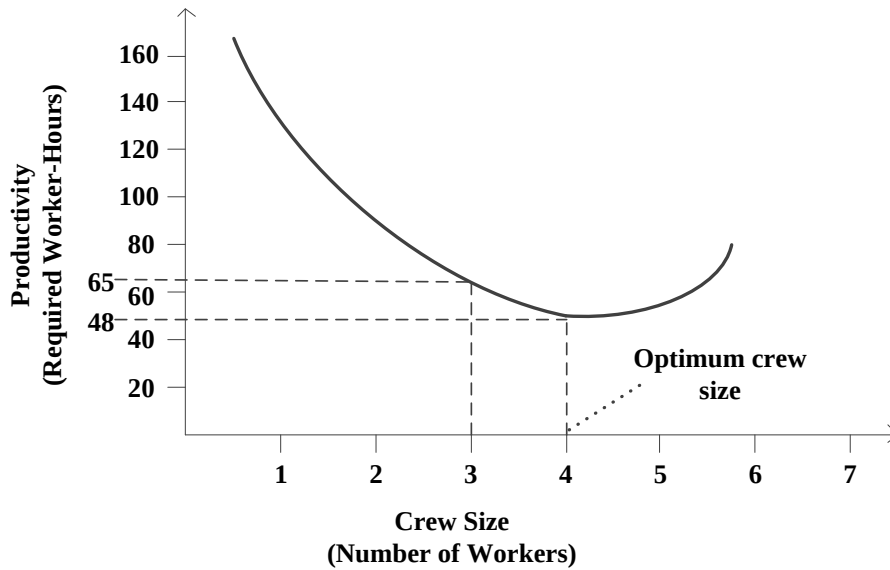
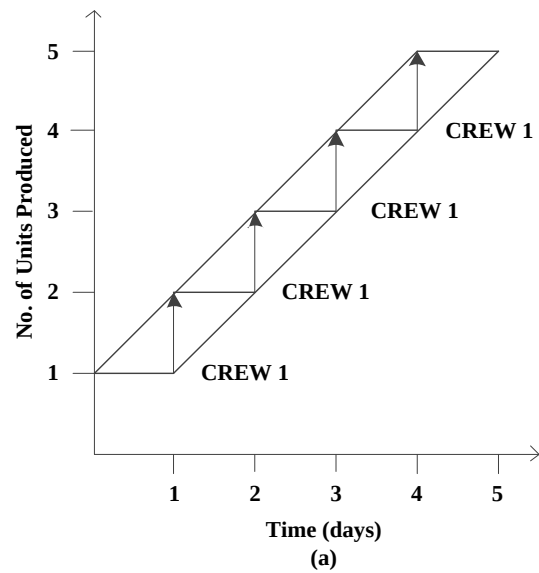
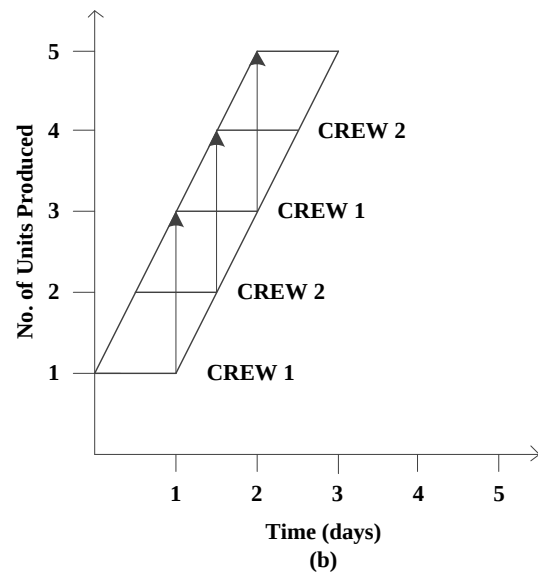


Figure 4.1 : Relationship between required worker-hours and crew size.

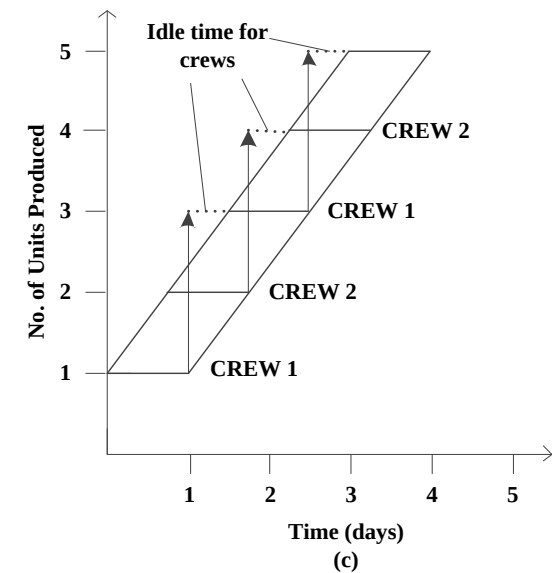
For example, Figures 4.2a and 4.2b show that doubling the production rate from 1 unit/day to 2 units/day is achieved by doubling the number of crews from 1 to 2. Note that in both cases the productivity remains the same (40 worker-hours/unit). Figure 4.2c shows that a production rate of 1.33 units/day (i.e., not a multiple of 1 unit/day) can only be achieved by using two crews at which time the productivity jumps from 40 worker-hours/unit in Figures 4.2a and 4.2b to 53 worker-hours/unit in Figure 4.2c because of the idle time for the crews. In other words, the situation in Figure 4.2c represents a rate of production that does not achieve natural rhythm (i.e., a multiple of 1 unit/day), with a direct consequence of increased worker-hours per unit. Even if a manager reduces the number of workers per crew to minimize idle time, productivity is still going to suffer because of the relationship presented in Figure 4.1. The principles of “optimum crew size” and “natural rhythm” provide the basis for the resource leveling model that is presented in this study.



Workforce: 1 crew of 5 workers
Start-to-start production rate: 1 unit per day
Productivity: 40 worker-hours/unit
Natural rhythm: Achieved



Workforce: 2 crews of 5 workers
Start-to-start production rate: 2 units per day
Productivity: 40 worker-hours/unit
Natural rhythm: Achieved



Workforce: 2 crews of 5 workers
Start-to-start production rate: 1.33 units per day
Productivity: 53 worker- hours/unit
Natural rhythm: Not achieved

Figure 4.2 : Examples of LOB diagram.

The principle of “natural rhythm” is an important part of LOB technology (Lumsden 1968), but has been largely ignored by most researchers who developed different linear scheduling alternatives over the years. It allows shifting the start times of an activity forwards or backwards at different units by changing the number of crews of the activity. This procedure does not change the duration of an activity in any unit since the activity is always carried out by a crew of optimal size. Furthermore, the total project duration and the precedence relationships between activities remain unchanged during the implementation of this procedure. The change of the number of crews of an activity in order to shift the start time of an activity forwards or backwards at different units is based on the following principles:

- Only activities such as Activity B in Figure 4.3a and Activity E in Figure 4.3b are candidates for the proposed procedure. These activities should have a finish to start relationship with the preceding and succeeding activities in the first (Figure 4.3a) or the last (Figure 4.3b) unit. Note that no buffer is used in this diagram. Had there been any buffer, the same principle would hold without violating buffer times.
- If an activity has a finish to start relationship with the preceding and succeeding activities in the first unit, such as Activity B in Figure 4.3a then the slope of the two lines that define it (i.e., its start-to-start or finish-to-finish production rate) must be less than the slope of the preceding activity and greater than the slope of the succeeding activity (Figure 4.3a). If an activity has a finish to start relationship with the preceding and succeeding activities in the last unit, such as Activity E in Figure 4.3b, then the slope of the two lines that define it (i.e., its start-to-start or finish-to-finish production rate) must be greater than the slope of the preceding activity and less than the slope of the succeeding activity (Figure 4.3b).

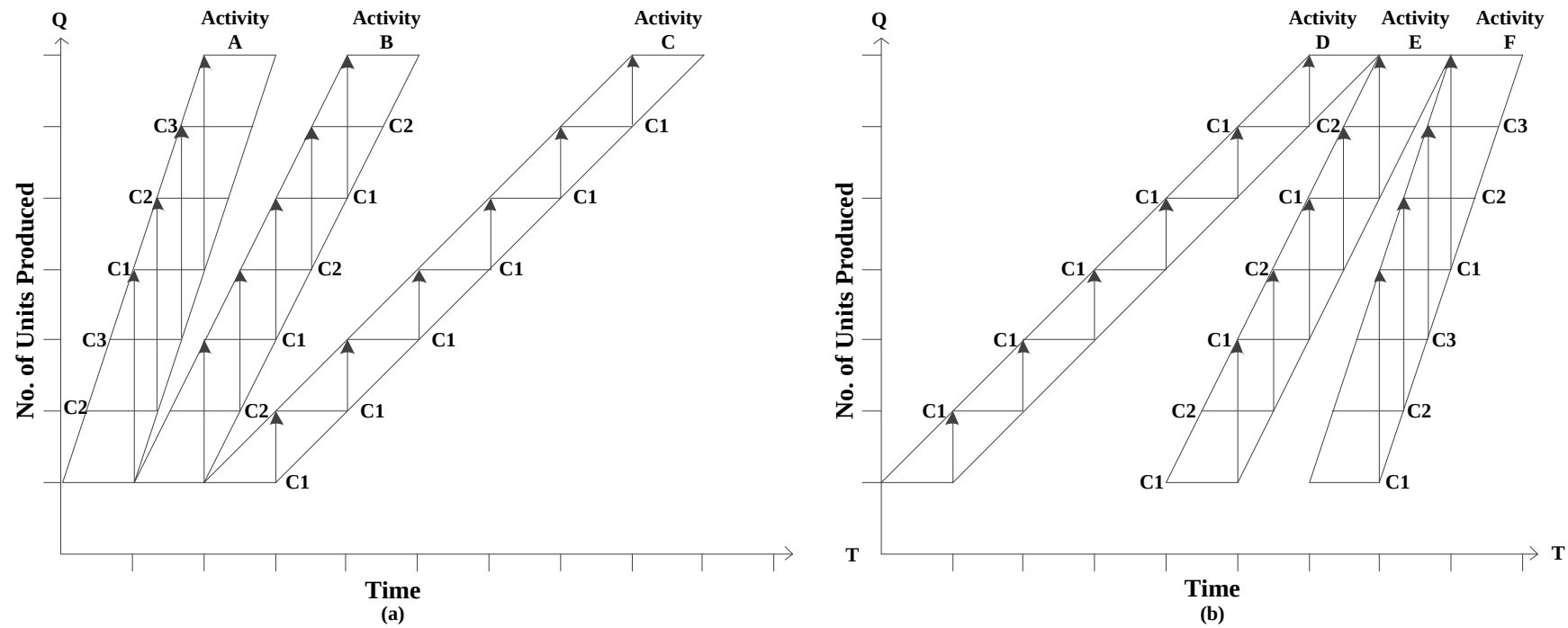


Figure 4.3 : Examples of LOB diagrams before using the principle of “natural rhythm” for resource leveling.

- The construction manager may use one or more than one crew on an activity, each crew working on a separate unit. If it is the first unit that sets up the precedence relationship between two activities, such as Activities A and B in Figure 4.3a, the number of crews used in Activity B can be equal to but should not be less than the number of crews this activity started out with (see Activity B in Figure 4.4a). The time between the finish time of Activity B in the last unit and the start of Activity C in the last unit constitutes the float of Activity B (Figure 4.3a), and can be used to accommodate resource leveling without affecting total project duration (Figure 4.4a). If it is the last unit that sets up the precedence relationship between two activities such as Activities E and F in Figure 4.3b, the number of crews in Activity E can be equal to but should not be greater than the number of crews this activity started out with (see Activity E in Figure 4.4b). The earliest change in the number of crews can be accommodated only after the first crew moves to its next destination (Figure 4.4a). The time between the finish time of Activity D in the first unit and the start of Activity E in the first unit constitutes the float of Activity E (Figure 4.3b), and can be used to accommodate resource leveling without affecting total project duration (Figure 4.4b).
- An activity that is eligible for resource leveling cannot be interrupted after it is been initiated.

Adjusting the number of crews in activities that meet the conditions mentioned above, makes it possible to obtain an optimum LOB schedule where the activity duration does not change from unit to unit, and where the same precedence relationships hold, but where a smoother distribution of resources is achieved over time. A LOB schedule of a pipeline project was used in order to demonstrated the principles that are explained above.

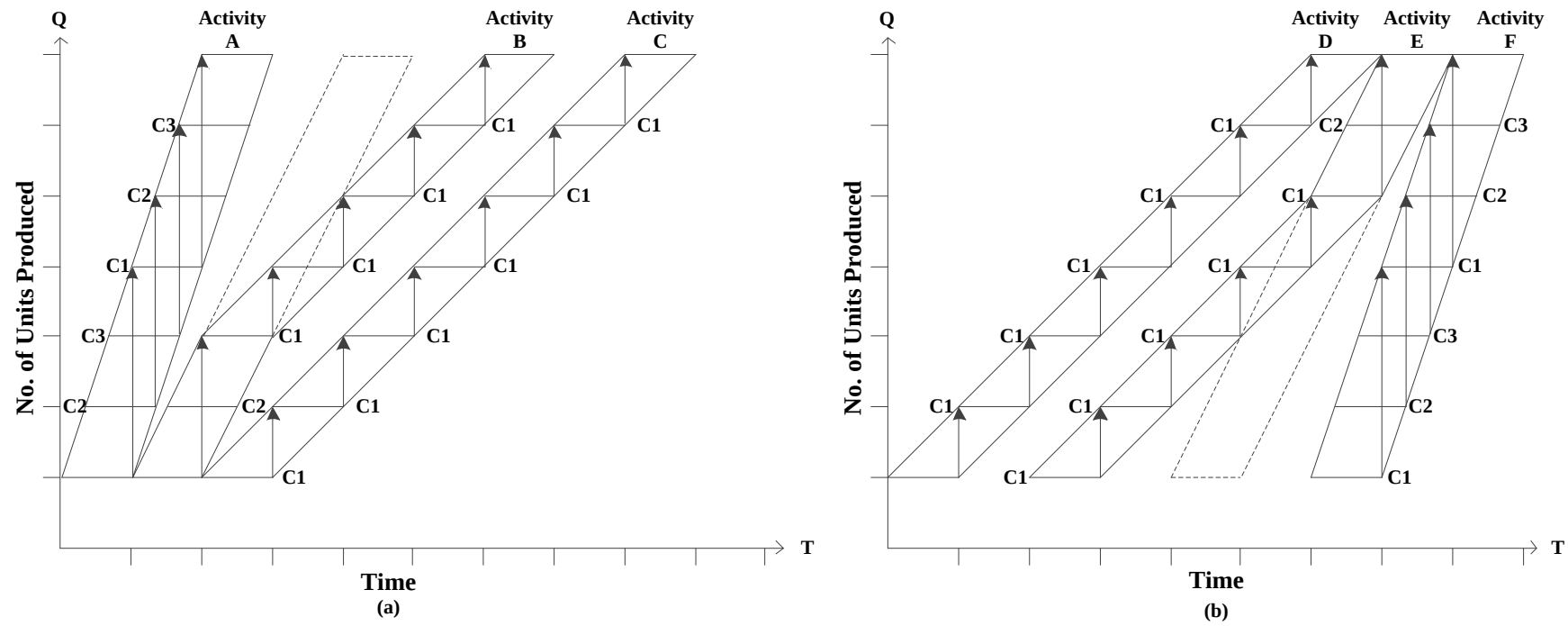


Figure 4.4 : Examples of LOB diagrams after using the principle of “natural rhythm” for resource leveling.

4.2 Example Pipeline Project

The impacts of using different objective functions for resource leveling in LOB can be best demonstrated through an example project. A LOB schedule for a pipeline project was established for this purpose. The length of the pipeline is 26 km and it should be completed in 65 days according to the contract. The pipeline project operations consist of seven consecutive activities that repeat themselves kilometer after kilometer throughout the project:

- Locating and clearing (Activity A),
- Excavating (Activity B),
- Laying aggregate (Activity C),
- Laying pipes (Activity D),
- Testing (Activity E),
- Backfilling (Activity F),
- Compacting (Activity G).

Each kilometer of pipeline is considered to be a unit of production. The LOB schedule has seven repetitive activities that are performed consecutively. Two different resource allocation scenarios are considered in this study. Scenario 1 considers a single resource being used in all activities, whereas in Scenario 2 a different single resource is being used in only few of the several activities. The information for each activity concerning worker hours, crew sizes, and daily working hours is shown in the left half of Table 4.2 for each scenario. This information can be obtained through the company's database or by direct interaction with a site manager who has experience in similar projects. Even though other resources are necessary for completing the activities of this pipeline project, only workers were considered in this study for demonstration purposes.

Each activity's duration in a unit is calculated by using the information for productivity, optimum crew size, and daily working hours. All durations are presented in Table 4.2. For example, given that resource is used in Activity B – Excavating for Scenario 1:

$$\begin{aligned}
\text{Duration per unit} &= \frac{\text{Required worker – hours}}{\text{Number of workers per crew} \times \text{Number of working hours per day}} \\
&= \frac{64 \text{ worker-hours per km}}{8 \text{ workers/crew} \times 8 \text{ hours/day}} \\
&= 1 \text{ day/km}
\end{aligned} \tag{4.2}$$

The rate of production of each activity is calculated on the basis of the duration and number of crews provided by the resource as long as the rate of production is limited to a multiple of the natural rhythm. For example, using the information in Table 5.2, for Activity B – Excavating in Scenario 1:

$$\begin{aligned}
\text{Production Rate} &= \text{Natural rhythm} \times \text{Number of crews} \\
&= \frac{1 \text{ unit}}{\text{Duration to produce one unit using one crew of optimal size}} \times \text{Number of crews of optimal size} \\
&= \frac{1 \text{ km}}{1 \text{ day}} \times 2 \text{ crews} \\
&= 2 \text{ km/day}
\end{aligned} \tag{4.3}$$

Table 4.2 : Information about activities.

Activity Name	Required Worker Hours to Finish Unit		Number of Workers in Optimum Crew		Daily Working Hours		Duration (days)		Number of Crews		Start-to-Start Productivity Rate (km/day)	
	S1*	S2**	S1*	S2**	S1*	S2**	S1*	S2**	S1*	S2**	S1*	S2**
(A) Locating and clearing	96	-	6	-	8	-	2	2	2	2	1	1
(B) Excavating	64	48	8	4	8	8	1	1.50	2	3	2	2
(C) Laying aggregate	80	24	10	3	8	8	1	1	3	4	3	4
(D) Laying pipes	84	40	7	5	8	8	1.5	1	2	2	1.33	2
(E) Testing	80	-	10	-	8	-	1	1	4	4	4	4
(F) Backfilling	96	24	6	3	8	8	2	1	5	3	2.5	3
(G) Compacting	144	36	9	3	8	8	2	1.5	2	2	1	1.33

Note: *S1: Scenario 1

**S2: Scenario 2

The first schedule for the pipeline project was established by using basic LOB calculations. It was assumed that only one crew is used in each activity. The schedule provided a project duration that exceeds the contract duration of 65 days. The schedule was then accelerated by using the principles put forward by Tokdemir et al. (2006), i.e., by increasing the number of crews in selected activities in order to meet the required completion time constraint. In other words, the schedule was

reestablished assuming no resource limitations in order to complete the project in 65 days, as seen in Figure 4.5 and Figure 4.6. Note that no buffer is used in this diagram. Had there been any buffer, the “natural rhythm” principle would hold without violating buffer times.

The resource histograms in Figure 4.7 and Figure 4.8 were plotted before leveling to reflect the conditions in the initial LOB schedule. The number of workers in an optimum size crew (for example, according to Table 4.2, 8 workers in Activity B in Scenario 1) was multiplied by the duration of the activity (in Table 4.2, 2 days for Activity B in Scenario 1) and by the number of kilometers of pipeline in the project (26 km) in order to calculate the total number of workers used in an activity (in this example, Activity B). The total workforce used in the project consists of the sum of the workers used in each and every activity A through G in the project (2,093 workers for Scenario 1, and 559 workers for Scenario 2). The average number of workers per day is calculated by dividing the total workforce used in the project (2,093 workers in Scenario 1 and 559 workers in Scenario 2) by the duration of the project (65 days in Scenario 1 and 53 days in Scenario 2). The outcomes for Scenario 1 and Scenario 2 are 32.2 workers/day and 10.6 workers/day, respectively. These results are rounded up to 33 workers/day for Scenario 1 and 11 workers/day for Scenario 2 due to the nature of the resource (i.e., worker) that is used in this study. Also, based on the criteria presented earlier, the activities that are eligible for resource leveling are excavating (Activity B) and backfilling (Activity F).

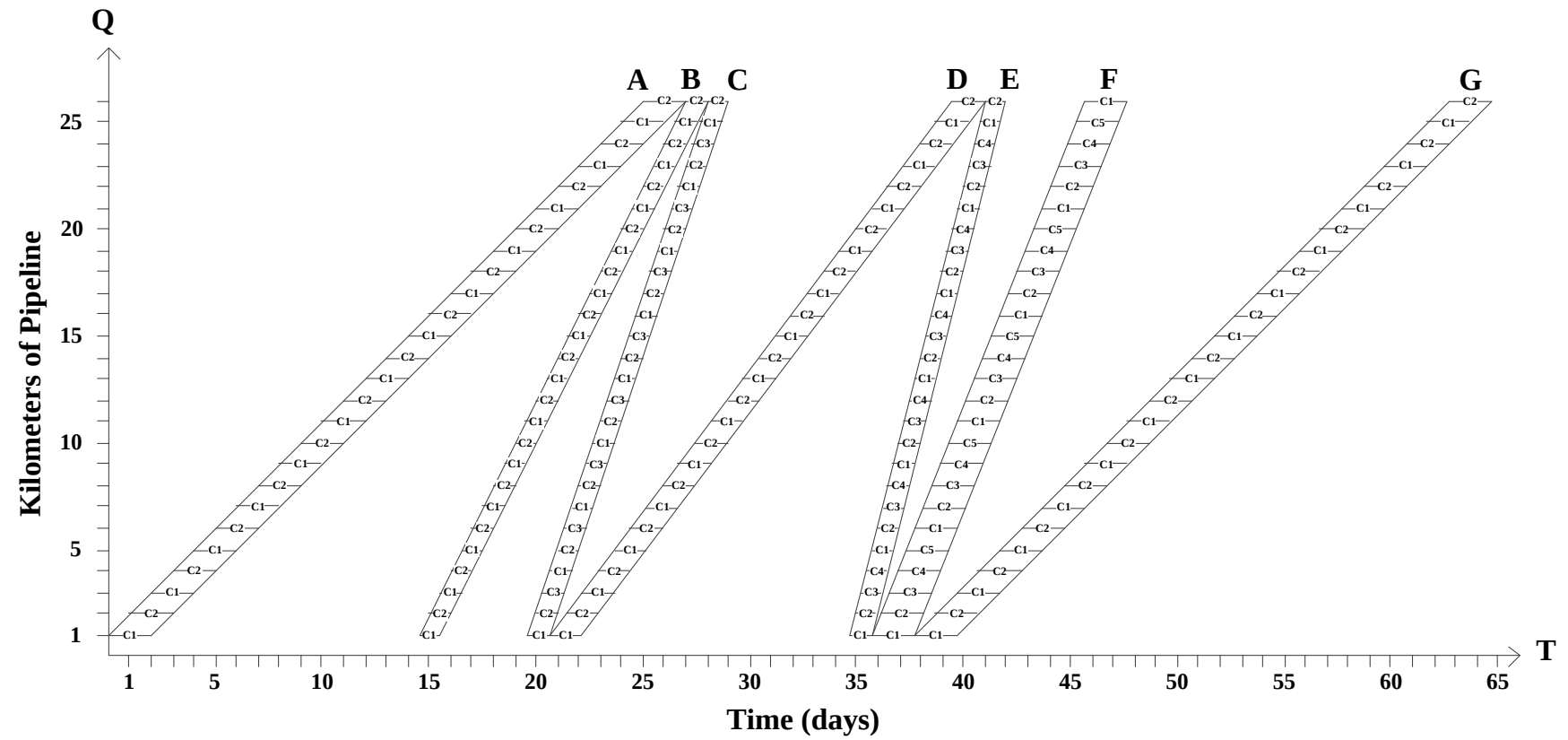


Figure 4.5 : The LOB schedule before resource leveling for Scenario 1.

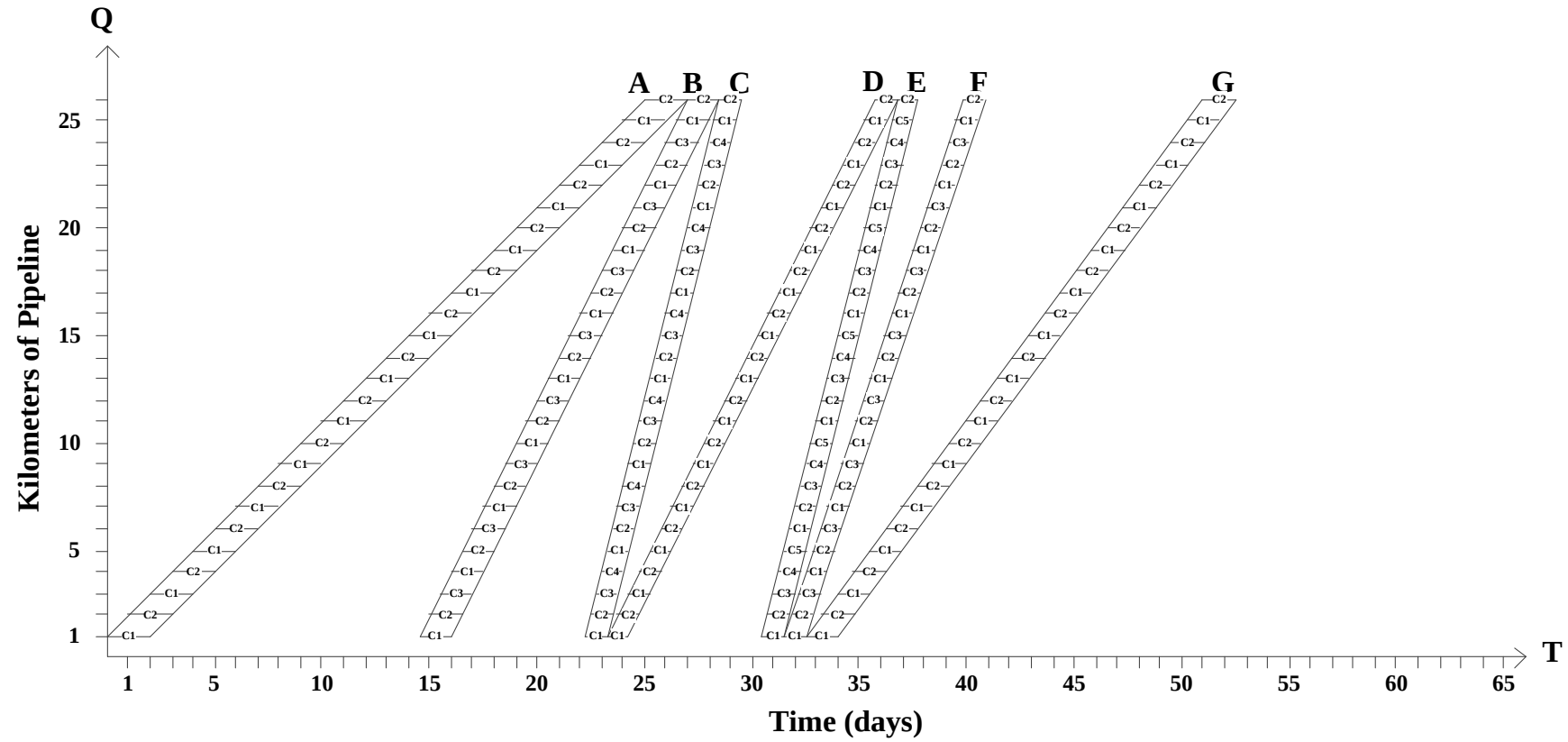


Figure 4.6 : The LOB schedule before resource leveling for Scenario 2.

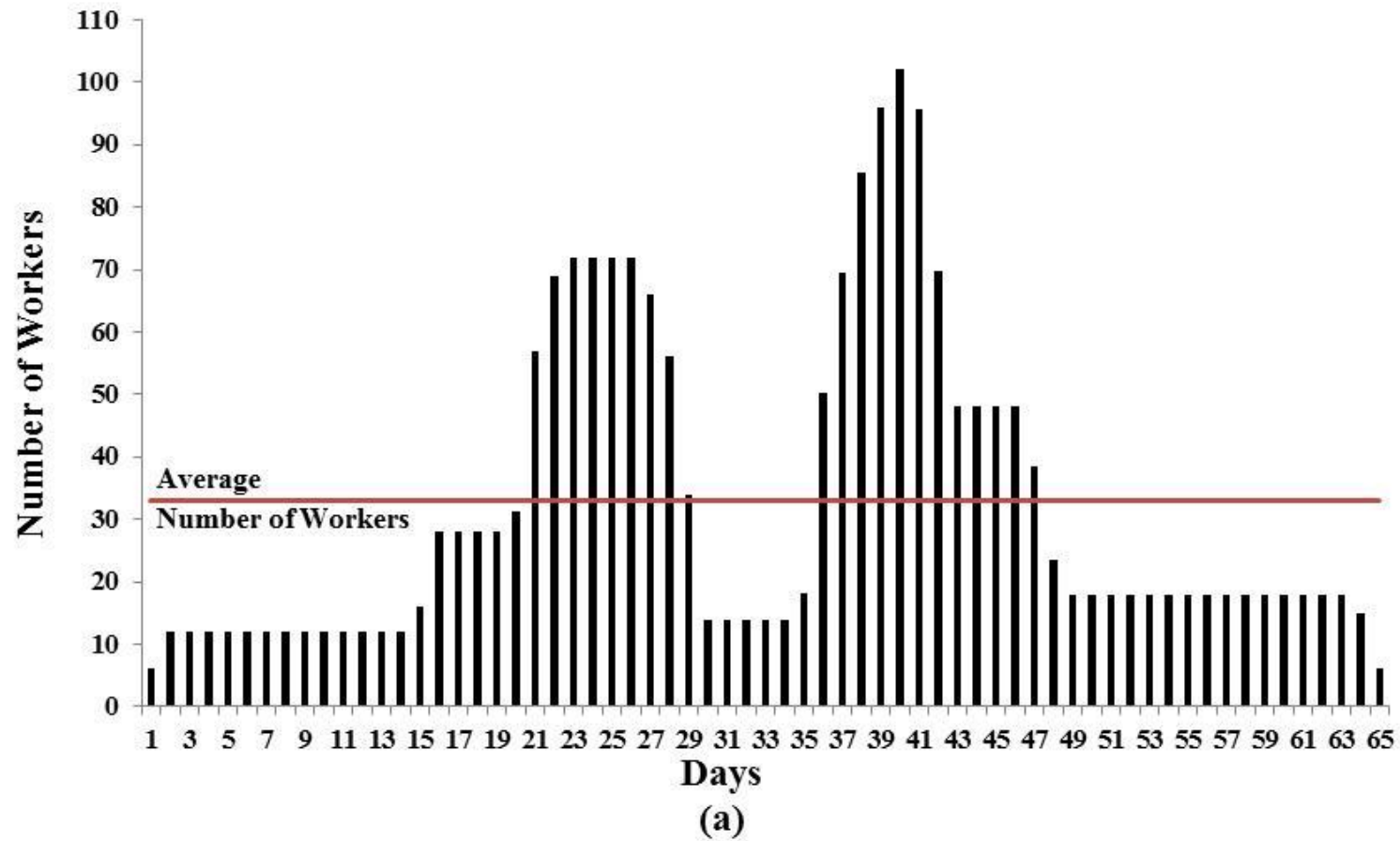


Figure 4.7 : Resource histogram before resource leveling for Scenario 1.

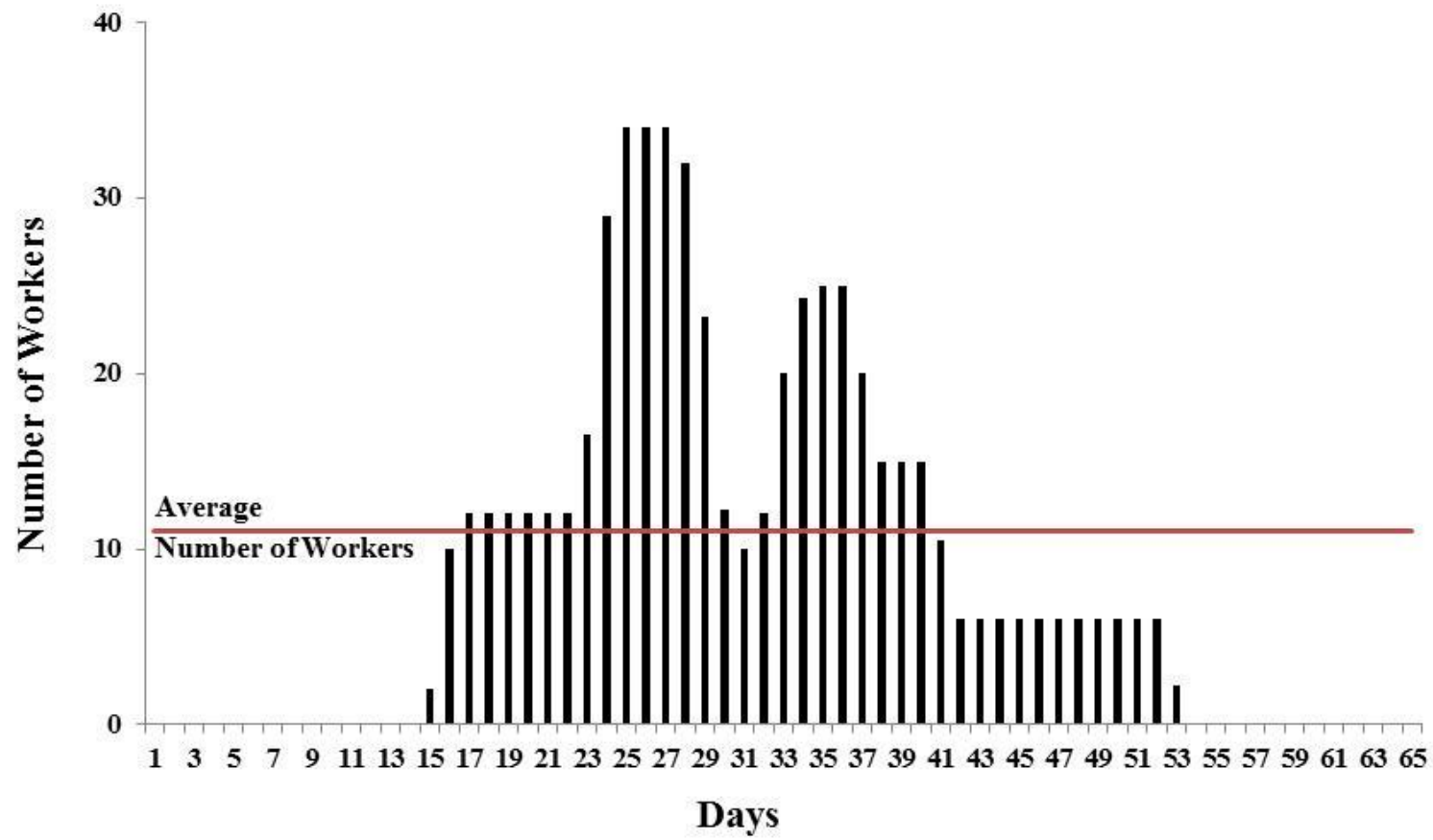


Figure 4.8 : Resource histogram before resource leveling for Scenario 2.

As it is seen in the resource histograms that are constructed before resource leveling, there are often fluctuations in resource usage. This situation is an obstacle for using the resources in an efficient manner. Resource leveling can clear away this obstacle. Resource leveling was made within the completion time of the construction project (65 days) and by making sure that the logical constraints and interdependencies are not violated.

The genetic algorithm-based resource leveling model was developed through an add-in program for MS Excel called Evolutionary Solver. Evolutionary Solver was selected because it features fast model setup and a user friendly menu. The model involved four steps, namely:

- Defining the MS Excel cells that represent the variables,
- Defining the objective function,
- Defining the constraints, and
- Determining the values of the genetic algorithm operators.

The first step sets up a chromosome representation. Each chromosome consists of genes and represents a solution for the resource leveling problem (Liu et al. 2005). In this study, a chromosome consists of the number of crews used in an activity. For instance, the chromosome [4, 4, 4, 4, 4, 3, 3, 3, ..., 3] represents the situation where four crews are used in the first five units, and three crews are used as of Unit 6. The total number of genes is equal to the total number of units that need to be completed during the project. Evolutionary Solver enables the user to determine the range of the variables. The variables of this study are integers that range between one crew (the minimum number of crews) and the initial number of crews given in Table 4.2. In addition, the number of crews can only be changed without violating precedence relationships.

The second step is the determination of the objective function that is required for the evaluation of the chromosomes in the population. In this study, nine different objective functions were considered. The formulations of the objective functions are presented in Table 4.3.

Table 4.3 : Objective Functions for Resource Leveling.

Objective Function No	Optimization Criteria	Formulas	Notations
1	Minimization of the sum of the absolute deviations in daily resource usage	$Z = \min \sum_{i=1}^T Rdev_i $	<i>min</i> = minimize; <i>i</i> = day under consideration; <i>T</i> = the duration of the project; <i>Rdev_i</i> = deviation between resources required on day <i>i</i> and <i>i</i> +1.
2	Minimization of the sum of only the increases in daily resource usage from one day to the next	$Z = \min \sum_{i=1}^T Rinc_i $	<i>min</i> = minimize; <i>i</i> = day under consideration; <i>T</i> = the duration of the project; <i>Rinc_i</i> = increase in between resources required on day <i>i</i> and <i>i</i> + 1.
3	Minimization of the sum of the absolute deviations between daily resource usage and the average resource usage	$Z = \min \sum_{i=1}^T R_i - A_{rr} $	<i>min</i> = minimize; <i>i</i> = day under consideration; <i>T</i> = the duration of the project; <i>R_i</i> = resources required on day <i>i</i> ; <i>A_{rr}</i> = average resource usage
4	Minimization of the maximum daily resource usage	$Z = \min [\max(R_i)]$	<i>min</i> = minimize; <i>max</i> = maximum; <i>i</i> = day under consideration; <i>R_i</i> = resources required on day <i>i</i>
5	Minimization of the maximum deviation in daily resource usage	$Z = \min [\max(Rdev_i)]$	<i>min</i> = minimize; <i>max</i> = maximum; <i>i</i> = day under consideration; <i>Rdev_i</i> = deviation between resources required on day <i>i</i> and <i>i</i> +1
6	Minimization of the maximum absolute deviation between daily resource usage and the average resource usage	$Z = \min [\max R_i - A_{rr}]$	<i>min</i> = minimize; <i>max</i> = maximum; <i>i</i> = day under consideration; <i>R_i</i> = resources required on day <i>i</i> ; <i>A_{rr}</i> = average resource usage
7	Minimization of the sum of the square of daily resource usage	$Z = \min M_x = \sum_{i=1}^T (R_i)^2$	<i>min</i> = minimize; <i>i</i> = day under consideration; <i>T</i> = the duration of the project; <i>R_i</i> = resources required on day <i>I</i>
8	Minimization of the sum of the square of the deviations in daily resource usage	$Z = \min \sum_{i=1}^T (Rdev_i)^2$	<i>min</i> = minimize; <i>i</i> = day under consideration; <i>T</i> = the duration of the project; <i>Rdev_i</i> = deviation between resources required on day <i>i</i> and <i>i</i> +1
9	Minimization of the sum of the square of the deviations between daily resource usage and the average resource usage	$Z = \min \sum_{i=1}^T (R_i - A_{rr})^2$	<i>min</i> = minimize; <i>i</i> = day under consideration; <i>T</i> = the duration of the project; <i>R_i</i> = resources required on day <i>i</i> ; <i>A_{rr}</i> = average resource usage

The third step involves the specification of the constraints. The genetic algorithm-based model discards the solutions that do not meet the constraints that have been specified. The first constraint ensures that the earliest change in the number of crews can be accommodated only after the first crew moves to its next destination. The second constraint specifies the minimum and maximum number of crews that can be used in activities that are eligible for resource leveling. The number of crews in an activity that is eligible for resource leveling can be equal to its initial value (given in Table 4.2 in this example) or less. In Figures 4.5 and 4.6, based on the criteria set

earlier in the paper, Activities B and F appear to be eligible for resource leveling. Activity B's precedence relationship with the preceding (Activity A) and succeeding (Activity C) activities is governed at the last unit. The number of crews used in Activity B can be equal to the initial value (from Table 4.2: 2 crews) or less. Activity F's precedence relationship with the preceding (Activity E) and succeeding (Activity G) activities is governed at the first unit. The number of crews used in Activity F can be equal to the initial value (from Table 4.2: 5 crews) or less. The last constraint reflects the principle of "natural rhythm" in that it specifies the minimum and maximum slopes (start-to-start or finish-to-finish production rate) of activities that are eligible for resource leveling. This constraint makes sure that the slopes are adjusted only by reducing the number of crews, and prevents an activity from clashing with the preceding and succeeding activities. For example, the slope of Activity B (excavating) should be less than the slope of Activity C and greater than the slope of the Activity A, because Activity B has a finish-to-start relationship with Activities A and C in the last unit. The slope of Activity F (backfilling) should be less than the slope of Activity E and greater than the slope of the Activity G, because Activity F has a finish-to-start relationship with Activities E and G in the first unit.

The final step consists of specifying the population size and mutation rate. The population size is one of the important factors that affect the process of finding the optimum solution. The probability of finding the optimum solution is much higher in larger populations. On the other hand, it can take much longer to find the solution in larger populations (Hegazy 1999, Hegazy and Kassab 2003). The population size was set as 100 in this study as it was in studies conducted by Senouci and Eldin (2004) and Chen and Weng (2009). The mutation rate was set as 0.075, which is the default value of Evolutionary Solver. Evolutionary Solver does not allow the user to specify the crossover rate because it automatically runs multiple variations of mutation and crossover rates using two different default crossover strategies (Risk Solver Platform 2011).

After the completion of the all steps for model setup, the information about unit numbers, start times, finish times, number of crews, slopes (start-to-start or finish-to-finish production rates), durations, required man-hours to finish one unit, optimum number of workers in a crew, daily working hours, buffers, and the resources for each activity on different days of the project are all set on an MS Excel sheet. If the

start times of the activities change according to the changes in the number of crews, the resources that are assigned to the activities also change automatically. Thus, the model seeks the optimum or near-optimum solution for resource utilization as the start times of activities are systematically changed by the model. Once all the inputs were set, the process for the genetic algorithm-based resource leveling model was run by using Evolutionary Solver. The process was carried out separately for nine different objective functions on a personal computer with a 2.53 GHz Core2 Duo CPU and 4 GB RAM. The process was stopped after 50,000 trials because the model stopped generating a better solution. The schedules and resource histograms that were generated by the model after resource leveling are presented in Figures 4.9, 4.10, 4.11 and 4.12, respectively.

4.3 Discussion of the Results

Table 4 shows the results that were obtained by using all nine objective functions. It is observed that on each scenario, the different objective functions resulted in the same resource histogram and the same schedule (Figures 4.9, 4.10, 4.11, and 4.12).

Table 4.4 : Results after Resource Leveling.

Objective Function No	Optimization Criteria	Value of "Z" Before Leveling		Value of "Z" After Leveling		Percentage of Improvement (%)	
		S1*	S2**	S1*	S2**	S1*	S2**
1	The sum of the absolute deviations in daily resource usage	314	98	275	92	12	6
2	The sum of only the increases in daily resource usage from one day to the next	160	49	140	46	13	6
3	The sum of the absolute deviations between daily resource usage and the average resource usage	1,389	559	1,036	464	25	17
4	The maximum daily resource usage	102	34	88	34	14	-
5	The maximum deviation in daily resource usage	32	13	32	13	-	-
6	The maximum absolute deviation between daily resource usage and the average resource usage	70	23	56	23	20	-
7	The sum of the square of daily resource usage	109,630	11,332	94,840	9,638	14	15
8	The sum of the square of the deviations in daily resource usage	5,508	676	4,937	584	11	14
9	The sum of the square of the deviations between daily resource usage and the average resource usage	42,237	6784	27,447	5,089	35	25

Note: *S1: Scenario 1

**S2: Scenario 2

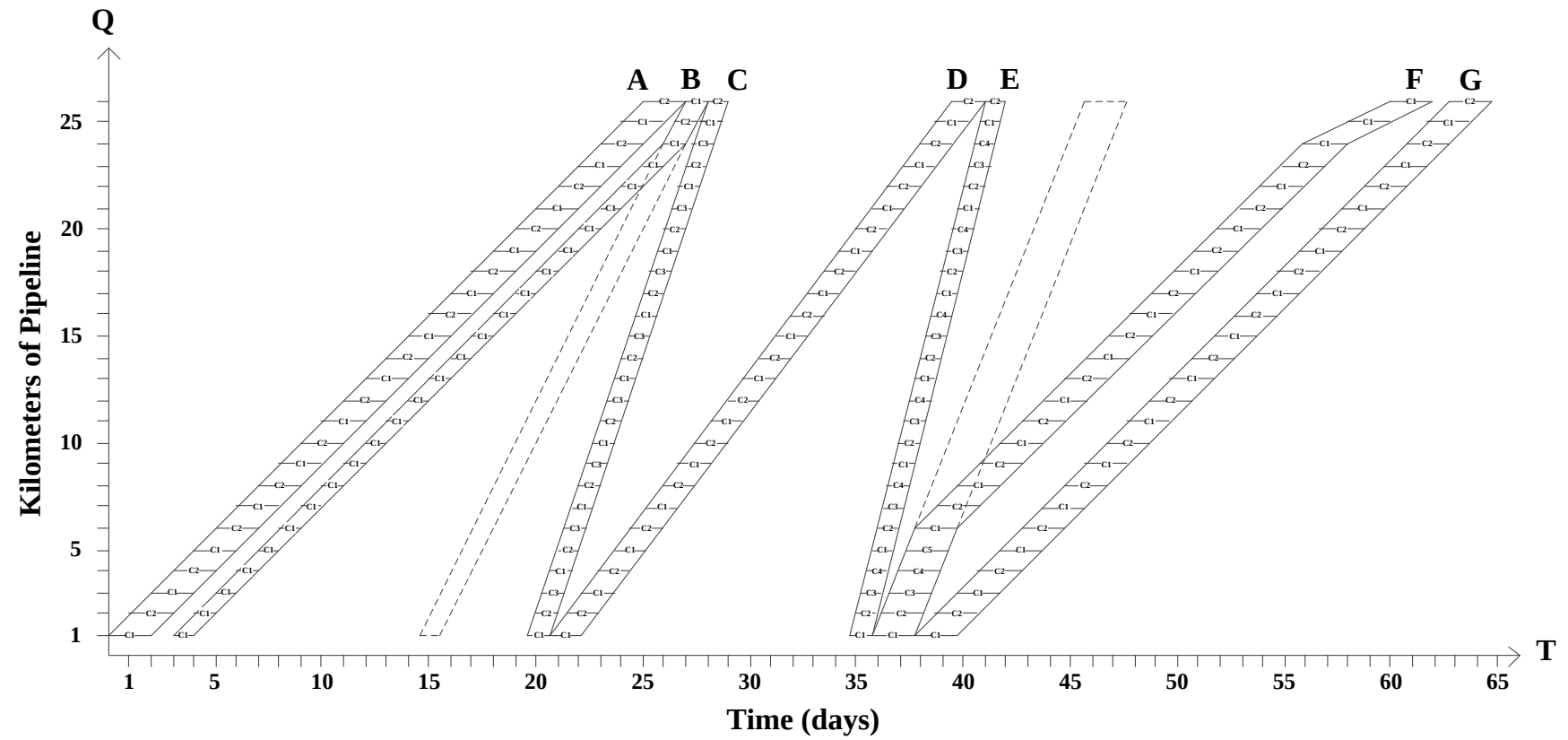


Figure 4.9 : Schedule after resource leveling for Scenario 1.

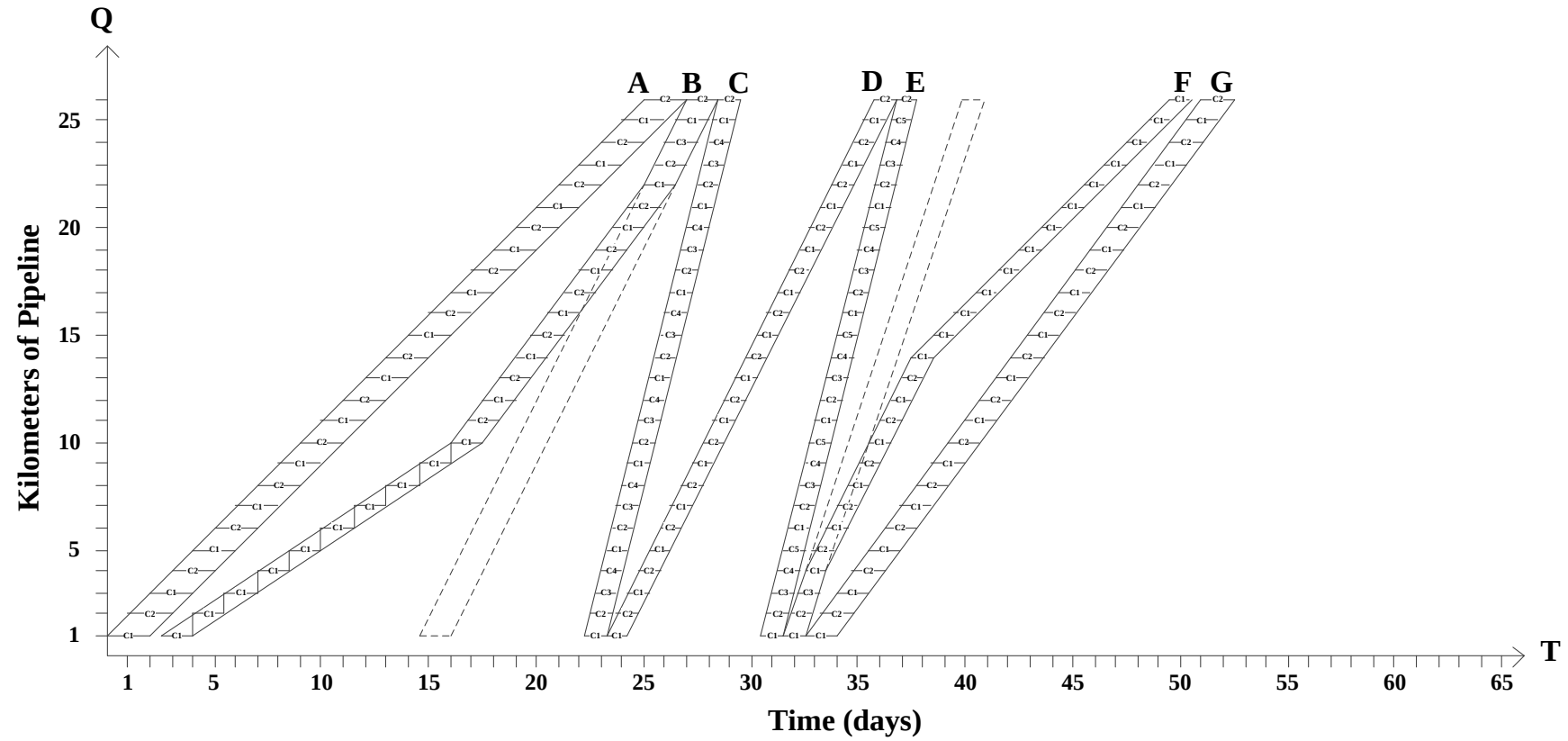


Figure 4.10 : Schedule after resource leveling for Scenario 2.

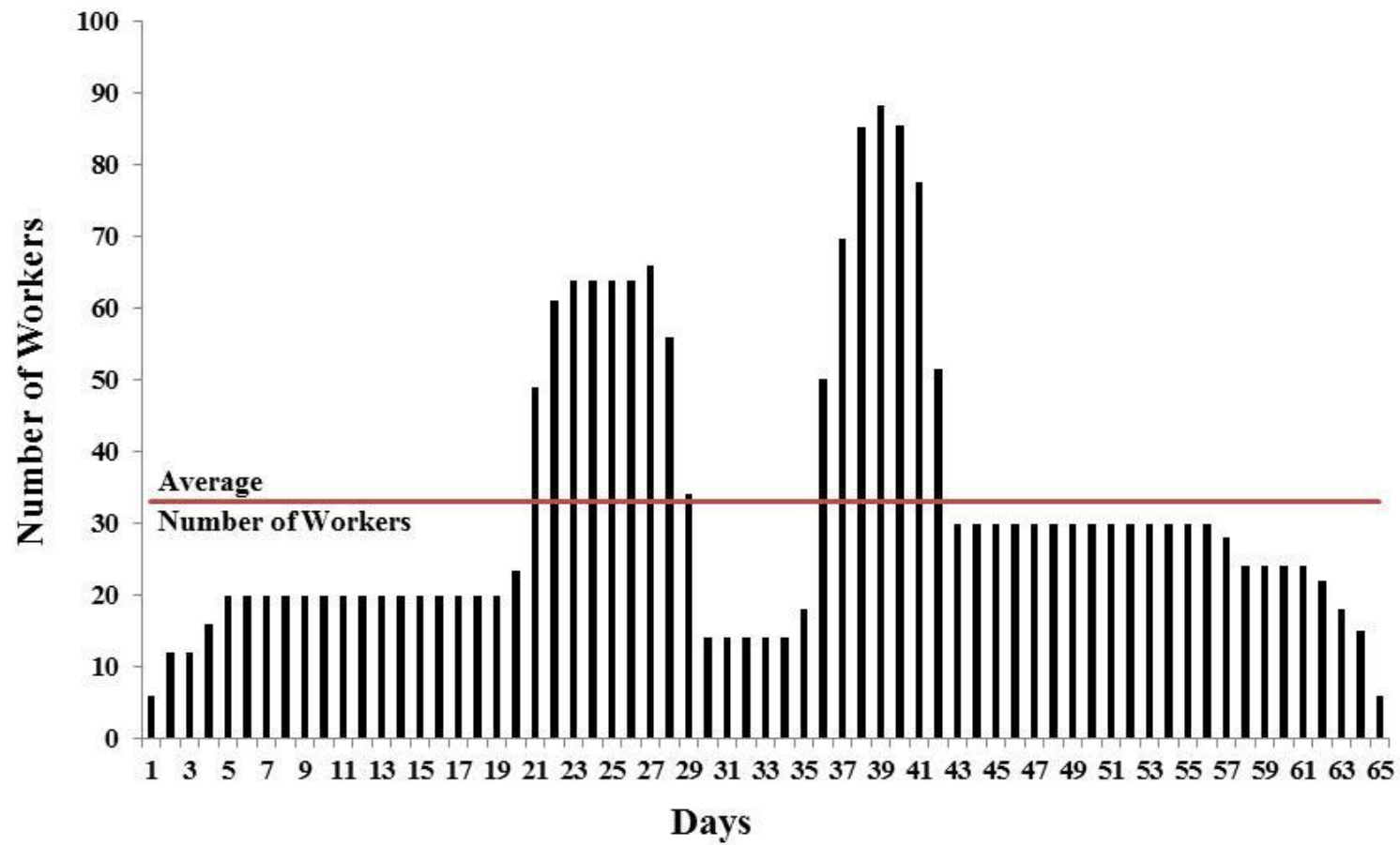


Figure 4.11 : Resource histogram after resource leveling for Scenario 1.

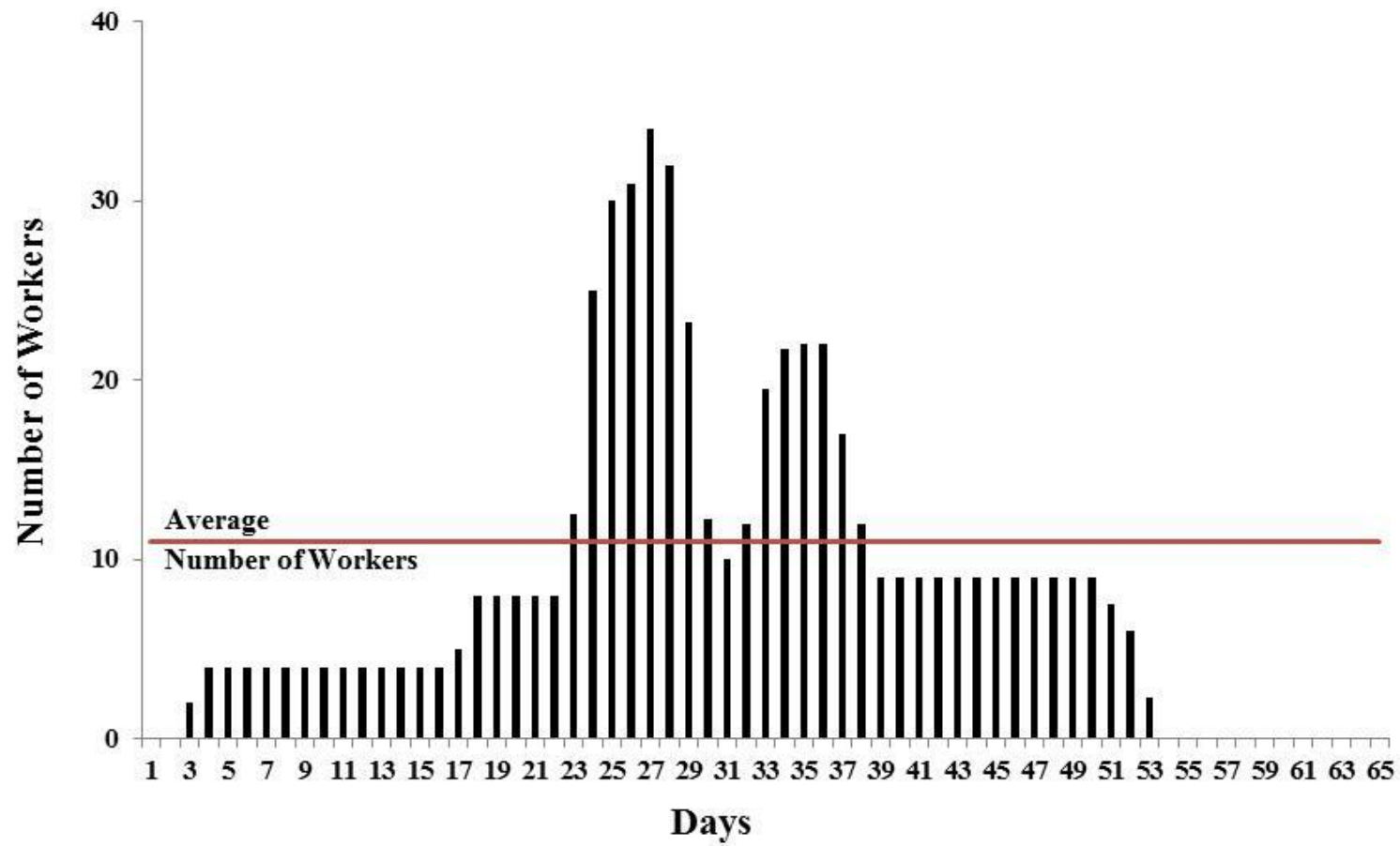


Figure 4.12 : Resource histogram after resource leveling for Scenario 2.

When a similar study of the same nine objective functions was conducted in network-based schedules (Damci and Polat 2012), it was found that each objective function resulted in a different schedule and a different resource histogram. This situation can be explained by the differences between LOB and network-based schedules. LOB schedules have fewer activities than network-based schedules. While the pipeline project that was used as an example in this study was represented by seven activities in the LOB schedule, it would have been represented by 182 activities (7 activities x 26 km) in a network-based schedule. Given the fact that an LOB schedule is both time- and resource-driven, as opposed to network-based schedules that are solely time-driven, LOB schedules typically have fewer non-critical activities. According to Moder et al. (1983), the proportion of non-critical activities in network-based schedules is around 85%, whereas it was only less than 30% in the LOB schedule used in the example pipeline project. Also, the use of the available float of the non-critical activities is different in LOB schedules. The totality of the float of non-critical activities can be used when leveling resources in network-based schedules, whereas the use of the float is limited in LOB schedules, because the principle of “natural rhythm” only allows using multiple crews of optimum size in order to prevent idle time for crews in between units.

The limitation of the study is that the outcome is observed in only two scenarios, each displaying a different resource, different crew sizes, different activity durations, and different rates of production, but making use of the same linear precedence relationships. In order to generalize the outcome with certainty, it would be desirable to test the nine objective functions in a multitude of scenarios including different precedence relationships and parallel activities used simultaneously. Based on the argument articulated in the preceding paragraph, this study concludes that it is likely that the nine objective functions would generate the same schedules and resource histograms after leveling, but the impacts of different precedence relationships and parallel activities remain to be seen.

5. MULTI-RESOURCE LEVELING IN LINE-OF-BALANCE

Some research has been conducted into single-resource leveling in linear schedules (e.g., Elwany et al. 1998, Georgy 2008, Lucko 2010), but only few researchers dealt with leveling multiple resources. For example, Dubey (1993) modified the minimum moment algorithm, a resource leveling procedure formerly developed by Harris (1978), by using a natural weighting that favors the resource with a larger contribution to the deviation in daily resource usage. Mattila and Abraham (1998) proposed an integer linear programming model that allows the user to assign weights while combining the multiple resources for multi-resource leveling. Yen (2005) presented a model that handles both resource allocation and leveling simultaneously. Even though these studies dealt with multi-resource leveling in linear schedules, they largely ignored the principles of “optimum crew size” and “natural rhythm” which provide the basis of the resource leveling procedure proposed in this study.

It is much easier to keep “natural rhythm” when only a single resource is considered for an activity. If there are multiple resources, the scheduler has to decide which resource will be picked as the dominant resource. The dominant resource will dictate the duration of an activity in a unit, its rate of production, and the number of crews to be used. In the example presented in Figure 5.1, the duration of the activity in a unit is calculated as 2 days if Resource 1 is used (Figure 5.1a), and 1.5 days if Resource 2 is used (Figure 5.1b). If both resources are used in the same activity, the scheduler should use the duration, the production rate, and the number of crews obtained with the resource that provides the longest duration (in this example Resource 1), because the activity cannot be completed in less time. In this case, the activity is said to be “dominated” by Resource 1. It is obvious that Resource 2 will not be able to keep its “natural rhythm” since it has to follow the same duration and production rate generated by Resource 1. As a result, the productivity of Resource 2 will suffer due to the higher worker-hours required ($2 \text{ days/unit} \times 4 \text{ workers/crew} \times 8 \text{ hours/day} = 64 \text{ worker-hours/unit}$). If the crew size of Resource 2 is reduced from 4 to 3 workers, theoretically speaking, the required worker-hours can be reduced to the original 48

worker-hours/unit (2 days/unit x 3 workers/crew x 8 hours/day = 48 worker-hours/unit). But because of the implications of the principle of “optimum crew size”, the actual required worker-hours will be 65 (higher than the original 48 worker-hours), as seen in Figure 5.1.

The LOB schedule can be established only after the selection of the dominant resource is made in each and every activity. Once the durations of all activities are established and the precedence relationships are set, a first LOB diagram can be plotted that uses 1 crew in each activity. If the duration determined in the schedule is not within the specified contract duration, as is mostly the case, selected activities in the schedule are accelerated by assigning more optimal size crews as long as they are available. As per Tokdemir et al.’s (2006) recommendation, the selection of the activities is done in descending order of duration per unit. The process stops when a scheduled duration is reached that is equal to or less than the duration specified in the contract.

The resource histogram for each resource can be plotted after the LOB schedule is established. But a combined resource histogram needs to be developed in order to perform multi-resource leveling. The degree of influence of each resource should be determined before using a combined resource histogram (Harris 1978). The scheduler can assign weights to each resource according to a preferred criterion. The daily cost of a resource is used as a criterion in this study implying that a more costly resource deserves priority in leveling compared to a less costly resource. For example, the weights for Resources 1 and 2 are expressed in Equations 5.1 and 5.2, respectively.

$$W_{R1} = \frac{COST_{R1}}{COST_{R1} + COST_{R2}} \quad (5.1)$$

$$W_{R2} = \frac{COST_{R2}}{COST_{R1} + COST_{R2}} \quad (5.2)$$

where W_{R1} = Weight for Resource 1; W_{R2} = Weight for Resource 2; $COST_{R1}$ = Daily cost for Resource 1; $COST_{R2}$ = Daily cost for Resource 2.

A combined resource histogram is plotted by summing up the weighted usage of resources on each day of the project. Once the LOB schedule is established and a combined weighted resource histogram is set up, resource leveling is performed.

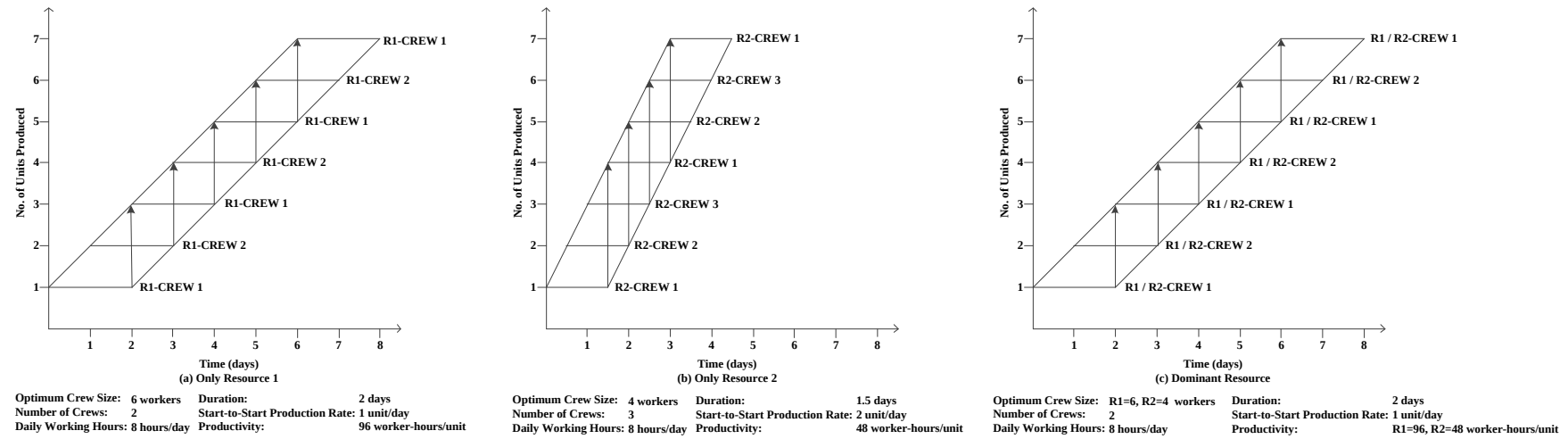


Figure 5.1 : Examples of LOB diagrams with multiple resources.

5.1 Example: Pipeline Project

The same pipeline project that is used for single resource leveling is also maintained for the illustration of the proposed multi-resource leveling. Two different resources are used to complete the project, and are considered in establishing the LOB schedule in this study for demonstration purposes. Resource 1 and Resource 2 are two different crews that consist of workers that are being used in all activities. The information for each activity concerning worker-hours, crew sizes, and daily working hours is shown in Table 5.1 for both Resource 1 and Resource 2. This information can be extracted from a company's database or from a site manager who has experience in similar projects.

Table 5.1 : Information about activities.

Activity Name	Required Worker Hours to Finish Unit		Number of Workers in Optimum Crew		Daily Working Hours		Duration (days)		Number of Crews	Start-to-Start Productivity Rate (km/day)
	R1	R2	R1	R2	R1	R2	R1	R2		
(A) Locating and clearing	96	36	6	3	8	8	2*	1.5	2	1
(B) Excavating	64	28	8	7	8	8	1*	0.5	2	2
(C) Laying aggregate	32	80	8	10	8	8	0.5	1*	3	3
(D) Laying pipes	84	32	7	4	8	8	1.5*	1	2	1.33
(E) Testing	24	64	2	4	8	8	1.5	2*	5	2.5
(F) Backfilling	24	96	3	6	8	8	1	2*	3	1.5
(G) Compacting	60	72	3	6	8	8	2.5*	1.5	2	0.8

Note: R1: Resource 1
R2: Resource 2

* Dominant resource

The proposed methodology requires that the resource that generates the longest duration per unit be considered as the “dominant” resource. As per the duration information in Table 5.1, Resource 1 is the “dominant” resource in the activities Clearing (Activity A), Excavating (Activity B), Laying Pipes (Activity D), and Compacting (Activity G). The rest of the activities, i.e., Laying Aggregate (Activity C), Testing (Activity E), and Backfilling (Activity F) are dominated by Resource 2. The rate of production of each activity is calculated on the basis of the duration and number of crews provided by the “dominant” resource as long as the rate of production is limited to a multiple of the natural rhythm.

The initial LOB schedule shown in Figure 5.2 of the pipeline project is established after the duration of the project is reduced to the 69 days specified in the contract by increasing the number of crews in selected activities using an order recommended by

Tokdemir et al. (2006). The final number of crews used in each activity, as well as the rate of production of each activity are presented in the last two columns of Table 5.1. Note that no buffer is used in this diagram. Had there been any buffer, the “natural rhythm” principle would hold without violating buffer times.

Given that the daily costs of Resources 1 and 2 are \$800/day and \$200/day, respectively, the weights of Resources 1 and 2 are computed by using Equations 5.3 and 5.4:

$$\begin{aligned} W_{R1} &= \frac{800}{800 + 200} \\ &= 0.80 \end{aligned} \tag{5.3}$$

$$\begin{aligned} W_{R2} &= \frac{200}{800 + 200} \\ &= 0.20 \end{aligned} \tag{5.4}$$

The combined histogram of weighted resources is used only for resource leveling purposes. It does not reflect the actual daily resource usage. The sum of all the y-coordinates of each and every bar in Figure 5.3 gives a total weighted workforce of 1,497.60 workers. The average number of workers per day is calculated by dividing the total weighted workforce (1,497.60 workers) by the duration of the project (69 days). The outcome is 21.81 workers/day. This result is rounded up to 22 due to the nature of the resource (i.e., worker) that is used in this study. According to the LOB diagram in Figure 5.2, Excavating (Activity B) and Backfilling (Activity E) are the activities that are eligible for resource leveling according to the criteria presented earlier.

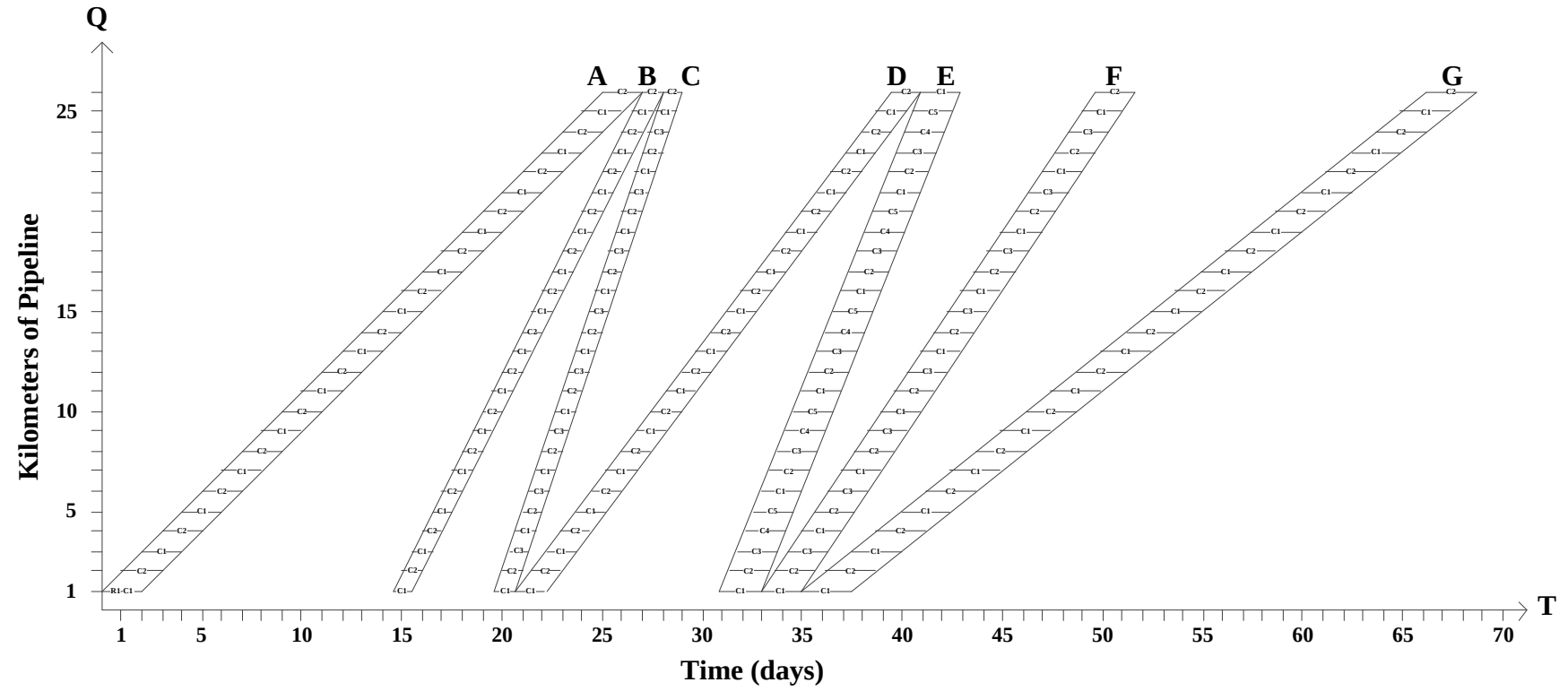


Figure 5.2 : The LOB schedule before resource leveling.

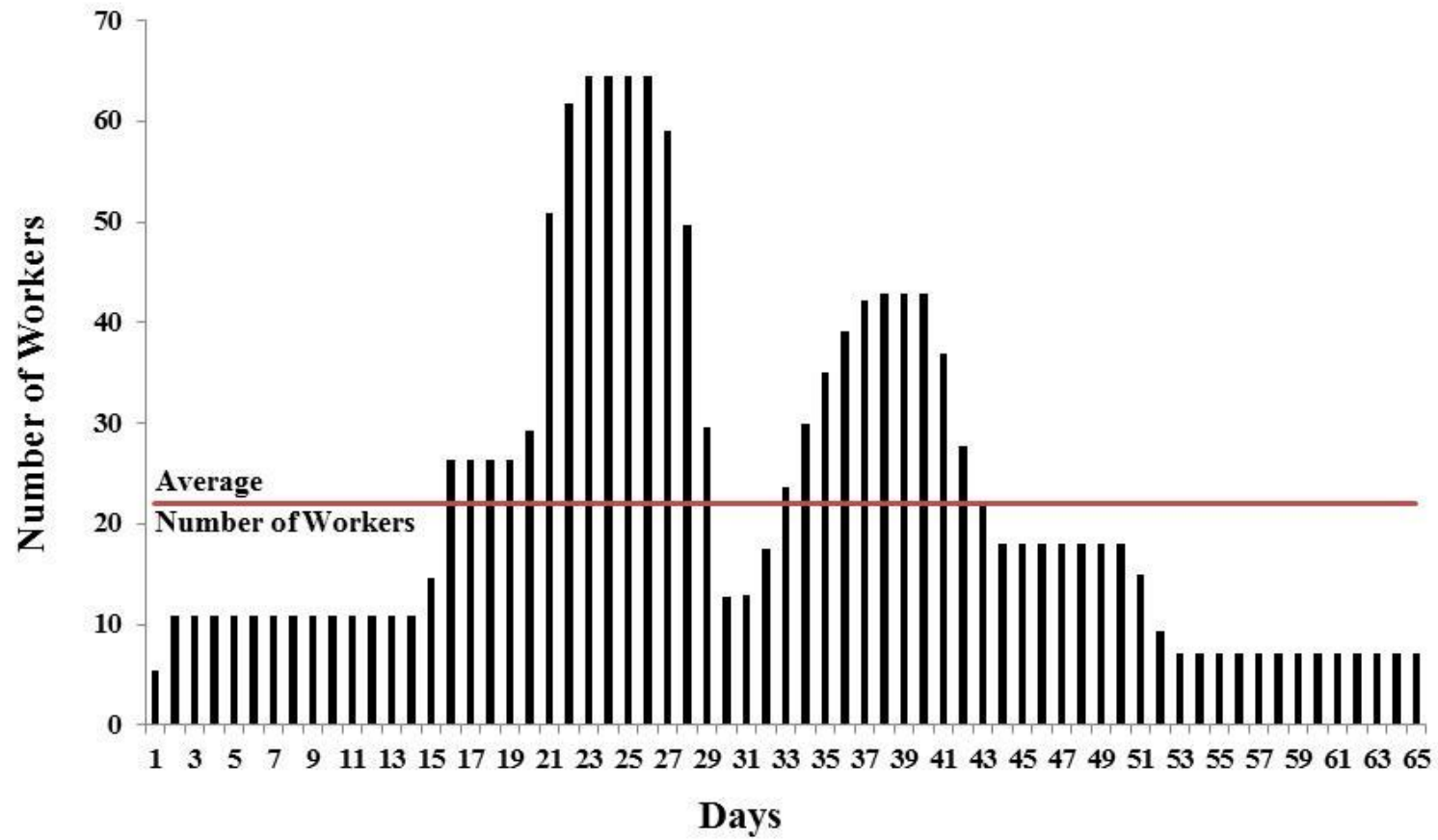


Figure 5.3 : Combined histogram of weighted resource usage before resource leveling.

The same genetic algorithm-based resource leveling model that is developed through an add-in program for MS Excel called Evolutionary Solver for single resource leveling model is also used for multi-resource leveling.

The objective function that evaluates each generated chromosome is determined in the second step. The minimization of the sum of the absolute deviations between daily resource requirements and the average resource requirement is selected as the objective function, because this is one of the most commonly used objective functions for resource leveling (Mattila and Abraham 1998). An MS Excel cell is set up to represent the objective function in Equation 5.5.

$$Z = \min \sum_{i=1}^T |R_i - Ave| \quad (5.5)$$

where i = day under consideration; T = the duration of the project; R_i = Resources required on day i ; Ave = average resource requirement.

The optimum solution for multiple resource utilization is found as the start times of activities are systematically changed by the genetic algorithm model. The process was carried out on a personal computer with a 2.53 GHz Core2 Duo CPU and 4 GB RAM. The process was stopped after 50,000 trials because the model stopped generating better solutions. The schedule and resource histograms that are generated by the model after resource leveling are shown in Figures 5.4, 5.5, 5.6, 5.7, and 5.8 respectively.

Improvements of 21% and 23% were obtained for Resources 1 and 2, respectively since the sum of the absolute deviations between daily resource usage and average resource usage were reduced to 774 and 854 from 974 and 1,111 for Resources 1 and 2, respectively (Figures 5.5, 5.6, 5.7, and 5.8). Besides, the maximum resource usage for Resources 1 and 2 were reduced from 66 and 58 to 60 and 55 as compared with the initial resource histograms.

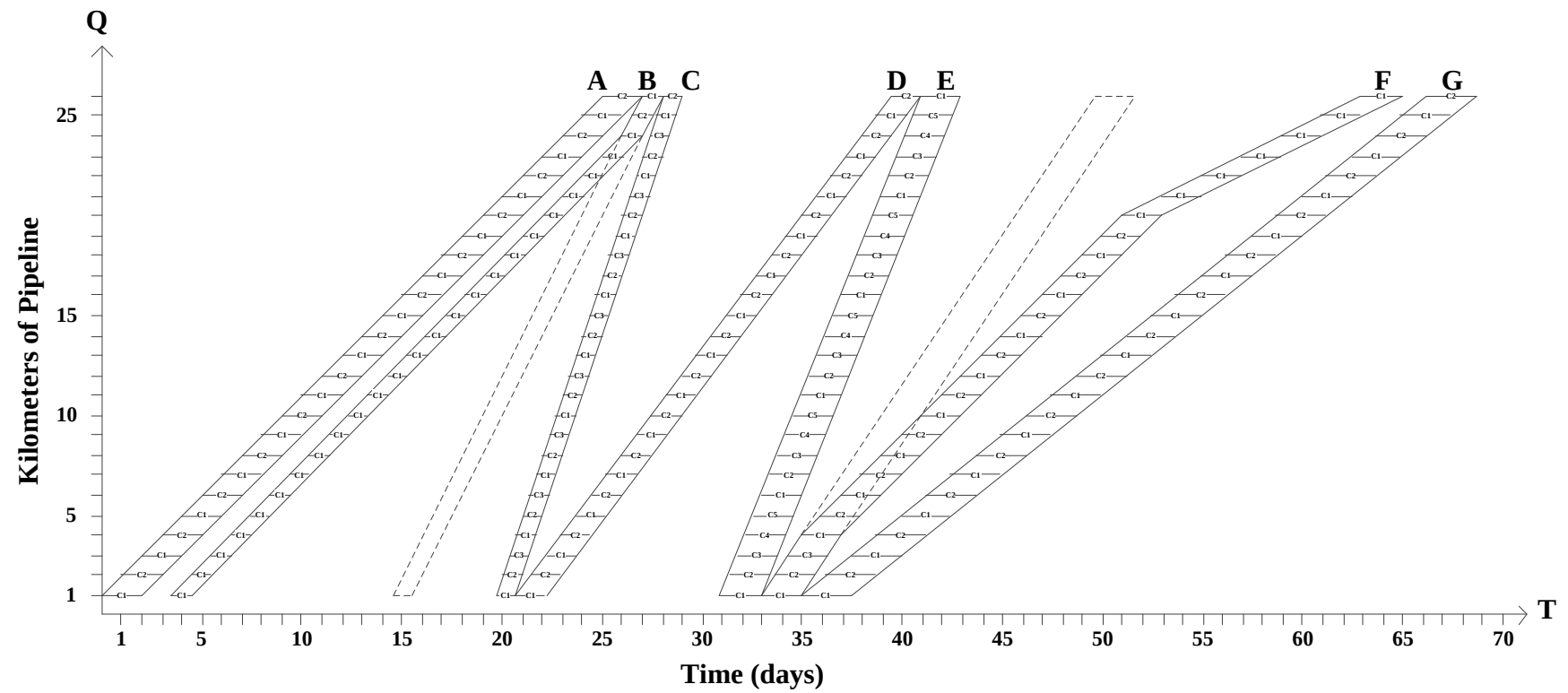


Figure 5.4 : The LOB schedule after resource leveling.

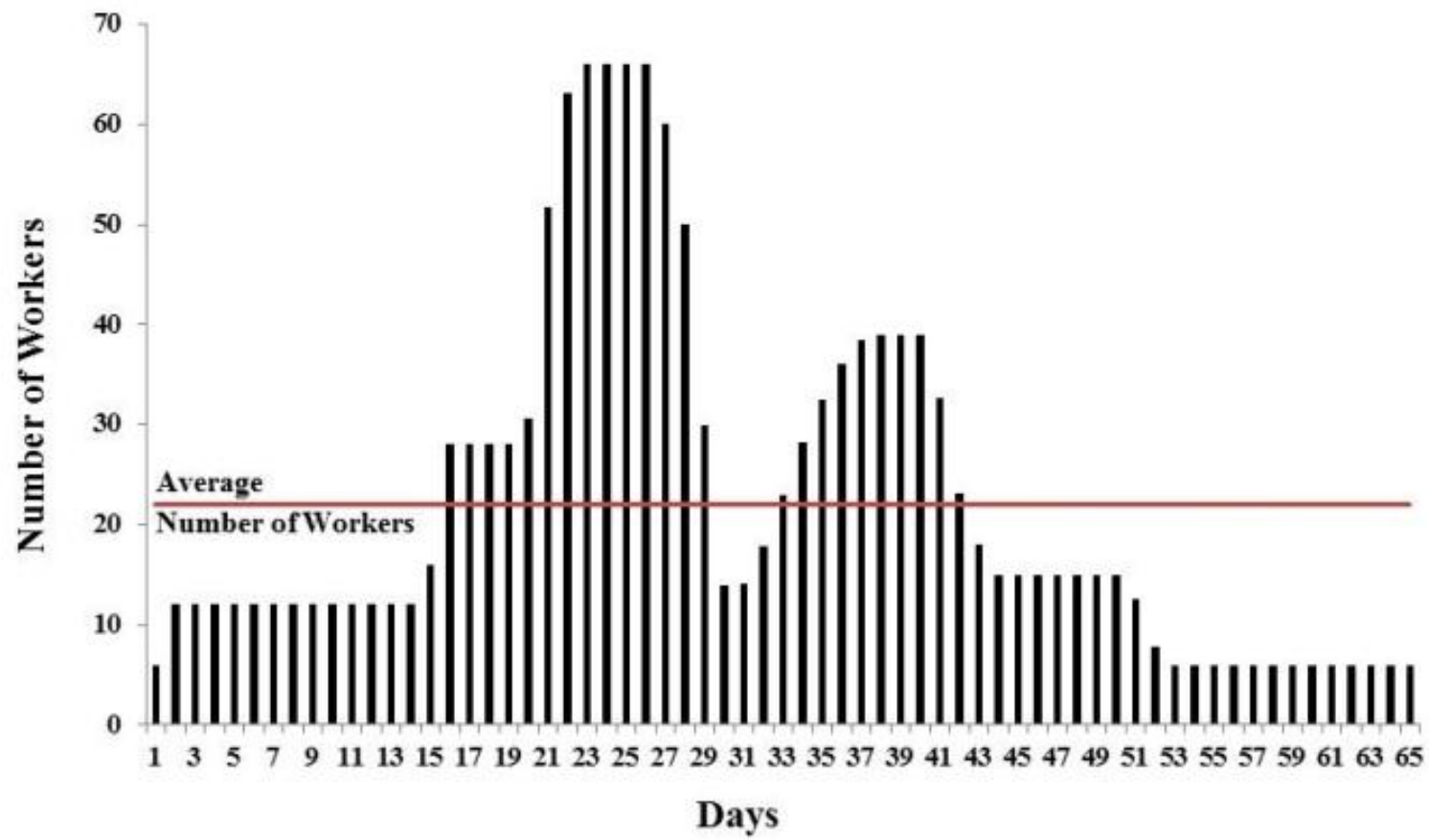


Figure 5.5 : Resource histogram before resource leveling for Resource 1.

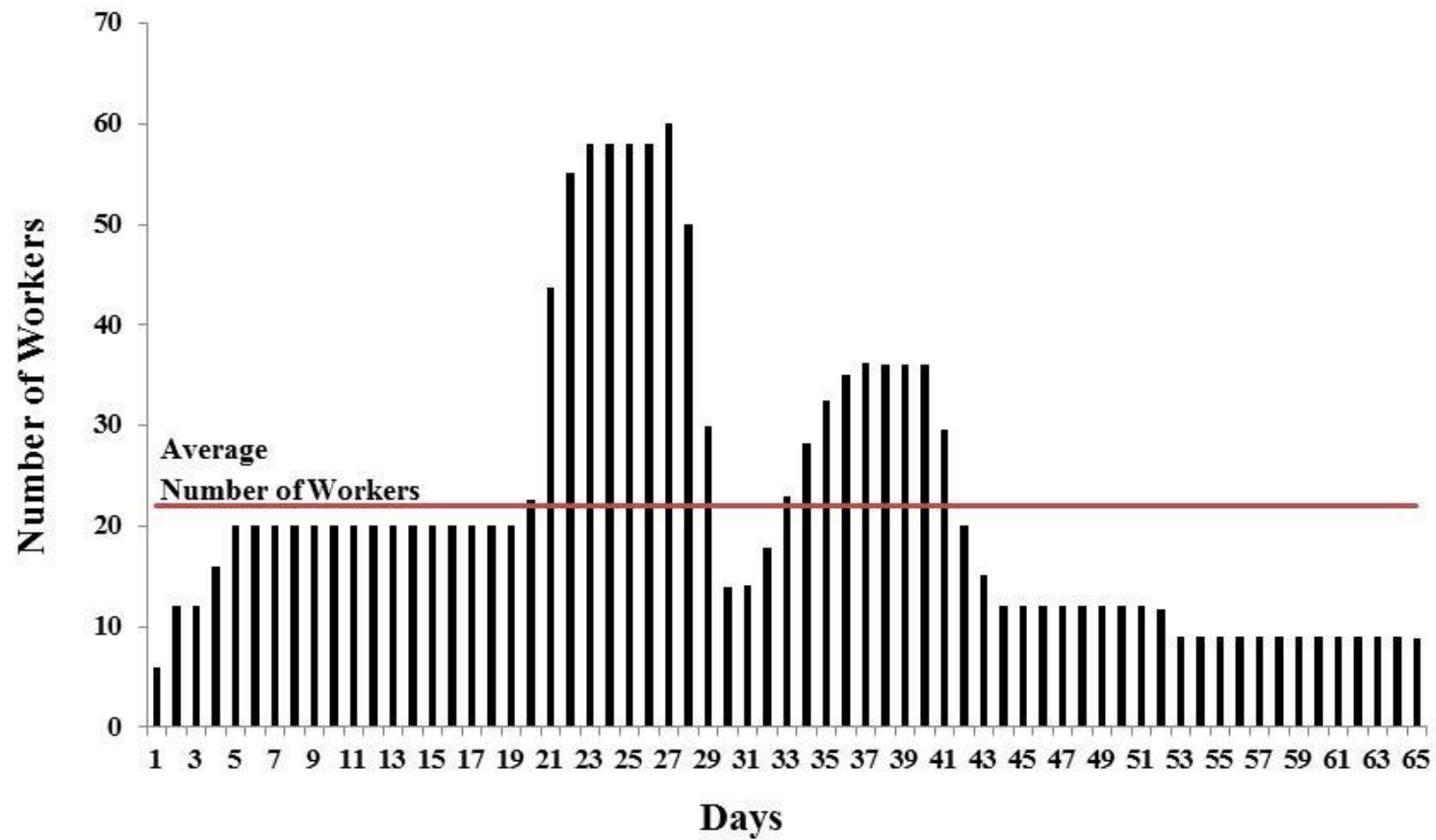


Figure 5.6 : Resource histogram after resource leveling for Resource 1.

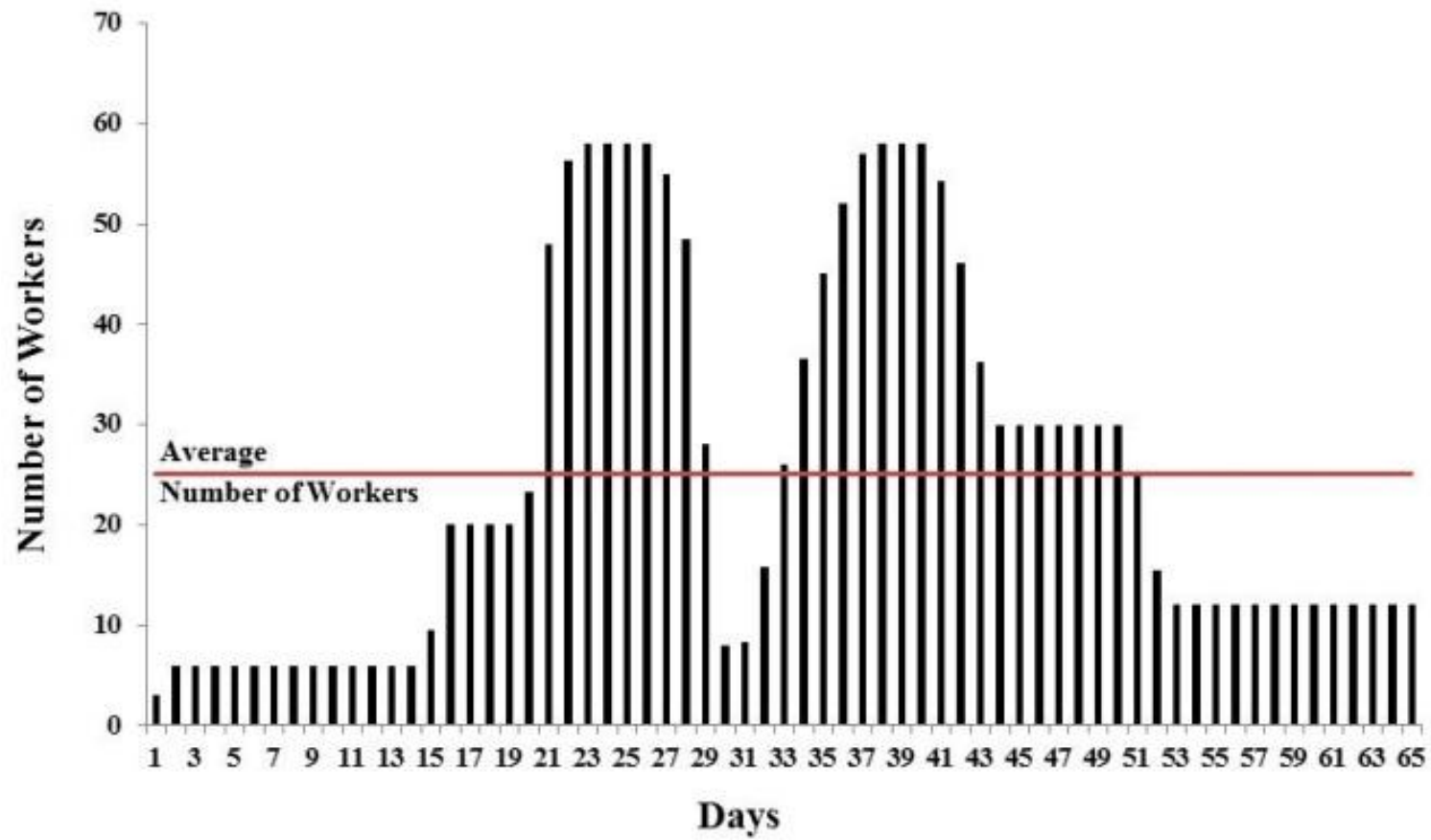


Figure 5.7 : Resource histogram before leveling for Resource 2.

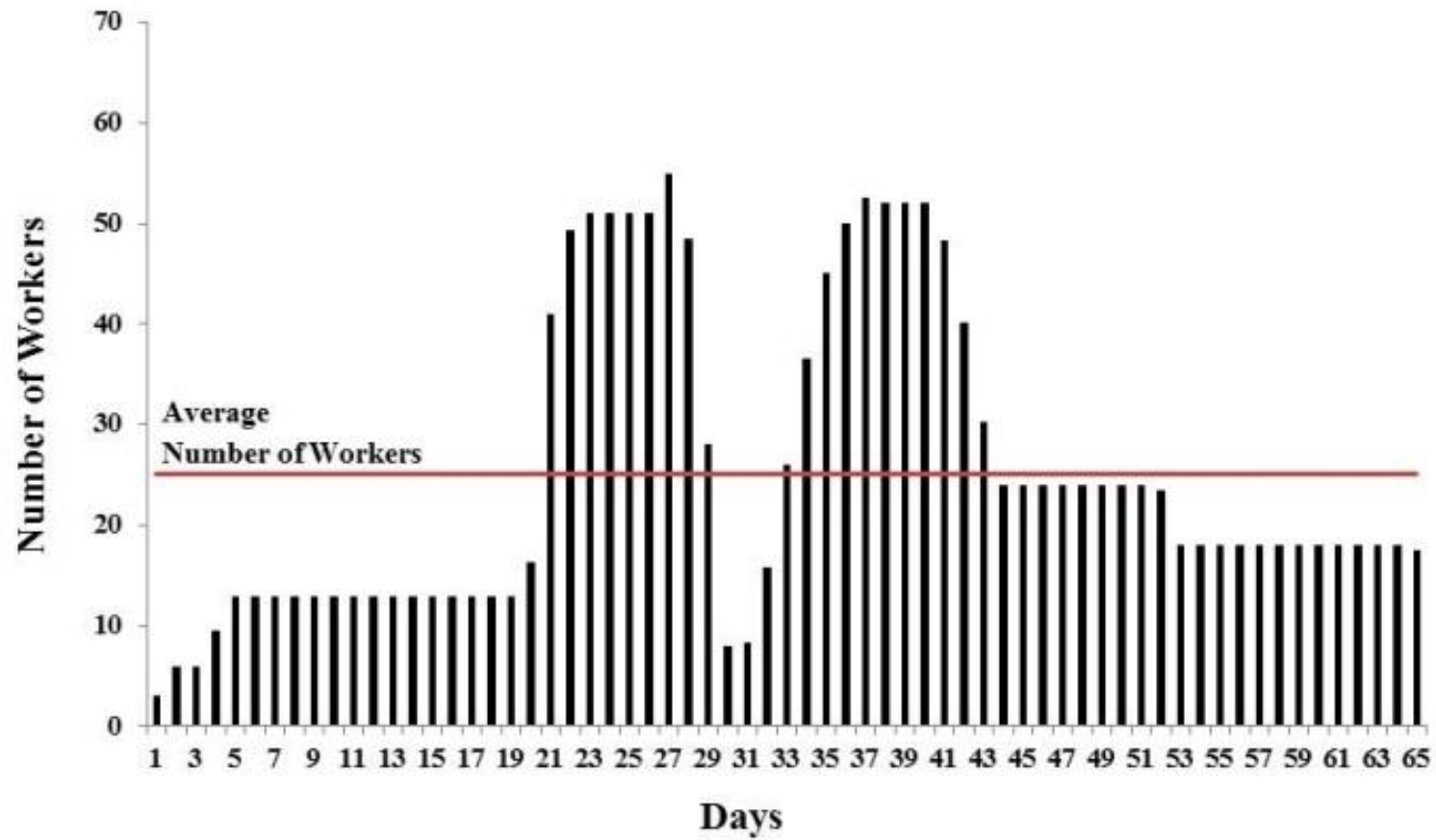


Figure 5.8 : Resource histograms after resource leveling for Resource 2.

6. CONCLUSION AND RECOMMENDATIONS

The use of an inappropriate scheduling method can easily result in failure to achieve project goals. It is commonly claimed that linear scheduling methods such as LOB are more appropriate than network-based scheduling methods such as CPM in linear construction projects (e.g., highways, tunnels, pipelines, high-rise buildings, railways, etc.) which exhibit repetitive characteristics where the same basic unit is repeated several times. However, the use of linear scheduling methods is not enough to complete a linear construction project without a failure. The management of resources is as important as using an appropriate scheduling method especially in linear and repetitive construction where the smooth and continuous use of resources is key to project success.

Construction researchers and professionals have used two approaches for the management of resources, namely (1) resource allocation and (2) resource leveling. One of the earliest attempts to develop a model for resource management in linear construction projects was made by Perera (1983) who used linear programming to determine the resource requirements in various activities and to allocate resources by considering hourly resource usage. The method provides the opportunity to share resources that are available in limited quantities. However, the method does not take into account all resource constraints. Dubey (1993) modified the minimum moment algorithm which is a resource leveling procedure for linear schedules formerly developed by Harris (1978). The new model was named “modified minimum moment algorithm” and involved (1) new rules that considered multiple locations and variable resource usage for activities, and (2) some heuristic rules to increase computational efficiency. Elwany et al. (1998) developed a linear programming model for the allocation and smoothing of a single resource in repetitive construction projects which minimizes the number of changes in resource requirements. Mattila and Abraham (1998) presented a model for resource leveling of a linear construction schedule by using integer linear programming where the floats of activities are used in the shifting of non-controlling activities in order to level the resources. Liu (1999)

proposed an approach that consists of two heuristic models that aim to minimize the project duration of linear construction projects under resource constraints. The first is a rule-of-thumb heuristic model that integrates activity precedence relationship, float analysis, and the controlling activity path concept. The second heuristic model seeks a near-optimal solution by using the Tabu Search algorithm. Leu and Hwang (2001) proposed a genetic algorithm-based model for an optimal repetitive schedule under resource constraints by considering the integration of resource allocation and resource sharing. El-Rayes and Moselhi (2001) presented an automated and dynamic programming-based model for optimizing resource utilization in repetitive construction projects through the identification of an optimum crew formation and interruption option for each activity. Yen (2005) developed a model that handles both resource allocation and leveling simultaneously to schedule linear construction projects with multiple resource constraints by improving the model developed by Liu (1999). Essentially, the model intends to achieve the goal of minimizing the project duration and the fluctuation in resource usage by a simulated annealing search algorithm. Liu and Wang (2006) presented a constraint programming-based model that minimizes the total project duration or total cost for linear construction projects by considering the temporary addition of resources required to shorten the duration of specific activities. Georgy (2008) presented a model that automates the resource leveling procedure of linear construction projects via the integration of genetic algorithms and AutoLISP programming language under AutoCAD. Hsie et al. (2009) developed an optimization model that considers limited availability of resources and that minimizes the project duration by automatically selecting the optimal set of production rates for activities in terms of crew composition and size in different time periods. Lucko (2010) proposed a model for the resource leveling of linear schedules by using singularity functions that makes use of all possible permutations of shifting activities or changing their resource rates and that provides subsequent optimization via a genetic algorithm.

All of these studies have dealt with various aspects of resource allocation and resource leveling in schedules developed by linear scheduling methods. There has, however, been no attempt to develop a resource leveling model associated with the theory and practice of LOB. The LOB methodology aims to produce a work schedule where resource use is continuous and uninterrupted. It automatically performs

resource allocation, but a more refined distribution is achievable by resource leveling even if multiple resources are involved in some activities.

The objectives of this study were (1) to develop a genetic algorithm-based model for single resource leveling and multi-resource leveling in LOB schedules and (2) to investigate the impacts of using different objective functions in leveling resources of LOB schedules. For this purpose, nine different objective functions were identified after a review of prior studies on resource leveling models used in network-based and linear scheduling methods and the principles of “optimum crew size” and “natural rhythm” are adopted from Lumsden’s (1968) work for the proposed resource leveling model. The principle of “natural rhythm” assumes that the highest productivity can be achieved as long as an activity is performed in a unit of production by a crew of optimum size. Therefore, one needs to change the number of crews employed to shift the start times of an activity forwards or backwards at different units of production. The total project duration, the duration of an activity in any unit and the precedence relationships between activities remain the same during this procedure.

Two LOB schedules were established for two different single resource scenarios of a pipeline project and were used to illustrate the proposed resource leveling model. Nine objective functions were used in a genetic algorithm-based model that was developed for resource leveling in LOB schedules. When implemented on a simple pipeline project that consists of seven consecutive activities, it was observed that the objective functions generated the same LOB schedule and the same resource histogram. The reason why different objective functions generated the same improvements in the resource distributions can be explained by the facts that (1) the LOB schedule used has only few non-critical activities that can be used in resource leveling, and (2) the use of the float of the non-critical activities is constrained in LOB schedules by the principle of “natural rhythm”. The practical implication of the study is that schedulers should consider the nine objective functions due to the fact that the objective functions may or may not provide the same optimal resource distribution depending on the number activities and their float distribution.

Although single-resource leveling has been investigated in linear scheduling methods, multi-resource leveling has not been adequately considered in LOB schedules. The same pipeline project is used for the illustration of the proposed multi-resource leveling model. The proposed model postulates that the production

rate and duration of an activity are governed by the resource that requires the longest duration in completing a unit. Two different resources are used to complete the project, and are considered in establishing the LOB schedule in this study for demonstration purposes. Resource 1 and Resource 2 are two different crews that consist of workers that are being used in all activities. When the genetic algorithm-based resource leveling model was run, it was observed that it generated smoother resource utilization histograms for the project with minimal impact on required worker-hours. However, it is obvious that the resources that have to follow the same duration and production rate of the dominant resource will not be able to keep their “natural rhythm”.

The product of this thesis is a resource leveling model that deals either with a single resource or multiple resources. The contributions of the study are presented below:

- This research was initiated in response to the absence of a resource leveling model for LOB schedules. The LOB methodology, by its very nature, deals with resource allocation, but not with resource leveling. The number of the crews used in the activities that are eligible for resource leveling can be changed in order to obtain a schedule that provides smoother resource utilization diagram. This study makes construction professionals aware of the fact that resource leveling can be implemented in LOB schedules.
- The important advantage of the proposed model is its ability to level the resources without any concession from productivity. Most of the previous studies in resource leveling of linear schedules (e.g., Dubey 1993, Mattila 1997) ignored the principles of “optimum crew size” and “natural rhythm”, which provide the basis for achieving the highest productivity. The principle of “natural rhythm” assumes that the highest productivity can be achieved as long as an activity is performed in a unit of production by a crew of optimum size. Any crew that is composed of fewer or more workers is bound to result in lower productivity. The ability to keep productivity constant even if the production rate changes is beneficial to contractors.
- The simplicity of the resource leveling model is another important advantage for the schedulers who would consider leveling resources in LOB schedules.

The use of MS Excel and an add-in program for MS Excel make the model easy to implement.

The proposed model can be improved by conducting further studies. The recommendations for future studies are presented below:

- Investigating the impacts of different precedence relationships and parallel activities would be a potential improvement for the study.
- In this study, the genetic algorithm was developed separately from the basic LOB calculations and the identification of the activities that are eligible for resource leveling. The procedure can be fully automated by using a computer programming language.

REFERENCES

- Ahuja, H. N.** (1976). *Construction Performance Control by Networks*, John Wiley and Sons, New York.
- Al-Tabtabai, H. and Alex, A. P.** (1999). Using Genetic Algorithms to Solve Optimization Problems in Construction. *Engineering, Construction and Architectural Management*, **6**(2), 121-132.
- Arditi, D., Tokdemir, O. B. and Kangsuk, S.** (2001a). Scheduling System for Repetitive Unit Construction Using Line-of-Balance Technology. *Engineering, Construction and Architectural Management*, **8**(2), 90-103.
- Arditi, D., Tokdemir, O. B. and Kangsuk, S.** (2001b). Effect of Learning on Line-of-Balance Scheduling. *International Journal of Project Management*, **19**(5), 265-277.
- Arditi, D., Sikangwan, P. and Tokdemir, O. B.** (2002a). Scheduling System for High Rise Building Construction. *Construction Management and Economics*, **20**(4), 353-364.
- Arditi, D., Tokdemir, O. B. and Kangsuk, S.** (2002b). Challenges in Line-of-Balance Scheduling. *Journal of Construction Engineering and Management*, **128**(6), 545-556.
- Arditi, D. and Albulak, M. Z.** (1986). Line-of-Balance Scheduling in Pavement Construction. *Journal of Construction Engineering and Management*, **112**(3), 411-424.
- Battersby, A.** (1970). *Network analysis for planning and scheduling*, John-Wiley and Sons, New York.
- Burgess, A. R. and Killebrew, J. B.** (1962). Variation in activity level on a cyclical arrow diagram. *Journal of Industrial Engineering*, **13**(2), 76-83.
- Callahan M. T., Quackenbush, D. G., and Rowings, J. E.** (1992). *Construction Project Scheduling*, McGraw-Hill, Inc., New York.
- Carter, A. E., and Ragsdale, C. T.** (2002). Scheduling pre-printed newspaper advertising inserts using genetic algorithms. *OMEGA The International Journal of Management Science*, **30**, 415-421.
- Chen, P. H., and Weng, H.** (2009). A two-phase GA model for resource-constrained project scheduling. *Automation in Construction*, **18**(4), 485-498.
- Christodoulou, S., Ellinas, G. and Aslani, P.** (2000). Entropy-based scheduling of resource-constrained construction projects. *Automation in Construction*, **18**(7), 919-928.

- Damci, A. and Polat, G.** (Unpublished results). Impacts of different objective functions on resource leveling in construction projects, *Journal of Civil Engineering and Management*.
- Doulabi, S. H. H., Seifi, A., and Shariat, S. Y.** (2010). An Efficient Hybrid Genetic Algorithm for Resource Leveling via Activity Splitting. *Journal of Construction Engineering and Management*, **137**(2), 137-146.
- Dubey, A.** (1993). Resource Leveling and Linear Scheduling, *MSc Thesis*, The University of British Columbia, Vancouver, Canada.
- Easa, S.M.** (1989). Resource Leveling in Construction by Optimization. *Journal of Construction Engineering and Management*, **115**(2), 302-316.
- El-Rayes, K. and Moselhi, O.** (2001). Optimizing Resource Utilization for Repetitive Construction Projects, *Journal of Construction Engineering and Management*, **127**(1), 18-27.
- Elwany, M. H., Korish, I. E., Barakat, M. A. and Hafez, S. M.** (1998). Resource Smoothing in Repetitive Projects. *Computers and Industrial Engineering*, **35**(3-4), 415-418.
- Georgy, M.E.** (2008). Evolutionary resource scheduler for linear projects. *Automation in Construction*, **17**(5), 573-583.
- Goldberg, D. E.** (1989). *Genetic algorithms in search, optimization, and machine learning*, Addison-Wesley, Reading, Mass.
- Hariga, M., and El-Sayegh, S. M.** (2010). Cost Optimization Model for the Multiresource Leveling Problem with Allowed Activity Splitting. *Journal of Construction Engineering and Management*, **137**(1), 56-64.
- Harmelink, D. J. and Rowings, J. E.** (1998). Linear Scheduling Model: Development of Controlling Activity Path. *Journal of Construction Engineering and Management*, **124**(4), 263-268.
- Harris R.B.** (1978). *Precedence and arrow networking techniques for construction*. John Wiley and Sons, New York, USA.
- Harris, R.B.** (1990). Packing Method for Resource Leveling (PACK). *Journal of Construction Engineering and Management*, **116**(2), 331-350.
- Hegazy, T.** (1999). Optimization of Resource Allocation and Leveling using Genetic Algorithms. *Journal of Construction Engineering and Management*, **125**(3), 167-175.
- Hegazy, T. and Ersahin, T.** (2001). Simplified Spreadsheet Solutions. II: Overall Schedule Optimization. *Journal of Construction Engineering and Management*, **127**(6), 469-475.
- Hegazy, T. and Kassab, M.** (2003). Resource Optimization Using Combined Simulation and Genetic Algorithms. *Journal of Construction Engineering and Management*, **129**(6), 698-705.
- Hegazy, T., Moselhi, O., Fazio, P.** (1993). BAL: An algorithm for scheduling and control of linear projects, *Transactions of ASCE International*, C.8.1.
- Hinze, J. W.** (2008). *Construction Planning and Scheduling*, Third Edition, Pearson Education, Inc., Upper Saddle River, New Jersey.

- Hiyassat, M. A. S.** (2000). Modification of minimum moment approach in resource leveling. *Journal of Construction Engineering and Management*, **126**(4), 278-284.
- Hiyassat, M. A. S.** (2001). Applying modified minimum moment method to multiple resource leveling. *Journal of Construction Engineering and Management*, **127**(3), 192-198.
- Horowitz, J.** (1980). *Critical Path Scheduling: Management Control Through CPM and PERT*, Krieger Publishing Company, Malabar, Florida.
- Hsie, M., Chang, C. J., Yang, I. T., and Huang, C. Y.** (2009). Resource-constrained scheduling for continuous repetitive projects with time-based production units. *Automation in Construction*, **18**(7), 942-949.
- Johnston, D.W.** (1981). Linear Scheduling Method for Highway Construction. *Journal of the Construction Division*, **107**(CO2), 247-261.
- Kenley, R. and Seppanen O.** (2010). *Location-based management for construction-Planning, scheduling and control*, Spon Press, New York, USA.
- Kim, B., and Hong, T.** (2012). Revised Case-Based Reasoning Model Development Based on Multiple Regression Analysis for Railroad Bridge Construction. *Journal of Construction Engineering and Management*, **138**(1), 154-162.
- Kim, K. J., and Kim, K.** (2010). Preliminary Cost Estimation Model Using Case-Based Reasoning and Genetic Algorithms. *Journal of Computing in Civil Engineering*, **24**(6), 499-505.
- Lee, J. G., Heaney, J. P. and Lai, F.** (2005). Optimization of Integrated Urban Wet-Weather Control Strategies. *Journal of Water Resources Planning and Management*, **131**(4), 307-315.
- Leu, S. S., and Yang, C.H.** (1999a). GA-based Multicriteria Optimal Model for Construction Scheduling. *Journal of Construction Engineering and Management*, **125**(6), 420-427.
- Leu, S. S., and Yang, C. H.** (1999b). A genetic-algorithm-based resource-constrained construction scheduling system. *Construction Management and Economics*, **17**(6), 767-776.
- Leu, S. S., Yang, C. H., and Huang, J. C.** (2000). Resource leveling in construction by genetic algorithm-based optimization and its decision support system application. *Automation in Construction*, **10**(1), 27-41.
- Leu, S. S., and Hung, T. H.** (2002). A genetic algorithm-based optimal resource-constrained scheduling simulation model. *Construction Management and Economics*, **20**(2), 131-141.
- Leu, S. S. and Hwang, S. T.** (2001). Optimal Repetitive Scheduling Model with Shareable Resource Constraint. *Journal of Construction Engineering and Management*, **127**(4), 270-280.
- Liu, S. S.** (1999). Resource-Constrained Scheduling of Linear Projects: A Heuristic Approach Using Tabu Search Heuristics, *PhD Thesis*, Purdue University.

- Liu, S. S. and Wang, C. J.** (2007). Optimization model for resource assignment problems of linear construction projects. *Automation in Construction*, **16**(4), 460-473.
- Liu, Y., Zhao, S. L., Du, X. K. and Li, S. Q.** (2005). Optimization of Resource Allocation in Construction Using Genetic Algorithms. *Proceedings of the Fourth International Conference on Machine Learning and Cybernetics*, 3428-3432.
- Lucko, G.** (2011). Integrating Efficient Resource Optimization and Linear Schedule Analysis with Singularity Functions. *Journal of Construction Engineering and Management*, **137**(1), 45-55.
- Lumsden, P.** (1968). *The Line-of-Balance Method*. Pergamon Press Limited, Great Britain.
- Man, K. F., Tang, K. S., and Kwong, S.** (1996). Genetic Algorithms: Concepts and Applications. *Transactions on Industrial Electronics*, **43**(5), 519-533.
- Mattila, K. G.** (1997). Resource leveling of linear schedules: a mathematical approach using integer linear programming, *Ph.D. Thesis*, Purdue University.
- Mattila, K. G. and Abraham, D. M.** (1998). Resource Leveling of Linear Schedules: Using Integer Linear Programming. *Journal of Construction Engineering and Management*, **124**(3), 232-244.
- Moder, J. J., Phillips, C. R. and Davis, E. W.** (1983). *Project management with CPM, PERT and precedence programming*, Van Nostrand Reinhold.
- Naylor, H. F. W.** (1995). *Construction Project Management: Planning and Scheduling*, Delmar Publishers, New York.
- O'Brein, J. J.** (1975). VPM Scheduling for High Rise Buildings. *Journal of the Construction Division*, **101**(CO4), 895-905.
- Osman, I. H. and Laporte, G.** (1996). Metaheuristics: A bibliography, *Annals of Operations Research*, **63**, 513-623.
- Prashant, M. P., and Ganguli, R.** (2011). *Structural Health Monitoring Using Genetic Fuzzy Systems*, Springer, New York.
- Peer, S. and Selinger, S.** (1973). *Construction Planning Method by Computer Based on Organizational Requirements*. Building Research Station, Technion - Israel Institute of Technology, Haifa, Israel.
- Perera, S.** (1983). Resource Sharing in Linear Construction. *Journal of Construction Engineering and Management*, **109**(1), 102-111.
- Pierce, D. R., Jr.** (1998). *Project Scheduling and Management for Construction*, Second Edition, R.S. Means Company, Inc., Kingston, MA.
- Popescu, C. M.** (1976). *How to use C.P.M. in Practice. Part II - Resources*, University of Texas at Austin.
- Reda, R.M.** (1990). RPM: Repetitive Project Modeling. *Journal of Construction Engineering and Management*, **116**(2), 316-330.
- Risk Solver Platform** (2011). *User Guide*, Frontline Systems Inc., NV.

- Roech, W.** (1972). Network Planning and Velocity Diagrams in Housing Construction Industry. *Proceedings of the Transportation Research Board 71st Annual Meeting*, Washington D.C.
- Sample, D. J. and Heaney, J. P.** (2006). Integrated Management of Irrigation and Urban Storm-Water Infiltration. *Journal of Water Resources Planning and Management*, **132**(5), 362-373.
- Senouci, A. B. and Adeli, H.** (2001). Resource Scheduling Using Neural Dynamics Model of Adeli and Park. *Journal of Construction Engineering and Management*, **127**(1), 28-34.
- Senouci, A. B. and Eldin, N. N.** (2004). Use of Genetic Algorithms in Resource Scheduling of Construction Projects. *Journal of Construction Engineering and Management*, **130**(6), 869-877.
- Son, J., and Skibniewski, M. J.** (1999). Multiheuristic Approach for Resource Leveling Problem in Construction Engineering: Hybrid Approach. *Journal of Construction Engineering and Management*, **125**(1), 23-31.
- Stevens, J. D.** (1990). *Techniques For Construction Network Scheduling*, McGraw-Hill, USA.
- Stradal, O. and Cacha, J.** (1982). Time Space Scheduling Method. *Journal of the Construction Division*, **108**(CO3), 445-457.
- Taha, H. A.** (1995). *Operations Research: An Introduction*. 5th edition, Prentice Hall International, Inc., NJ.
- Tokdemir, O. B., Arditi, D., and Balcik, C.** (2006). ALISS: Advanced Linear Scheduling System. *Construction Management and Economics*, **24**, 1253-1267.
- Wagner, H. M., Giglio, R. J., and Glaser, R. G.** (1964). Preventive maintenance scheduling by mathematical programming, *Management Science*, **10**(2), 316-334.
- Wenyuan, L.** (2011). *Probabilistic Transmission System Planning*. Wiley-IEEE Press, New Jersey.
- Wiest, J. D., and Levy, F. K.** (1977). *A Management Guide to PERT/CPM: with GERT/PDM/DCPM and other Networks*, Prentice-Hall, Inc., Englewood, New Jersey.
- Wright, L. T., Heaney, J. P., and Dent, S.** (2006). Prioritizing Sanitary Sewers for Rehabilitation Using Least-Cost Classifiers, *Journal of Infrastructure Systems*, **12**(3), 174-183.
- Yen, C.** (2005). Simulated Annealing for Optimizing Linear Scheduling Projects with Multiple Resource Constraints, *PhD Thesis*, Purdue University, West Lafayette, IN.

APPENDICES

APPENDIX A: Excel sheets of the model for Scenario 1 and Scenario 2

APPENDIX A

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7	DAY 8	DAY 9	DAY 10	DAY 11				
3	A	1	0.00	2.00	2	1.00	2.00	96	6	8	0	6	6	0	0	0	0	0	0	0	0	0	0	0	0	
4		2	1.00	3.00	2	1.00	2.00					0	6	6	0	0	0	0	0	0	0	0	0	0	0	
5		3	2.00	4.00	2	1.00	2.00					0	0	6	6	0	0	0	0	0	0	0	0	0	0	
6		4	3.00	5.00	2	1.00	2.00					0	0	0	6	6	0	0	0	0	0	0	0	0	0	
7		5	4.00	6.00	2	1.00	2.00					0	0	0	0	6	6	0	0	0	0	0	0	0	0	
8		6	5.00	7.00	2	1.00	2.00					0	0	0	0	0	6	6	0	0	0	0	0	0	0	
9		7	6.00	8.00	2	1.00	2.00					0	0	0	0	0	0	6	6	0	0	0	0	0	0	
10		8	7.00	9.00	2	1.00	2.00					0	0	0	0	0	0	0	6	6	0	0	0	0	0	
11		9	8.00	10.00	2	1.00	2.00					0	0	0	0	0	0	0	0	6	6	0	0	0	0	
12		10	9.00	11.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	6	6	0	0	0	
13		11	10.00	12.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	6	6	0	0	
14		12	11.00	13.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	6	6	0	
15		13	12.00	14.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	6	6	
16		14	13.00	15.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
17		15	14.00	16.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
18		16	15.00	17.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
19		17	16.00	18.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
20		18	17.00	19.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
21		19	18.00	20.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
22		20	19.00	21.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
23		21	20.00	22.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
24		22	21.00	23.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
25		23	22.00	24.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
26		24	23.00	25.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
27		25	24.00	26.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
28		26	25.00	27.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	6	
31	B	1	14.50	15.50	2	2.00	1.00	64	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
32		2	15.00	16.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
33		3	15.50	16.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
34		4	16.00	17.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
35		5	16.50	17.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
36		6	17.00	18.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
37		7	17.50	18.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
38		8	18.00	19.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
39		9	18.50	19.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
40		10	19.00	20.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
41		11	19.50	20.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
42		12	20.00	21.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
43		13	20.50	21.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
44		14	21.00	22.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
45		15	21.50	22.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
46		16	22.00	23.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
47		17	22.50	23.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
48		18	23.00	24.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
49		19	23.50	24.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
50		20	24.00	25.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
51		21	24.50	25.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
52		22	25.00	26.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
53		23	25.50	26.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
54		24	26.00	27.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
55		25	26.50	27.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
56		26	27.00	28.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
59		1	19.67	20.67	3	3.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
60		2	20.00	21.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
61		3	20.33	21.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Solver Options and Model Specifications

ModelPlatformEngineOutput

Sensitivity

Optimization

Objective

Variables

Constraints

\$A\$196 (Min)

Normal

\$I\$148:\$I\$167

\$I\$31:\$I\$53

Recourse

Normal

\$D\$167 <= \$C\$194

\$D\$3 <= \$C\$31

\$I\$149:\$I\$167 <= \$I\$148

\$I\$150:\$I\$167 <= \$I\$149

\$I\$151:\$I\$167 <= \$I\$150

\$I\$152:\$I\$167 <= \$I\$151

\$I\$153:\$I\$167 <= \$I\$152

\$I\$154:\$I\$167 <= \$I\$153

\$I\$155:\$I\$167 <= \$I\$154

\$I\$156:\$I\$167 <= \$I\$155

\$I\$157:\$I\$167 <= \$I\$156

\$I\$158:\$I\$167 <= \$I\$157

\$I\$159:\$I\$167 <= \$I\$158

\$I\$160:\$I\$167 <= \$I\$159

\$I\$161:\$I\$167 <= \$I\$160

\$I\$162:\$I\$167 <= \$I\$161

Solver Options and Model Specifications

Model Platform Engine Output

Sensitivity

Optimization

Objective

\$A\$196 (Min)

Variables

Normal

☒ \$I\$148:\$I\$167

☒ \$I\$31:\$I\$53

Recourse

Constraints

Normal

☒ \$D\$167 <= \$C\$194

☒ \$D\$3 <= \$C\$31

☒ \$I\$149:\$I\$167 <= \$I\$148

☒ \$I\$150:\$I\$167 <= \$I\$149

☒ \$I\$151:\$I\$167 <= \$I\$150

☒ \$I\$152:\$I\$167 <= \$I\$151

☒ \$I\$153:\$I\$167 <= \$I\$152

☒ \$I\$154:\$I\$167 <= \$I\$153

☒ \$I\$155:\$I\$167 <= \$I\$154

☒ \$I\$156:\$I\$167 <= \$I\$155

☒ \$I\$157:\$I\$167 <= \$I\$156

☒ \$I\$158:\$I\$167 <= \$I\$157

☒ \$I\$159:\$I\$167 <= \$I\$158

☒ \$I\$160:\$I\$167 <= \$I\$159

☒ \$I\$161:\$I\$167 <= \$I\$160

☒ \$I\$162:\$I\$167 <= \$I\$161

Model Diagnosis

Variables - Functions - Dependencies

	Vars	Fcns	Dpns
All	43	446	N/A
Smooth	N/A	N/A	N/A
Linear	N/A	N/A	N/A
Recourse	0	N/A	N/A
Uncertain	0	0	N/A

Other Model Elements

Figure A.1 : Excel sheet of the model for Activity A and B (Scenario 1 / Day 1 - 11)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO		
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 12	DAY 13	DAY 14	DAY 15	DAY 16	DAY 17	DAY 18	DAY 19	DAY 20	DAY 21	DAY 22						
1	A	1	0.00	2.00	2	1.00	2.00	96	6	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
2		1.00	3.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3		2.00	4.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4		3.00	5.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5		4.00	6.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6		5.00	7.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7		6.00	8.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8		7.00	9.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9		8.00	10.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10		9.00	11.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11		10.00	12.00	2	1.00	2.00	6					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12		11.00	13.00	2	1.00	2.00	6					6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13		12.00	14.00	2	1.00	2.00	0					6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14		13.00	15.00	2	1.00	2.00	0					0	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15		14.00	16.00	2	1.00	2.00	0					0	0	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
16		15.00	17.00	2	1.00	2.00	0					0	0	0	6	6	0	0	0	0	0	0	0	0	0	0	0	0
17		16.00	18.00	2	1.00	2.00	0					0	0	0	0	6	6	0	0	0	0	0	0	0	0	0	0	0
18		17.00	19.00	2	1.00	2.00	0					0	0	0	0	0	6	6	0	0	0	0	0	0	0	0	0	0
19		18.00	20.00	2	1.00	2.00	0					0	0	0	0	0	0	6	6	0	0	0	0	0	0	0	0	0
20		19.00	21.00	2	1.00	2.00	0					0	0	0	0	0	0	0	6	6	0	0	0	0	0	0	0	0
21		20.00	22.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	6	6	0	0	0	0	0	0	0
22		21.00	23.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	6	6	0	0	0	0	0	0
23		22.00	24.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	6	6	0	0	0	0	0
24		23.00	25.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	6	6	0	0	0	0
25		24.00	26.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	6	6	0	0	0
26		25.00	27.00	2	1.00	2.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	0	0
27	B	1	14.50	15.50	2	2.00	1.00	64	8	8	0	0	0	0	4	4	0	0	0	0	0	0	0	0				
2		15.00	16.00	2	2.00	1.00	0					0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	
3		15.50	16.50	2	2.00	1.00	0					0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	
4		16.00	17.00	2	2.00	1.00	0					0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	
5		16.50	17.50	2	2.00	1.00	0					0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	
6		17.00	18.00	2	2.00	1.00	0					0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	
7		17.50	18.50	2	2.00	1.00	0					0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	
8		18.00	19.00	2	2.00	1.00	0					0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	
9		18.50	19.50	2	2.00	1.00	0					0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	
10		19.00	20.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	
11		19.50	20.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	
12		20.00	21.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	
13		20.50	21.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	
14		21.00	22.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	
15		21.50	22.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0
16		22.00	23.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17		22.50	23.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18		23.00	24.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19		23.50	24.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20		24.00	25.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21		24.50	25.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22		25.00	26.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23		25.50	26.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24		26.00	27.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25		26.50	27.50	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26		27.00	28.00	2	2.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	C	1	19.67	20.67	3	3.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	3	7	0	0	0				
2		20.00	21.00	3	3.00	1.00	0					0	0	0	0	0	0	0	0	0	0	10	0	0	0	0		
3		20.33	21.33	3	3.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	7	3	0	0	0	
4		20.67	21.67	3	3.00	1.00	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Solver Options and Model Specifications

ModelPlatformEngineOutput

</

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$162:\$I\$167 <= \$I\$161
☒ \$I\$163:\$I\$167 <= \$I\$162
☒ \$I\$164:\$I\$167 <= \$I\$163
☒ \$I\$165:\$I\$167 <= \$I\$164
☒ \$I\$166:\$I\$167 <= \$I\$165
☒ \$I\$167 <= \$I\$166
☒ \$I\$31 <= \$I\$32
☒ \$I\$31:\$I\$32 <= \$I\$33
☒ \$I\$31:\$I\$33 <= \$I\$34
☒ \$I\$31:\$I\$34 <= \$I\$35
☒ \$I\$31:\$I\$35 <= \$I\$36
☒ \$I\$31:\$I\$36 <= \$I\$37
☒ \$I\$31:\$I\$37 <= \$I\$38
☒ \$I\$31:\$I\$38 <= \$I\$39
☒ \$I\$31:\$I\$39 <= \$I\$40
☒ \$I\$31:\$I\$40 <= \$I\$41
☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

Integers

Chance Constraints

Sparsity

129

43

0

Unknown

Figure A.2 : Excel sheet of the model for Activity A and B (Scenario 1 / Day 12 - 22)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 23	DAY 24	DAY 25	DAY 26	DAY 27	DAY 28	DAY 29	DAY 30	DAY 31	DAY 32	DAY 33				
1																										
3	A	1	0.00	2.00	2	1.00	2.00	96	6	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4		2	1.00	3.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5		3	2.00	4.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6		4	3.00	5.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
7		5	4.00	6.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
8		6	5.00	7.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9		7	6.00	8.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
10		8	7.00	9.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
11		9	8.00	10.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
12		10	9.00	11.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13		11	10.00	12.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
14		12	11.00	13.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
15		13	12.00	14.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
16		14	13.00	15.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
17		15	14.00	16.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
18		16	15.00	17.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
19		17	16.00	18.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
20		18	17.00	19.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
21		19	18.00	20.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
22		20	19.00	21.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
23		21	20.00	22.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
24		22	21.00	23.00	2	1.00	2.00					6	0	0	0	0	0	0	0	0	0	0	0	0	0	
25		23	22.00	24.00	2	1.00	2.00					6	6	0	0	0	0	0	0	0	0	0	0	0	0	
26		24	23.00	25.00	2	1.00	2.00					0	6	6	0	0	0	0	0	0	0	0	0	0	0	
27		25	24.00	26.00	2	1.00	2.00					0	0	6	6	0	0	0	0	0	0	0	0	0	0	
28		26	25.00	27.00	2	1.00	2.00					0	0	0	6	6	0	0	0	0	0	0	0	0	0	
31	B	1	14.50	15.50	2	2.00	1.00	64	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
32		2	15.00	16.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
33		3	15.50	16.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
34		4	16.00	17.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
35		5	16.50	17.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
36		6	17.00	18.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
37		7	17.50	18.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
38		8	18.00	19.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
39		9	18.50	19.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
40		10	19.00	20.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
41		11	19.50	20.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
42		12	20.00	21.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
43		13	20.50	21.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
44		14	21.00	22.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
45		15	21.50	22.50	2	2.00	1.00					4	0	0	0	0	0	0	0	0	0	0	0	0	0	
46		16	22.00	23.00	2	2.00	1.00					8	0	0	0	0	0	0	0	0	0	0	0	0	0	
47		17	22.50	23.50	2	2.00	1.00					4	4	0	0	0	0	0	0	0	0	0	0	0	0	
48		18	23.00	24.00	2	2.00	1.00					0	8	0	0	0	0	0	0	0	0	0	0	0	0	
49		19	23.50	24.50	2	2.00	1.00					0	4	4	0	0	0	0	0	0	0	0	0	0	0	
50		20	24.00	25.00	2	2.00	1.00					0	0	8	0	0	0	0	0	0	0	0	0	0	0	
51		21	24.50	25.50	2	2.00	1.00					0	0	4	4	0	0	0	0	0	0	0	0	0	0	
52		22	25.00	26.00	2	2.00	1.00					0	0	0	8	0	0	0	0	0	0	0	0	0	0	
53		23	25.50	26.50	2	2.00	1.00					0	0	0	4	4	0	0	0	0	0	0	0	0	0	
54		24	26.00	27.00	2	2.00	1.00					0	0	0	0	8	0	0	0	0	0	0	0	0	0	
55		25	26.50	27.50	2	2.00	1.00					0	0	0	0	4	4	0	0	0	0	0	0	0	0	
56		26	27.00	28.00	2	2.00	1.00					0	0	0	0	0	8	0	0	0	0	0	0	0	0	
59		1	19.67	20.67	3	3.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
60		2	20.00	21.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
61		3	20.33	21.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Solver Options and Model Specifications

ModelPlatformEngineOutput

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds	129
Integers	43
Chance Constraints	0
Sparsity	Unknown

Figure A.3 : Excel sheet of the model for Activity A and B (Scenario 1 / Day 23 - 33)

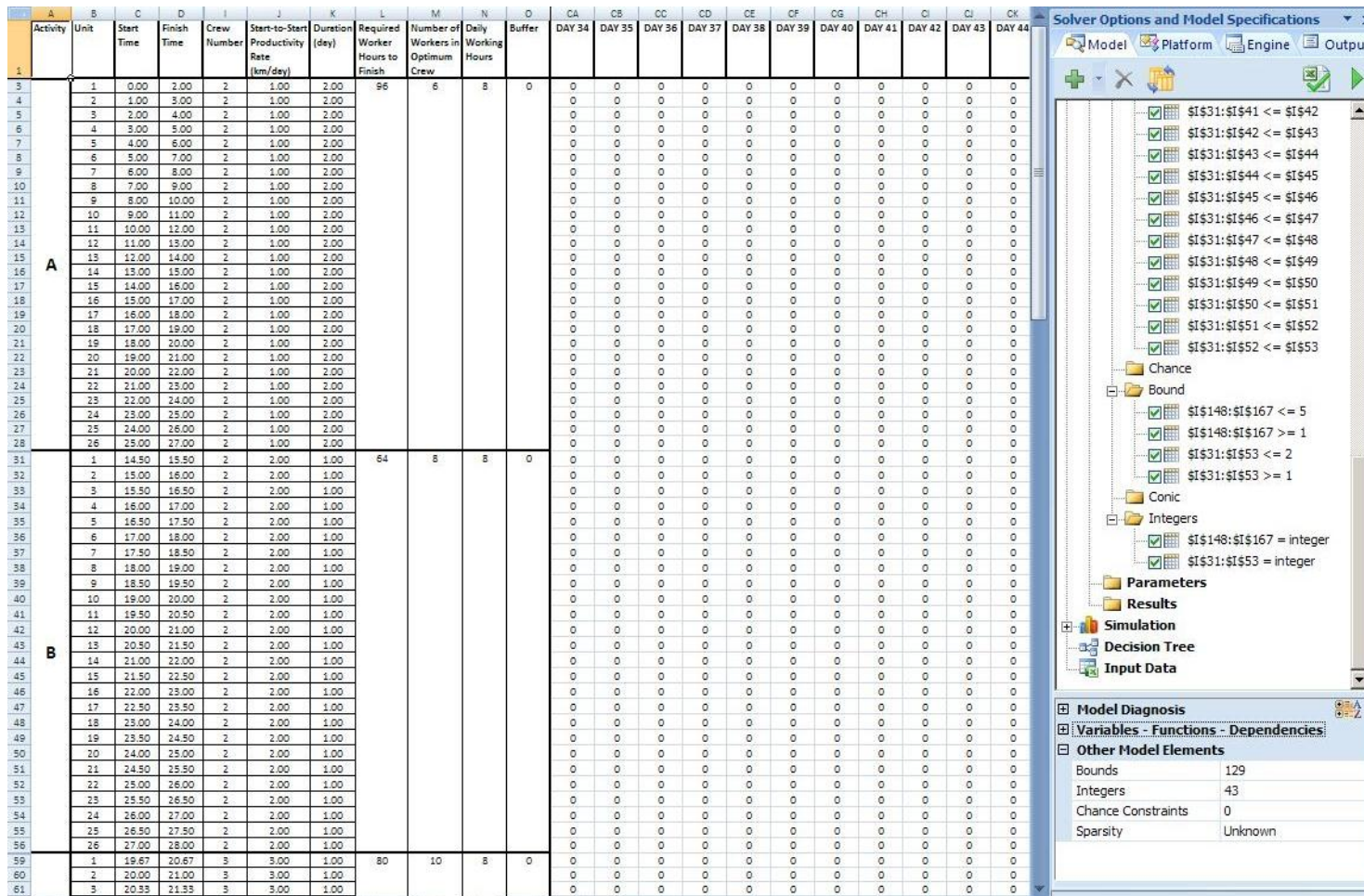


Figure A.4 : Excel sheet of the model for Activity A and B (Scenario 1 / Day 34 - 44)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 45	DAY 46	DAY 47	DAY 48	DAY 49	DAY 50	DAY 51	DAY 52	DAY 53	DAY 54	DAY 55				
1	A	1	0.00	2.00	2	1.00	2.00	96	6	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
4		2	1.00	3.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
5		3	2.00	4.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
6		4	3.00	5.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
7		5	4.00	6.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
8		6	5.00	7.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
9		7	6.00	8.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
10		8	7.00	9.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
11		9	8.00	10.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
12		10	9.00	11.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
13		11	10.00	12.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
14		12	11.00	13.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
15		13	12.00	14.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
16		14	13.00	15.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
17		15	14.00	16.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
18		16	15.00	17.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
19		17	16.00	18.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
20		18	17.00	19.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
21		19	18.00	20.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
22		20	19.00	21.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
23		21	20.00	22.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
24		22	21.00	23.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
25		23	22.00	24.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
26		24	23.00	25.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
27		25	24.00	26.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
28		26	25.00	27.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
31	B	1	14.50	15.50	2	2.00	1.00	64	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
32		2	15.00	16.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
33		3	15.50	16.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
34		4	16.00	17.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
35		5	16.50	17.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
36		6	17.00	18.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
37		7	17.50	18.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
38		8	18.00	19.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
39		9	18.50	19.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
40		10	19.00	20.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
41		11	19.50	20.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
42		12	20.00	21.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
43		13	20.50	21.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
44		14	21.00	22.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
45		15	21.50	22.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
46		16	22.00	23.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
47		17	22.50	23.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
48		18	23.00	24.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
49		19	23.50	24.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
50		20	24.00	25.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
51		21	24.50	25.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
52		22	25.00	26.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
53		23	25.50	26.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
54		24	26.00	27.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
55		25	26.50	27.50	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
56		26	27.00	28.00	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
59		1	19.67	20.67	3	3.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
60		2	20.00	21.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
61		3	20.33	21.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		

Solver Options and Model Specifications

ModelPlatformEngineOutput

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

129

Integers

43

Chance Constraints

0

Sparsity

Unknown

Figure A.5 : Excel sheet of the model for Activity A and B (Scenario 1 / Day 45 - 55)

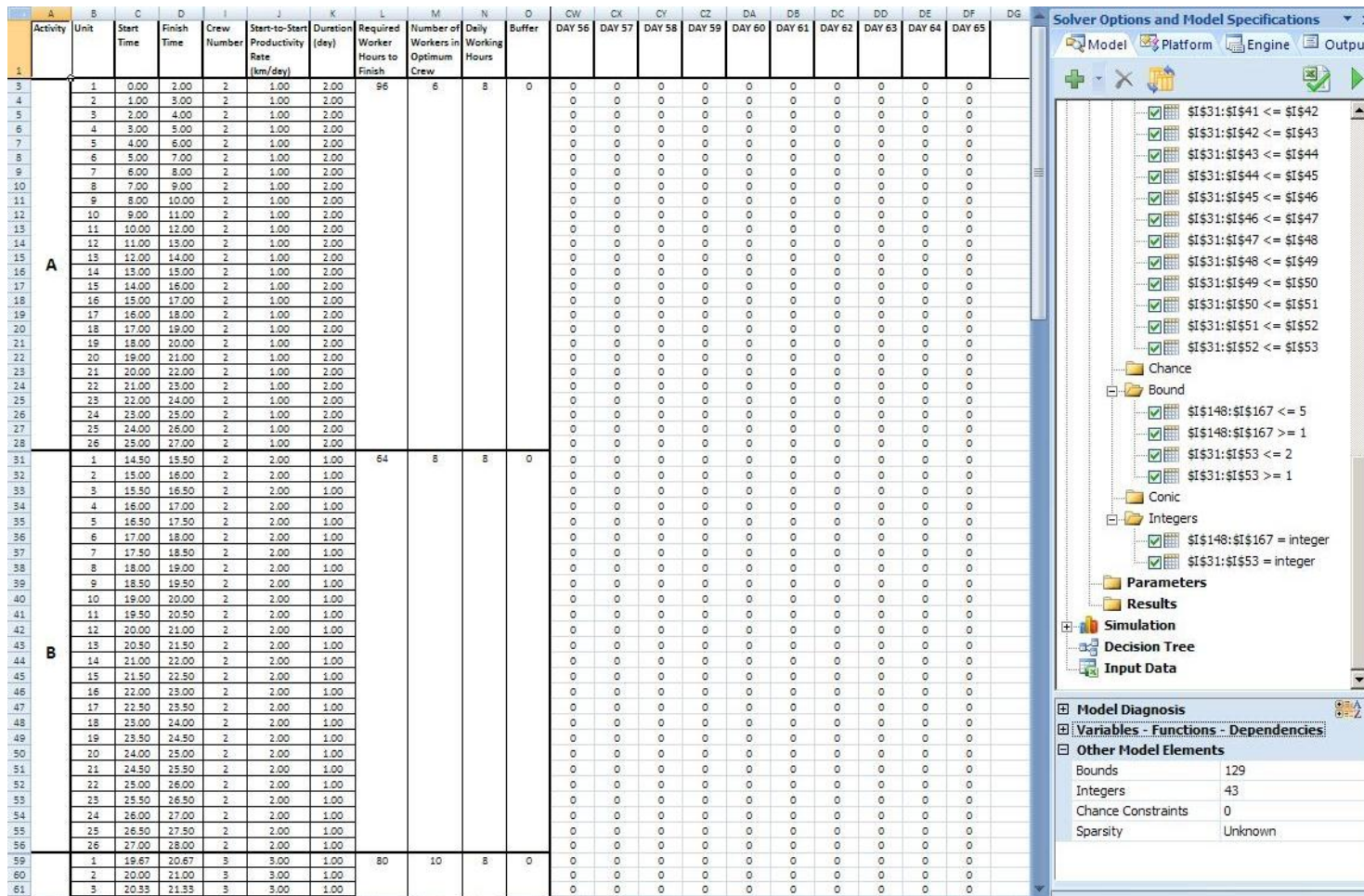


Figure A.6 : Excel sheet of the model for Activity A and B (Scenario 1 / Day 56 - 65)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7	DAY 8	DAY 9	DAY 10	DAY 11				
59	C	1	19.67	20.67	3	3.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0				
60		2	20.00	21.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
61		3	20.33	21.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
62		4	20.67	21.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
63		5	21.00	22.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
64		6	21.33	22.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
65		7	21.67	22.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
66		8	22.00	23.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
67		9	22.33	23.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
68		10	22.67	23.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
69		11	23.00	24.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
70		12	23.33	24.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
71		13	23.67	24.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
72		14	24.00	25.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
73		15	24.33	25.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
74		16	24.67	25.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
75		17	25.00	26.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
76		18	25.33	26.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
77		19	25.67	26.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
78		20	26.00	27.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
79		21	26.33	27.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
80		22	26.67	27.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
81		23	27.00	28.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
82		24	27.33	28.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
83		25	27.67	28.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
84		26	28.00	29.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
88	D	1	20.67	22.17	2	1.33	1.50	84	7	8	0	0	0	0	0	0	0	0	0	0	0	0				
89		2	21.42	22.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
90		3	22.17	23.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
91		4	22.92	24.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
92		5	23.67	25.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
93		6	24.42	25.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
94		7	25.17	26.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
95		8	25.92	27.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
96		9	26.67	28.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
97		10	27.42	28.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
98		11	28.17	29.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
99		12	28.92	30.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
100		13	29.67	31.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
101		14	30.42	31.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
102		15	31.17	32.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
103		16	31.92	33.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
104		17	32.67	34.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
105		18	33.42	34.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
106		19	34.17	35.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
107		20	34.92	36.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
108		21	35.67	37.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
109		22	36.42	37.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
110		23	37.17	38.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
111		24	37.92	39.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
112		25	38.67	40.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
113		26	39.42	40.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0				
115		1	34.67	35.67	4	4.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0				
116		2	34.92	35.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
117		3	35.17	36.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
118		4	35.42	36.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0				
119		5	35.67	36.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0				

Solver Options and Model Specifications

ModelPlatformEngineOutput

Sensitivity

Optimization

Objective

Variables

Constraints

\$AS\$196 (Min)

Normal

Recourse

Normal

☒

\$D\$167 <= \$C\$194

☒

\$D\$3 <= \$C\$31

☒

\$I\$149:\$I\$167 <= \$I\$148

☒

\$I\$150:\$I\$167 <= \$I\$149

☒

\$I\$151:\$I\$167 <= \$I\$150

☒

\$I\$152:\$I\$167 <= \$I\$151

☒

\$I\$153:\$I\$167 <= \$I\$152

☒

\$I\$154:\$I\$167 <= \$I\$153

☒

\$I\$155:\$I\$167 <= \$I\$154

☒

\$I\$156:\$I\$167 <= \$I\$155

☒

\$I\$157:\$I\$167 <= \$I\$156

☒

\$I\$158:\$I\$167 <= \$I\$157

☒

\$I\$159:\$I\$167 <= \$I\$158

☒

\$I\$160:\$I\$167 <= \$I\$159

☒

\$I\$161:\$I\$167 <= \$I\$160

☒

\$I\$162:\$I\$167 <= \$I\$161

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Vars

Fcns

Dpns

All

43

446

N/A

Smooth

N/A

N/A

N/A

Linear

N/A

N/A

N/A

Recourse

0

N/A

N/A

Uncertain

0

0

N/A

Solver Options and Model Specifications
Model Platform Engine Output

Sensitivity

Optimization

Objective

\$A\$5:\$196 (Min)

Variables

Normal

☒ \$I\$148:\$I\$167

☒ \$I\$31:\$I\$53

Recurse

Constraints

Normal

☒ \$D\$167 <= \$C\$194

☒ \$D\$3 <= \$C\$31

☒ \$I\$149:\$I\$167 <= \$I\$148

☒ \$I\$150:\$I\$167 <= \$I\$149

☒ \$I\$151:\$I\$167 <= \$I\$150

☒ \$I\$152:\$I\$167 <= \$I\$151

☒ \$I\$153:\$I\$167 <= \$I\$152

☒ \$I\$154:\$I\$167 <= \$I\$153

☒ \$I\$155:\$I\$167 <= \$I\$154

☒ \$I\$156:\$I\$167 <= \$I\$155

☒ \$I\$157:\$I\$167 <= \$I\$156

☒ \$I\$158:\$I\$167 <= \$I\$157

☒ \$I\$159:\$I\$167 <= \$I\$158

☒ \$I\$160:\$I\$167 <= \$I\$159

☒ \$I\$161:\$I\$167 <= \$I\$160

☒ \$I\$162:\$I\$167 <= \$I\$161

☒ \$I\$163:\$I\$167 <= \$I\$162

Model Diagnosis

Variables - Functions - Dependencies

	Vars	Fcns	Deps
All	43	446	N/A
Smooth	N/A	N/A	N/A
Linear	N/A	N/A	N/A
Recurse	0	N/A	N/A
Uncertain	0	0	N/A

Other Model Elements

Figure A.7 : Excel sheet of the model for Activity C and D (Scenario 1 / Day 1 - 11)

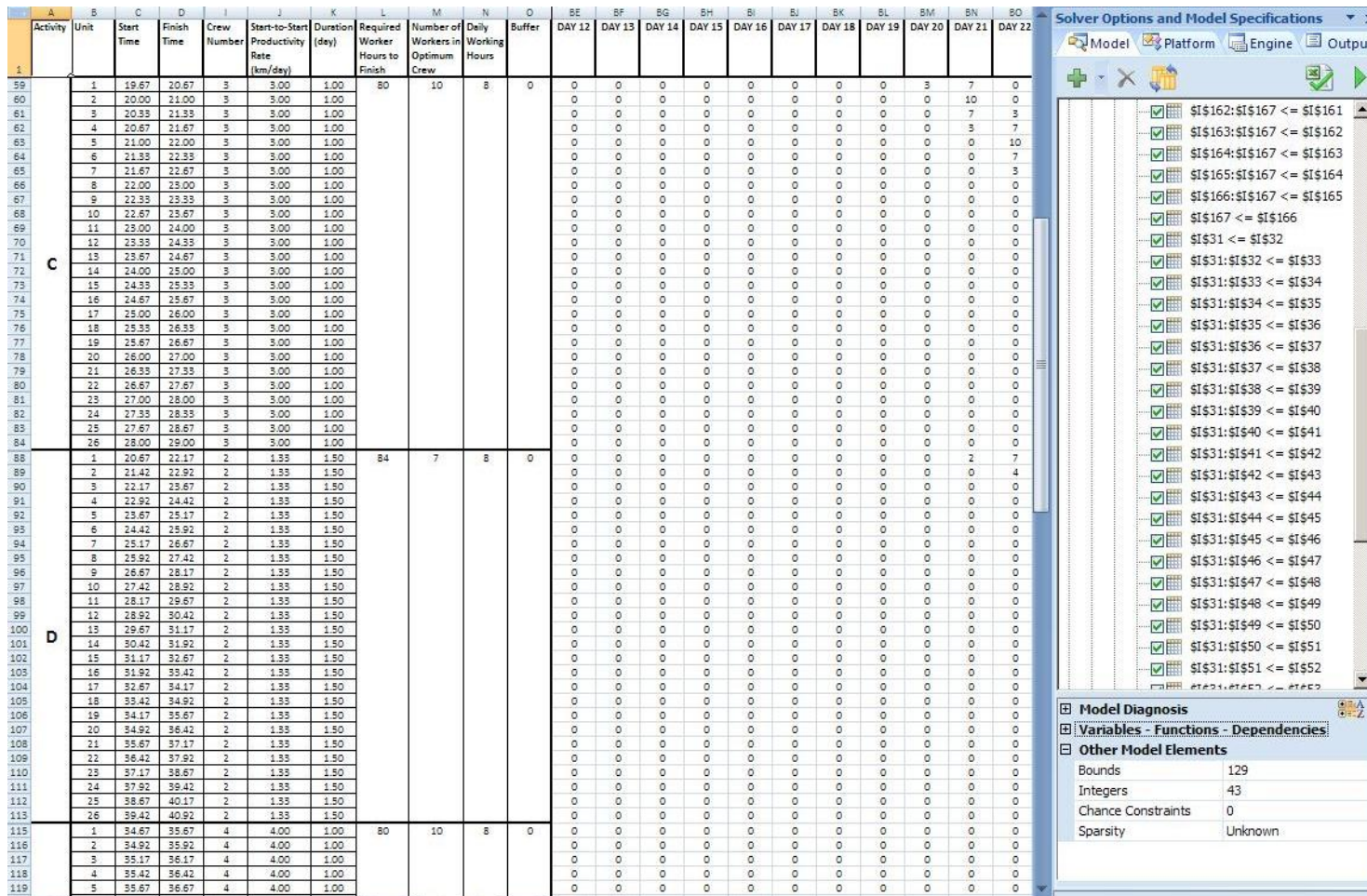


Figure A.8 : Excel sheet of the model for Activity C and D (Scenario 1 / Day 12 - 22)

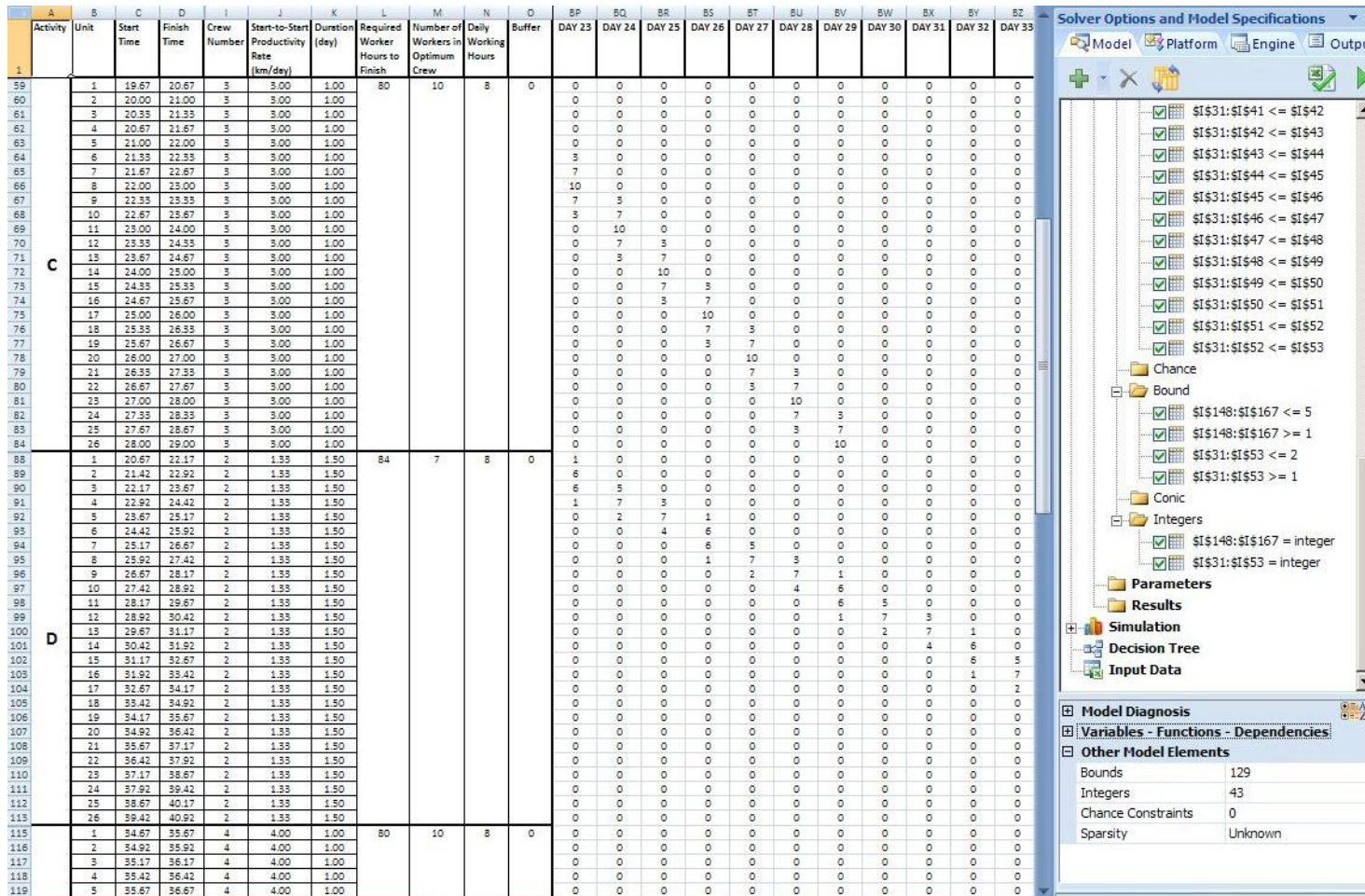


Figure A.9 : Excel sheet of the model for Activity C and D (Scenario 1 / Day 23 - 33)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 34	DAY 35	DAY 36	DAY 37	DAY 38	DAY 39	DAY 40	DAY 41	DAY 42	DAY 43	DAY 44				
59	C	1	19.67	20.67	3	3.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
60		2	20.00	21.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
61		3	20.33	21.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
62		4	20.67	21.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
63		5	21.00	22.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
64		6	21.33	22.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
65		7	21.67	22.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
66		8	22.00	23.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
67		9	22.33	23.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
68		10	22.67	23.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
69		11	23.00	24.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
70		12	23.33	24.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
71		13	23.67	24.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
72		14	24.00	25.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
73		15	24.33	25.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
74		16	24.67	25.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
75		17	25.00	26.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
76		18	25.33	26.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
77		19	25.67	26.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
78		20	26.00	27.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
79		21	26.33	27.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
80		22	26.67	27.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
81	D	23	27.00	28.00	3	3.00	1.00	84	7	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
82		24	27.33	28.33	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
83		25	27.67	28.67	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
84		26	28.00	29.00	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
88		1	20.67	22.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
89		2	21.42	22.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
90		3	22.17	23.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
91		4	22.92	24.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
92		5	23.67	25.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
93		6	24.42	25.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
94		7	25.17	26.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
95		8	25.92	27.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
96		9	26.67	28.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
97		10	27.42	28.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
98		11	28.17	29.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
99		12	28.92	30.42	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
100		13	29.67	31.17	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
101		14	30.42	31.92	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
102		15	31.17	32.67	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
103		16	31.92	33.42	2	1.33	1.50					3	0	0	0	0	0	0	0	0	0	0	0	0		
104		17	32.67	34.17	2	1.33	1.50					7	1	0	0	0	0	0	0	0	0	0	0	0		
105		18	33.42	34.92	2	1.33	1.50					4	6	0	0	0	0	0	0	0	0	0	0	0		
106		19	34.17	35.67	2	1.33	1.50					0	6	5	0	0	0	0	0	0	0	0	0	0		
107		20	34.92	36.42	2	1.33	1.50					0	1	7	3	0	0	0	0	0	0	0	0	0		
108		21	35.67	37.17	2	1.33	1.50					0	0	2	7	1	0	0	0	0	0	0	0	0		
109		22	36.42	37.92	2	1.33	1.50					0	0	0	4	6	0	0	0	0	0	0	0	0		
110		23	37.17	38.67	2	1.33	1.50					0	0	0	0	6	5	0	0	0	0	0	0	0		
111		24	37.92	39.42	2	1.33	1.50					0	0	0	0	1	7	3	0	0	0	0	0	0		
112		25	38.67	40.17	2	1.33	1.50					0	0	0	0	0	2	7	1	0	0	0	0	0		
113		26	39.42	40.92	2	1.33	1.50					0	0	0	0	0	0	4	6	0	0	0	0	0		
115		1	34.67	35.67	4	4.00	1.00	80	10	8	0	0	3	7	0	0	0	0	0	0	0	0	0	0		
116		2	34.92	35.92	4	4.00	1.00					0	1	9	0	0	0	0	0	0	0	0	0	0		
117		3	35.17	36.17	4	4.00	1.00					0	0	8	2	0	0	0	0	0	0	0	0	0		
118		4	35.42	36.42	4	4.00	1.00					0	0	6	4	0	0	0	0	0	0	0	0	0		
119		5	35.67	36.67	4	4.00	1.00					0	0	3	7	0	0	0	0	0	0	0	0	0		

Solver Options and Model Specifications

ModelPlatformEngineOutput

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds 129
 Integers 43
 Chance Constraints 0
 Sparsity Unknown

Figure A.10 : Excel sheet of the model for Activity C and D (Scenario 1 / Day 34 - 44)

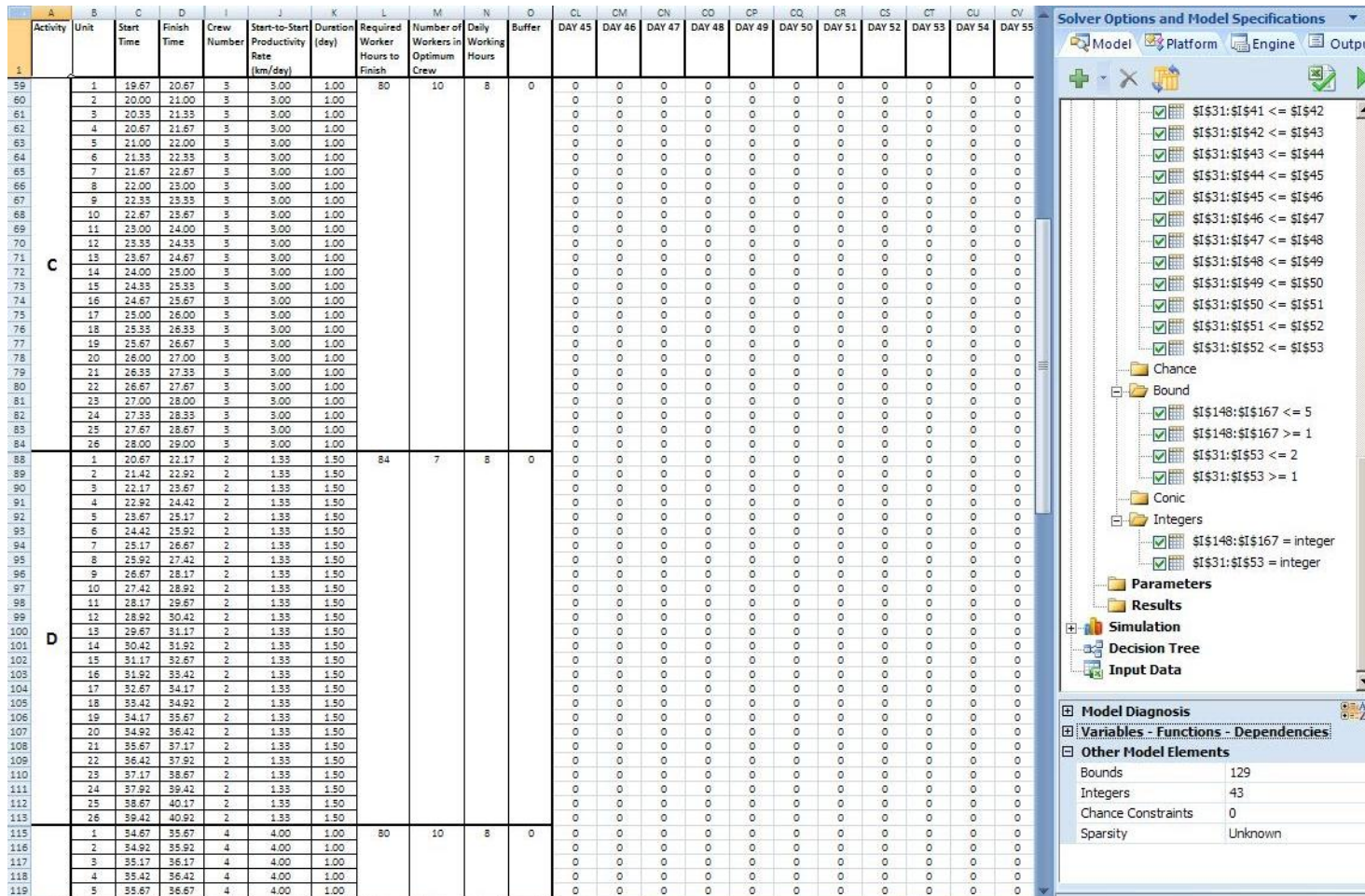


Figure A.11 : Excel sheet of the model for Activity C and D (Scenario 1 / Day 45 - 55)

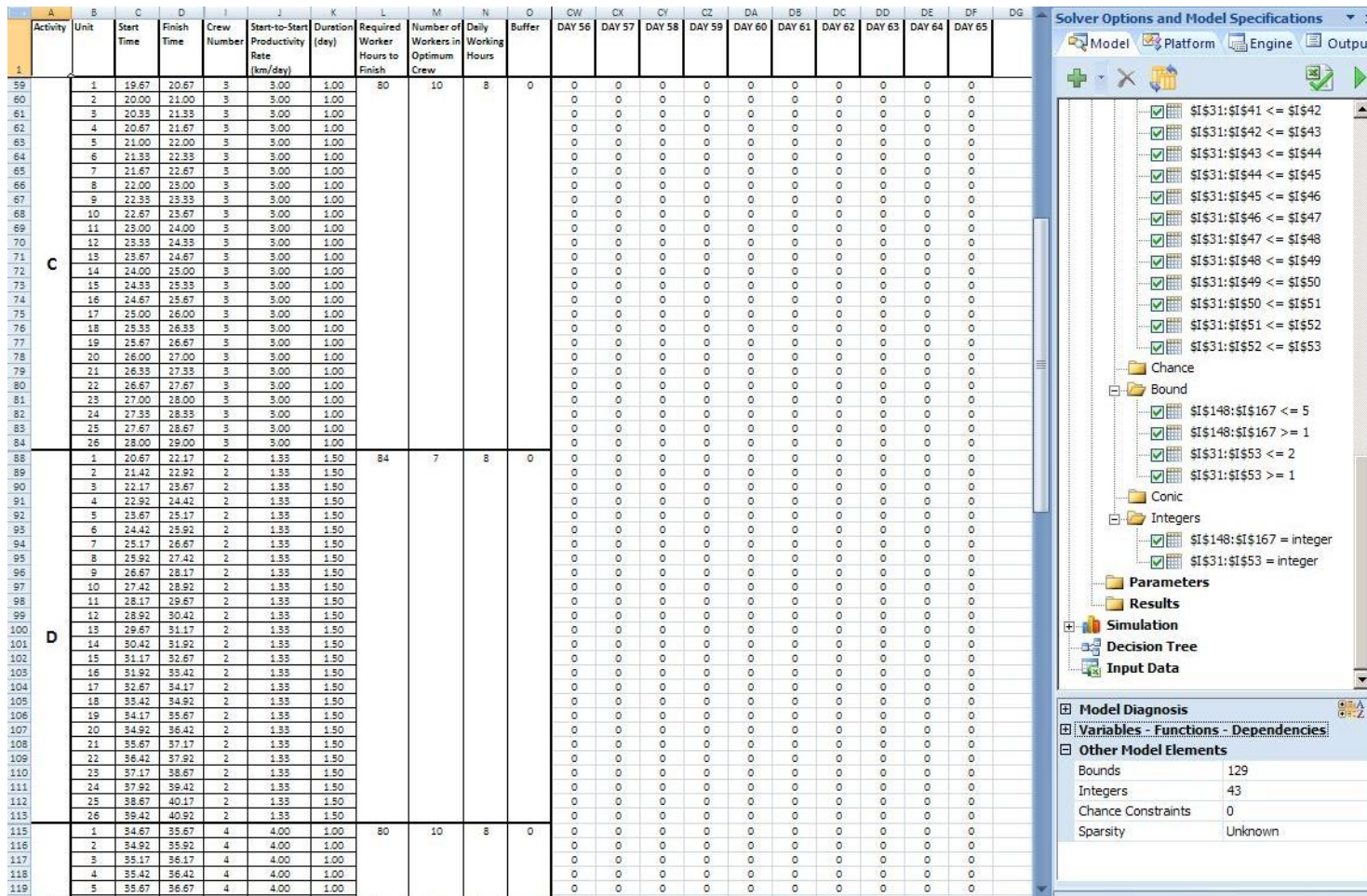


Figure A.12 : Excel sheet of the model for Activity C and D (Scenario 1 / Day 56 - 66)

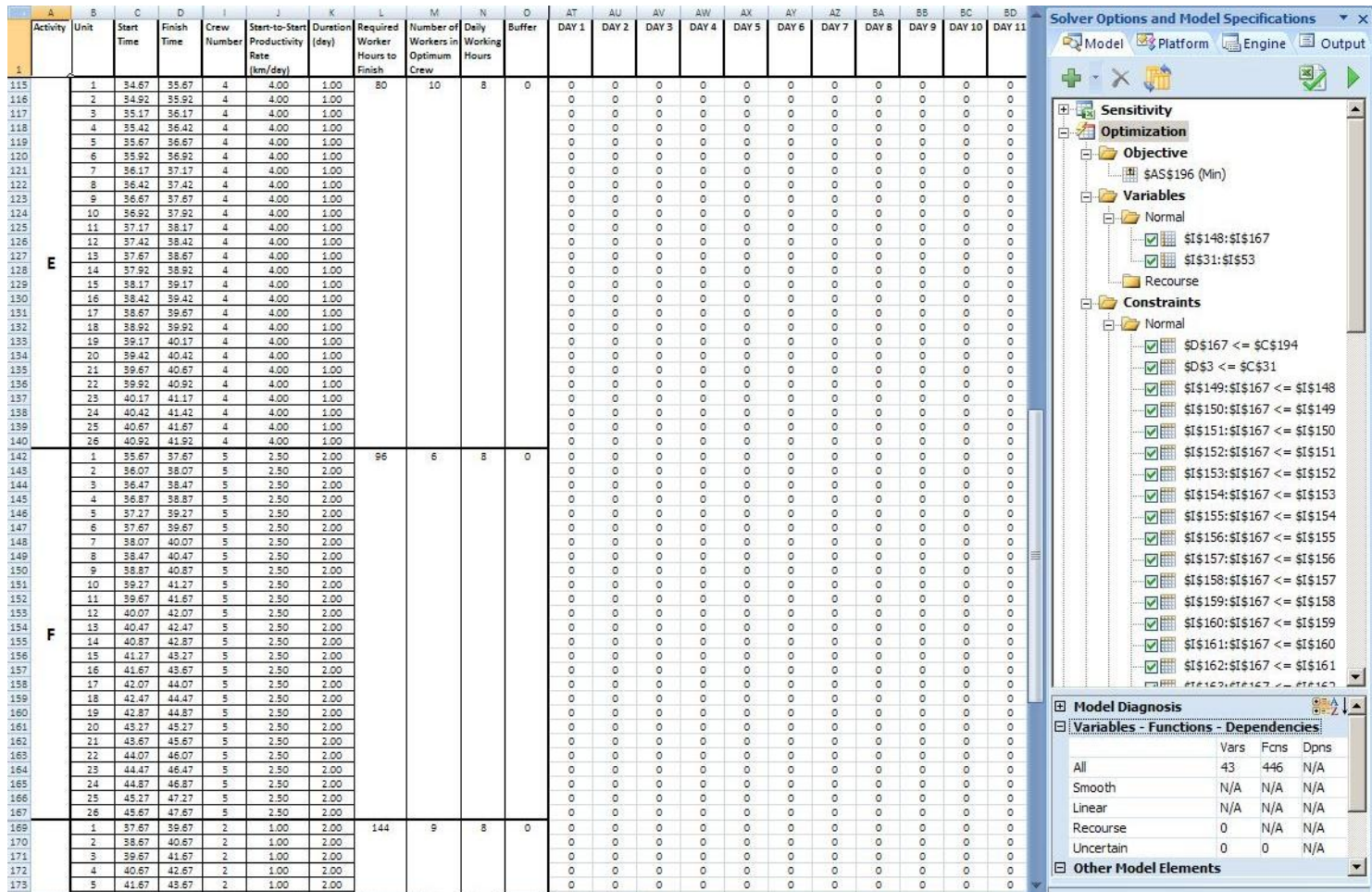


Figure A.13 : Excel sheet of the model for Activity E and F (Scenario 1 / Day 1 - 11)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 23	DAY 24	DAY 25	DAY 26	DAY 27	DAY 28	DAY 29	DAY 30	DAY 31	DAY 32	DAY 33				
115	E	1	34.67	35.67	4	4.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
116		2	34.92	35.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
117		3	35.17	36.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
118		4	35.42	36.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
119		5	35.67	36.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
120		6	35.92	36.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
121		7	36.17	37.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
122		8	36.42	37.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
123		9	36.67	37.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
124		10	36.92	37.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
125		11	37.17	38.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
126		12	37.42	38.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
127		13	37.67	38.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
128		14	37.92	38.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
129		15	38.17	39.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
130		16	38.42	39.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
131		17	38.67	39.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
132		18	38.92	39.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
133		19	39.17	40.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
134		20	39.42	40.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
135		21	39.67	40.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
136		22	39.92	40.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
137		23	40.17	41.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
138		24	40.42	41.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
139		25	40.67	41.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
140		26	40.92	41.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
142	F	1	35.67	37.67	5	2.50	2.00	96	6	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
143		2	36.07	38.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
144		3	36.47	38.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
145		4	36.87	38.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
146		5	37.27	39.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
147		6	37.67	39.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
148		7	38.07	40.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
149		8	38.47	40.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
150		9	38.87	40.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
151		10	39.27	41.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
152		11	39.67	41.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
153		12	40.07	42.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
154		13	40.47	42.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
155		14	40.87	42.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
156		15	41.27	43.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
157		16	41.67	43.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
158		17	42.07	44.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
159		18	42.47	44.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
160		19	42.87	44.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
161		20	43.27	45.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
162		21	43.67	45.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
163		22	44.07	46.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
164		23	44.47	46.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
165		24	44.87	46.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
166		25	45.27	47.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
167		26	45.67	47.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
169		1	37.67	39.67	2	1.00	2.00	144	9	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
170		2	38.67	40.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
171		3	39.67	41.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
172		4	40.67	42.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
173		5	41.67	43.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			

Solver Options and Model Specifications

ModelPlatformEngineOutput

<

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

129

Integers

43

Chance Constraints

0

Sparsity

Unknown

Figure A.15 : Excel sheet of the model for Activity E and F (Scenario 1 / Day 23 - 33)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 45	DAY 46	DAY 47	DAY 48	DAY 49	DAY 50	DAY 51	DAY 52	DAY 53	DAY 54	DAY 55				
115	E	1	34.67	35.67	4	4.00	1.00	80	10	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
116		2	34.92	35.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
117		3	35.17	36.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
118		4	35.42	36.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
119		5	35.67	36.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
120		6	35.92	36.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
121		7	36.17	37.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
122		8	36.42	37.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
123		9	36.67	37.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
124		10	36.92	37.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
125		11	37.17	38.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
126		12	37.42	38.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
127		13	37.67	38.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
128		14	37.92	38.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
129		15	38.17	39.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
130		16	38.42	39.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
131		17	38.67	39.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
132		18	38.92	39.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
133		19	39.17	40.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
134		20	39.42	40.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
135		21	39.67	40.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
136		22	39.92	40.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
137		23	40.17	41.17	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
138		24	40.42	41.42	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
139		25	40.67	41.67	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
140		26	40.92	41.92	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
142	F	1	35.67	37.67	5	2.50	2.00	96	6	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
143		2	36.07	38.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
144		3	36.47	38.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
145		4	36.87	38.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
146		5	37.27	39.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
147		6	37.67	39.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
148		7	38.07	40.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
149		8	38.47	40.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
150		9	38.87	40.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
151		10	39.27	41.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
152		11	39.67	41.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
153		12	40.07	42.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
154		13	40.47	42.47	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
155		14	40.87	42.87	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
156		15	41.27	43.27	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
157		16	41.67	43.67	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
158		17	42.07	44.07	5	2.50	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
159		18	42.47	44.47	5	2.50	2.00					3	0	0	0	0	0	0	0	0	0	0	0	0	0	
160		19	42.87	44.87	5	2.50	2.00					5	0	0	0	0	0	0	0	0	0	0	0	0	0	
161		20	43.27	45.27	5	2.50	2.00					6	2	0	0	0	0	0	0	0	0	0	0	0	0	
162		21	43.67	45.67	5	2.50	2.00					6	4	0	0	0	0	0	0	0	0	0	0	0	0	
163		22	44.07	46.07	5	2.50	2.00					6	6	0	0	0	0	0	0	0	0	0	0	0	0	
164		23	44.47	46.47	5	2.50	2.00					3	6	3	0	0	0	0	0	0	0	0	0	0	0	
165		24	44.87	46.87	5	2.50	2.00					1	6	5	0	0	0	0	0	0	0	0	0	0	0	
166		25	45.27	47.27	5	2.50	2.00					0	4	6	2	0	0	0	0	0	0	0	0	0	0	
167		26	45.67	47.67	5	2.50	2.00					0	2	6	4	0	0	0	0	0	0	0	0	0	0	
169		1	37.67	39.67	2	1.00	2.00	144	9	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
170		2	38.67	40.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
171		3	39.67	41.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
172		4	40.67	42.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
173		5	41.67	43.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Solver Options and Model Specifications

ModelPlatformEngineOutput

Solver Options and Model Specifications
Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53
Chance
Bound
☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1
Conic
Integers
☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer
Parameters
Results
Simulation
Decision Tree
Input Data

Model Diagnosis
Variables - Functions - Dependencies
Other Model Elements

Bounds	129
Integers	43
Chance Constraints	0
Sparsity	Unknown

Figure A.17 : Excel sheet of the model for Activity E and F (Scenario 1 / Day 45 - 55)

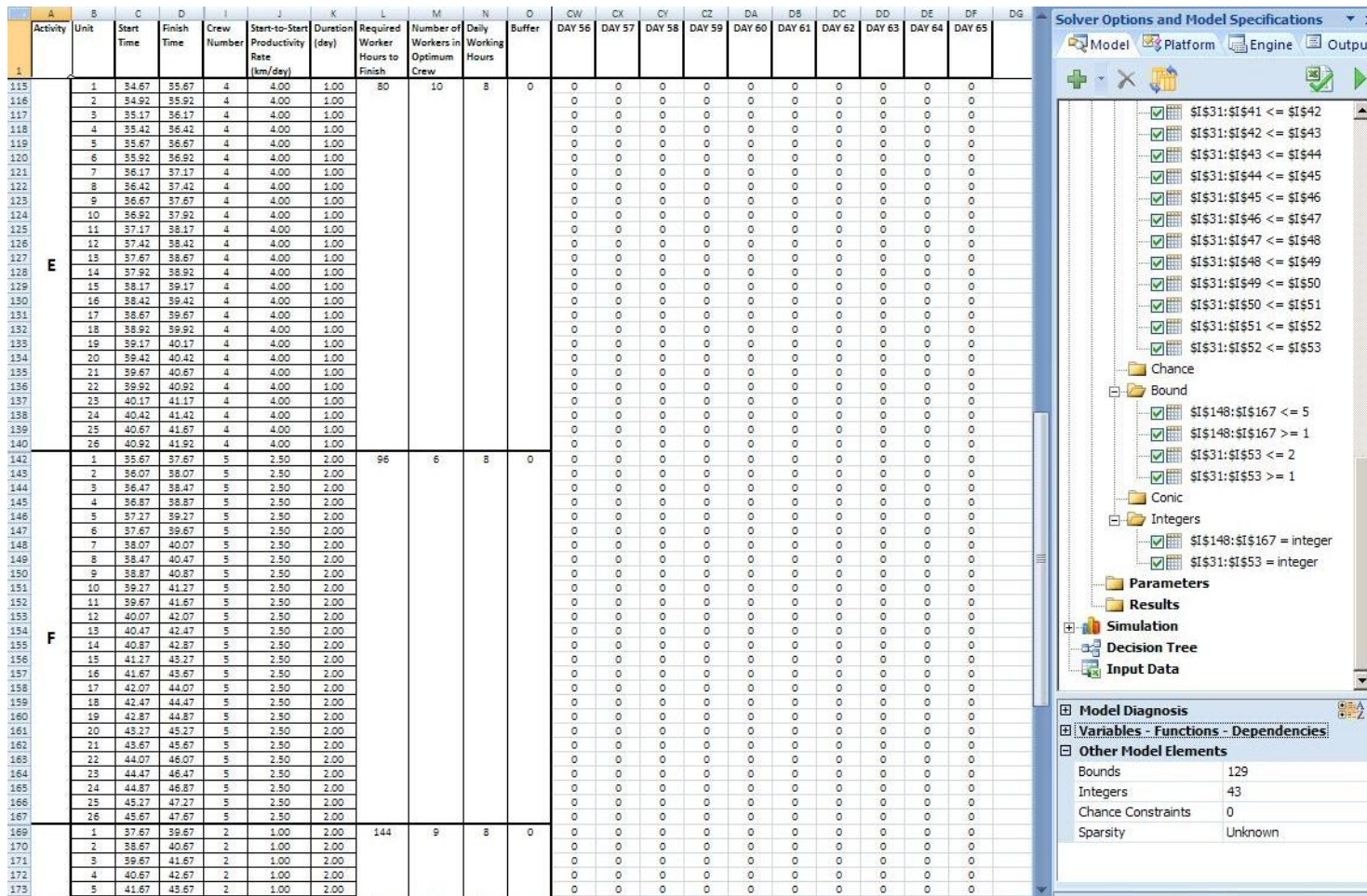


Figure A.18 : Excel sheet of the model for Activity E and F (Scenario 1 / Day 56 - 66)

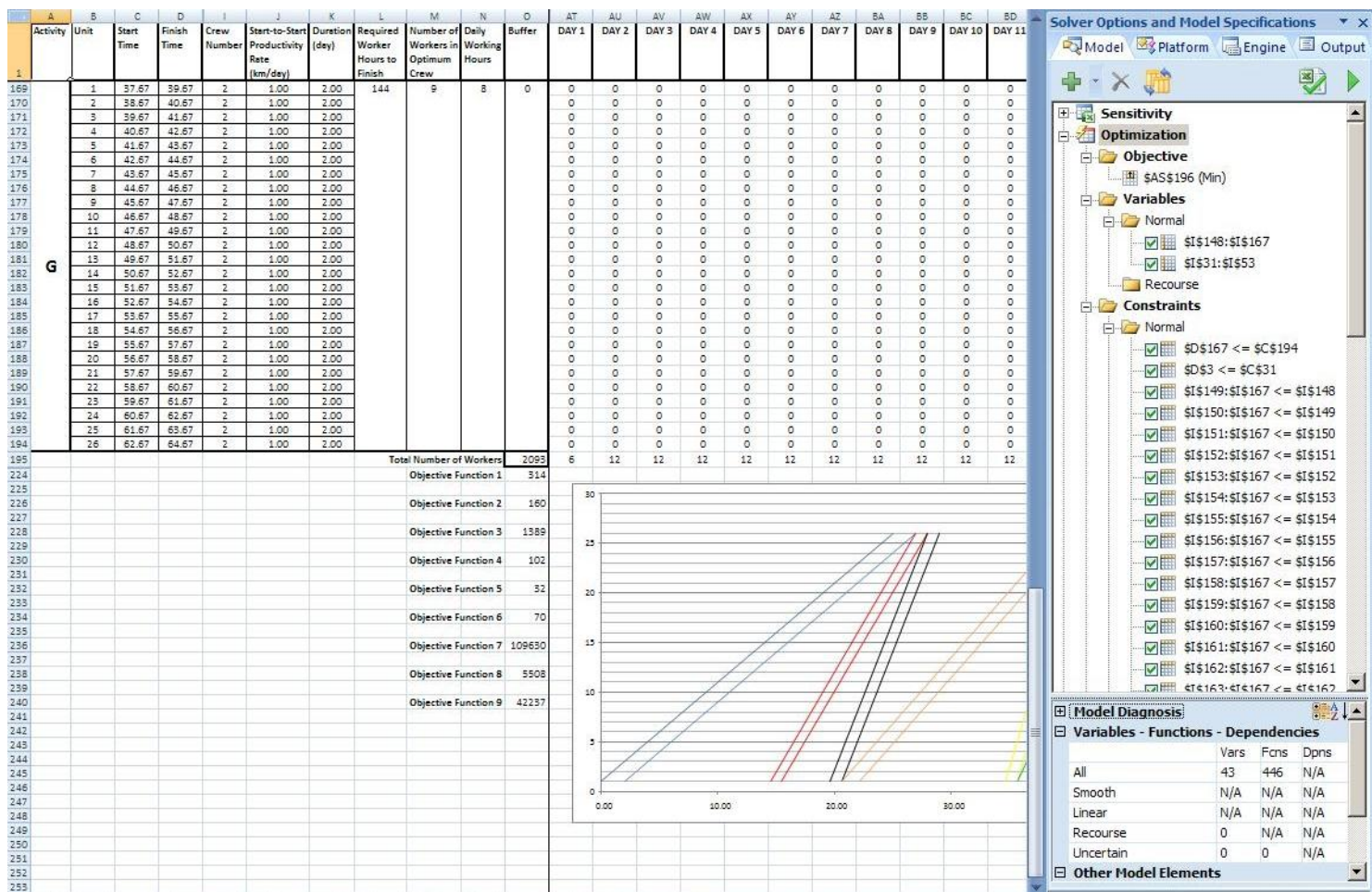


Figure A.19 : Excel sheet of the model for Activity G (Scenario 1 / Day 1 - 11)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 34	DAY 35	DAY 36	DAY 37	DAY 38	DAY 39	DAY 40	DAY 41	DAY 42	DAY 43	DAY 44				
169	G	1	37.67	39.67	2	1.00	2.00	144	9	8	0	0	0	0	0	3	9	6	0	0	0	0				
170		2	38.67	40.67	2	1.00	2.00					0	0	0	0	0	3	9	6	0	0	0				
171		3	39.67	41.67	2	1.00	2.00					0	0	0	0	0	0	3	9	6	0	0				
172		4	40.67	42.67	2	1.00	2.00					0	0	0	0	0	0	0	3	9	6	0				
173		5	41.67	43.67	2	1.00	2.00					0	0	0	0	0	0	0	0	3	9	6				
174		6	42.67	44.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	3	9				
175		7	43.67	45.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	3				
176		8	44.67	46.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
177		9	45.67	47.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
178		10	46.67	48.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
179		11	47.67	49.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
180		12	48.67	50.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
181		13	49.67	51.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
182		14	50.67	52.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
183		15	51.67	53.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
184		16	52.67	54.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
185		17	53.67	55.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
186		18	54.67	56.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
187		19	55.67	57.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
188		20	56.67	58.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
189		21	57.67	59.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
190		22	58.67	60.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
191		23	59.67	61.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
192		24	60.67	62.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
193		25	61.67	63.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
194		26	62.67	64.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
224								Total Number of Workers	2093			14	18	50	70	85	96	102	96	70	48	48				
225								Objective Function 1	314																	
226								Objective Function 2	160																	
227								Objective Function 3	1389																	
228								Objective Function 4	102																	
229								Objective Function 5	32																	
230								Objective Function 6	70																	
231								Objective Function 7	109630																	
232								Objective Function 8	5508																	
233								Objective Function 9	42237																	
234																										
235																										
236																										
237																										
238																										
239																										
240																										
241																										
242																										
243																										
244																										
245																										
246																										
247																										
248																										
249																										
250																										
251																										
252																										
253																										

Solver Options and Model Specifications

ModelPlatformEngineOutput

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

129

Integers

43

Chance Constraints

0

Sparsity

Unknown

Figure A.22 : Excel sheet of the model for Activity G (Scenario 1 / Day 34 - 44)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 45	DAY 46	DAY 47	DAY 48	DAY 49	DAY 50	DAY 51	DAY 52	DAY 53	DAY 54	DAY 55				
169	G	1	37.67	39.67	2	1.00	2.00	144	9	8	0	0	0	0	0	0	0	0	0	0	0	0				
170		2	38.67	40.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
171		3	39.67	41.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
172		4	40.67	42.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
173		5	41.67	43.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
174		6	42.67	44.67	2	1.00	2.00					6	0	0	0	0	0	0	0	0	0	0				
175		7	43.67	45.67	2	1.00	2.00					9	6	0	0	0	0	0	0	0	0	0				
176		8	44.67	46.67	2	1.00	2.00					3	9	6	0	0	0	0	0	0	0	0				
177		9	45.67	47.67	2	1.00	2.00					0	3	9	6	0	0	0	0	0	0	0				
178		10	46.67	48.67	2	1.00	2.00					0	0	3	9	6	0	0	0	0	0	0				
179		11	47.67	49.67	2	1.00	2.00					0	0	0	3	9	6	0	0	0	0	0				
180		12	48.67	50.67	2	1.00	2.00					0	0	0	0	3	9	6	0	0	0	0				
181		13	49.67	51.67	2	1.00	2.00					0	0	0	0	0	3	9	6	0	0	0				
182		14	50.67	52.67	2	1.00	2.00					0	0	0	0	0	0	3	9	6	0	0				
183		15	51.67	53.67	2	1.00	2.00					0	0	0	0	0	0	0	3	9	6	0				
184		16	52.67	54.67	2	1.00	2.00					0	0	0	0	0	0	0	0	3	9	6				
185		17	53.67	55.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	3	9				
186		18	54.67	56.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	3				
187		19	55.67	57.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
188		20	56.67	58.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
189		21	57.67	59.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
190		22	58.67	60.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
191		23	59.67	61.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
192		24	60.67	62.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
193		25	61.67	63.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
194		26	62.67	64.67	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0				
195								Total Number of Workers	2093			48	48	38	24	18	18	18	18	18	18	18				
224								Objective Function 1	514																	
225								Objective Function 2	160																	
226								Objective Function 3	1389																	
227								Objective Function 4	102																	
228								Objective Function 5	32																	
229								Objective Function 6	70																	
230								Objective Function 7	109630																	
231								Objective Function 8	5508																	
232								Objective Function 9	42237																	
233																										

Solver Options and Model Specifications

ModelPlatformEngineOutput

Chance

Bound

Conic

Integers

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

Integers

Chance Constraints

Sparsity

129

43

0

Unknown

Figure A.23 : Excel sheet of the model for Activity G (Scenario 1 / Day 45 - 55)

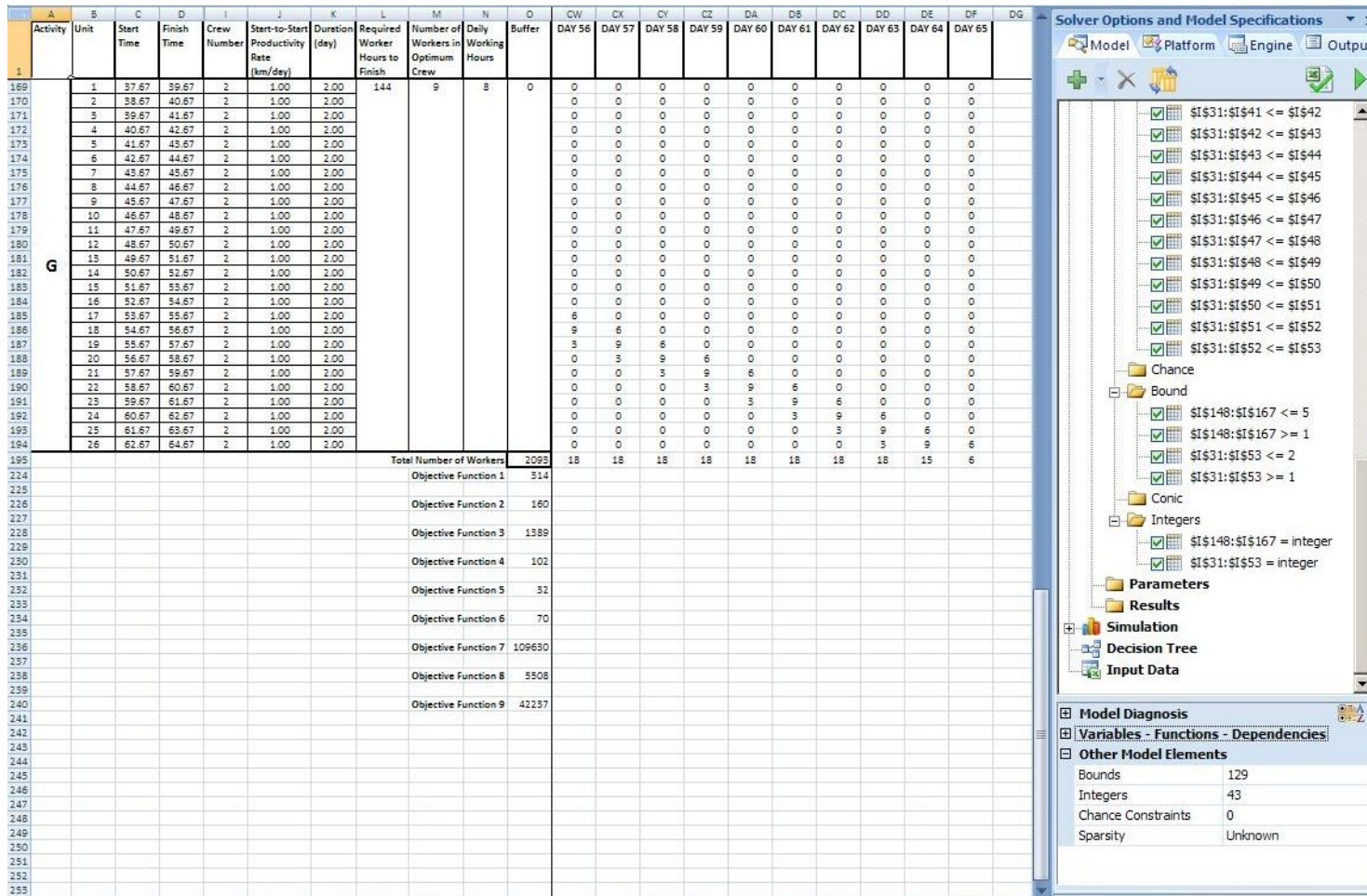


Figure A.24 : Excel sheet of the model for Activity G (Scenario 1 / Day 56 - 65)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7	DAY 8	DAY 9	DAY 10	DAY 11				
1																										
3	A	1	0.00	2.00	2	1.00	2.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4		2	1.00	3.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
5		3	2.00	4.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
6		4	3.00	5.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
7		5	4.00	6.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
8		6	5.00	7.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
9		7	6.00	8.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
10		8	7.00	9.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
11		9	8.00	10.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
12		10	9.00	11.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
13		11	10.00	12.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
14		12	11.00	13.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
15		13	12.00	14.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
16		14	13.00	15.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
17		15	14.00	16.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
18		16	15.00	17.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
19		17	16.00	18.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
20		18	17.00	19.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
21		19	18.00	20.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
22		20	19.00	21.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
23		21	20.00	22.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
24		22	21.00	23.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
25		23	22.00	24.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
26		24	23.00	25.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
27		25	24.00	26.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
28		26	25.00	27.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
31	B	1	14.50	16.00	3	2.00	1.50	48	4	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
32		2	15.00	16.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
33		3	15.50	17.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
34		4	16.00	17.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
35		5	16.50	18.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
36		6	17.00	18.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
37		7	17.50	19.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
38		8	18.00	19.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
39		9	18.50	20.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
40		10	19.00	20.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
41		11	19.50	21.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
42		12	20.00	21.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
43		13	20.50	22.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
44		14	21.00	22.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
45		15	21.50	23.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
46		16	22.00	23.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
47		17	22.50	24.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
48		18	23.00	24.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
49		19	23.50	25.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
50		20	24.00	25.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
51		21	24.50	26.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
52		22	25.00	26.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
53		23	25.50	27.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
54		24	26.00	27.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
55		25	26.50	28.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
56		26	27.00	28.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
59		1	22.25	23.25	4	4.00	1.00	24	3	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
60		2	22.50	23.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		

Solver Options and Model Specifications

ModelPlatformEngineOutput

Sensitivity

Optimization

Objective

Variables

Normal

Recourse

Constraints

Normal

\$AS\$196 (Min)

\$148:\$167

\$131:\$153

Recourse

\$D\$167 <= \$C\$194

\$D\$3 <= \$C\$31

\$149:\$167 <= \$148

\$150:\$167 <= \$149

\$151:\$167 <= \$150

\$152:\$167 <= \$151

\$153:\$167 <= \$152

\$154:\$167 <= \$153

\$155:\$167 <= \$154

\$156:\$167 <= \$155

\$157:\$167 <= \$156

\$158:\$167 <= \$157

\$159:\$167 <= \$158

\$160:\$167 <= \$159

\$161:\$167 <= \$160

\$162:\$167 <= \$161

</

Solver Options and Model Specifications

Model Platform Engine Output

Sensitivity

Optimization

Objective

\$A\$196 (Min)

Variables

Normal

☒ \$I\$148:\$I\$167
 ☒ \$I\$31:\$I\$53

Recourse

Constraints

Normal

☒ \$D\$167 <= \$C\$194
 ☒ \$D\$3 <= \$C\$31
 ☒ \$I\$149:\$I\$167 <= \$I\$148
 ☒ \$I\$150:\$I\$167 <= \$I\$149
 ☒ \$I\$151:\$I\$167 <= \$I\$150
 ☒ \$I\$152:\$I\$167 <= \$I\$151
 ☒ \$I\$153:\$I\$167 <= \$I\$152
 ☒ \$I\$154:\$I\$167 <= \$I\$153
 ☒ \$I\$155:\$I\$167 <= \$I\$154
 ☒ \$I\$156:\$I\$167 <= \$I\$155
 ☒ \$I\$157:\$I\$167 <= \$I\$156
 ☒ \$I\$158:\$I\$167 <= \$I\$157
 ☒ \$I\$159:\$I\$167 <= \$I\$158
 ☒ \$I\$160:\$I\$167 <= \$I\$159
 ☒ \$I\$161:\$I\$167 <= \$I\$160
 ☒ \$I\$162:\$I\$167 <= \$I\$161

Model Diagnosis

Variables - Functions - Dependencies

	Vars	Fcns	Dpns
All	43	446	N/A
Smooth	N/A	N/A	N/A
Linear	N/A	N/A	N/A
Recourse	0	N/A	N/A
Uncertain	0	0	N/A

Other Model Elements

Figure A.25 : Excel sheet of the model for Activity A and B (Scenario 2 / Day 1 - 11)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 12	DAY 13	DAY 14	DAY 15	DAY 16	DAY 17	DAY 18	DAY 19	DAY 20	DAY 21	DAY 22				
1																										
3	A	1	0.00	2.00	2	1.00	2.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
4		2	1.00	3.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
5		3	2.00	4.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
6		4	3.00	5.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
7		5	4.00	6.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
8		6	5.00	7.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
9		7	6.00	8.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
10		8	7.00	9.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
11		9	8.00	10.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
12		10	9.00	11.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
13		11	10.00	12.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
14		12	11.00	13.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
15		13	12.00	14.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
16		14	13.00	15.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
17		15	14.00	16.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
18		16	15.00	17.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
19		17	16.00	18.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
20		18	17.00	19.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
21		19	18.00	20.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
22		20	19.00	21.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
23		21	20.00	22.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
24		22	21.00	23.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
25		23	22.00	24.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
26		24	23.00	25.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
27		25	24.00	26.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
28		26	25.00	27.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
31	B	1	14.50	16.00	3	2.00	1.50	48	4	8	0	0	0	0	2	4	0	0	0	0	0	0	0			
32		2	15.00	16.50	3	2.00	1.50					0	0	0	0	4	2	0	0	0	0	0				
33		3	15.50	17.00	3	2.00	1.50					0	0	0	0	2	4	0	0	0	0	0				
34		4	16.00	17.50	3	2.00	1.50					0	0	0	0	0	4	2	0	0	0	0				
35		5	16.50	18.00	3	2.00	1.50					0	0	0	0	0	2	4	0	0	0	0				
36		6	17.00	18.50	3	2.00	1.50					0	0	0	0	0	0	4	2	0	0	0				
37		7	17.50	19.00	3	2.00	1.50					0	0	0	0	0	0	2	4	0	0	0				
38		8	18.00	19.50	3	2.00	1.50					0	0	0	0	0	0	0	4	2	0	0				
39		9	18.50	20.00	3	2.00	1.50					0	0	0	0	0	0	0	2	4	0	0				
40		10	19.00	20.50	3	2.00	1.50					0	0	0	0	0	0	0	0	4	2	0				
41		11	19.50	21.00	3	2.00	1.50					0	0	0	0	0	0	0	0	2	4	0				
42		12	20.00	21.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	4	2				
43		13	20.50	22.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	2	4				
44		14	21.00	22.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	4				
45		15	21.50	23.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	2				
46		16	22.00	23.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
47		17	22.50	24.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
48		18	23.00	24.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
49		19	23.50	25.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
50		20	24.00	25.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
51		21	24.50	26.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
52		22	25.00	26.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
53		23	25.50	27.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
54		24	26.00	27.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
55		25	26.50	28.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
56		26	27.00	28.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
59		1	22.25	23.25	4	4.00	1.00	24	3	8	0	0	0	0	0	0	0	0	0	0	0	0	0			
60		2	22.50	23.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0			

Solver Options and Model Specifications

ModelPlatformEngineOutput

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$162:\$I\$167 <= \$I\$161
☒ \$I\$163:\$I\$167 <= \$I\$162
☒ \$I\$164:\$I\$167 <= \$I\$163
☒ \$I\$165:\$I\$167 <= \$I\$164
☒ \$I\$166:\$I\$167 <= \$I\$165
☒ \$I\$167 <= \$I\$166
☒ \$I\$31 <= \$I\$32
☒ \$I\$31:\$I\$32 <= \$I\$33
☒ \$I\$31:\$I\$33 <= \$I\$34
☒ \$I\$31:\$I\$34 <= \$I\$35
☒ \$I\$31:\$I\$35 <= \$I\$36
☒ \$I\$31:\$I\$36 <= \$I\$37
☒ \$I\$31:\$I\$37 <= \$I\$38
☒ \$I\$31:\$I\$38 <= \$I\$39
☒ \$I\$31:\$I\$39 <= \$I\$40
☒ \$I\$31:\$I\$40 <= \$I\$41
☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

Integers

Chance Constraints

Sparsity

129

43

0

Unknown

Figure A.26 : Excel sheet of the model for Activity A and B (Scenario 2 / Day 12 - 22)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 23	DAY 24	DAY 25	DAY 26	DAY 27	DAY 28	DAY 29	DAY 30	DAY 31	DAY 32	DAY 33				
1																										
2	A	1	0.00	2.00	2	1.00	2.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3		2	1.00	3.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4		3	2.00	4.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5		4	3.00	5.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6		5	4.00	6.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
7		6	5.00	7.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
8		7	6.00	8.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9		8	7.00	9.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
10		9	8.00	10.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
11		10	9.00	11.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
12		11	10.00	12.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13		12	11.00	13.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
14		13	12.00	14.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
15		14	13.00	15.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
16		15	14.00	16.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
17		16	15.00	17.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
18		17	16.00	18.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
19		18	17.00	19.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
20		19	18.00	20.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
21		20	19.00	21.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
22		21	20.00	22.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
23		22	21.00	23.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
24		23	22.00	24.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
25		24	23.00	25.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
26		25	24.00	26.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
27		26	25.00	27.00	2	1.00	2.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
28																										
29	B	1	14.50	16.00	3	2.00	1.50	48	4	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
30		2	15.00	16.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
31		3	15.50	17.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
32		4	16.00	17.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
33		5	16.50	18.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
34		6	17.00	18.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
35		7	17.50	19.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
36		8	18.00	19.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
37		9	18.50	20.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
38		10	19.00	20.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
39		11	19.50	21.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
40		12	20.00	21.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
41		13	20.50	22.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
42		14	21.00	22.50	3	2.00	1.50					2	0	0	0	0	0	0	0	0	0	0	0	0	0	
43		15	21.50	23.00	3	2.00	1.50					4	0	0	0	0	0	0	0	0	0	0	0	0	0	
44		16	22.00	23.50	3	2.00	1.50					4	2	0	0	0	0	0	0	0	0	0	0	0	0	
45		17	22.50	24.00	3	2.00	1.50					2	4	0	0	0	0	0	0	0	0	0	0	0	0	
46		18	23.00	24.50	3	2.00	1.50					0	4	2	0	0	0	0	0	0	0	0	0	0	0	
47		19	23.50	25.00	3	2.00	1.50					0	2	4	0	0	0	0	0	0	0	0	0	0	0	
48		20	24.00	25.50	3	2.00	1.50					0	0	4	2	0	0	0	0	0	0	0	0	0	0	
49		21	24.50	26.00	3	2.00	1.50					0	0	2	4	0	0	0	0	0	0	0	0	0	0	
50		22	25.00	26.50	3	2.00	1.50					0	0	0	4	2	0	0	0	0	0	0	0	0	0	
51		23	25.50	27.00	3	2.00	1.50					0	0	0	2	4	0	0	0	0	0	0	0	0	0	
52		24	26.00	27.50	3	2.00	1.50					0	0	0	0	2	4	0	0	0	0	0	0	0	0	
53		25	26.50	28.00	3	2.00	1.50					0	0	0	0	0	2	4	0	0	0	0	0	0	0	
54		26	27.00	28.50	3	2.00	1.50					0	0	0	0	0	0	4	2	0	0	0	0	0	0	
55		1	22.25	23.25	4	4.00	1.00	24	3	8	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	
56		2	22.50	23.50	4	4.00	1.00					2	2	0	0	0	0	0	0	0	0	0	0	0	0	

Solver Options and Model Specifications

ModelPlatformEngineOutput

Chance

Bound

Conic

Integers

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

Integers

Chance Constraints

Sparsity

129

43

0

Unknown

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

129

Integers

43

Chance Constraints

0

Sparsity

Unknown

Figure A.27 : Excel sheet of the model for Activity A and B (Scenario 2 / Day 23 - 33)

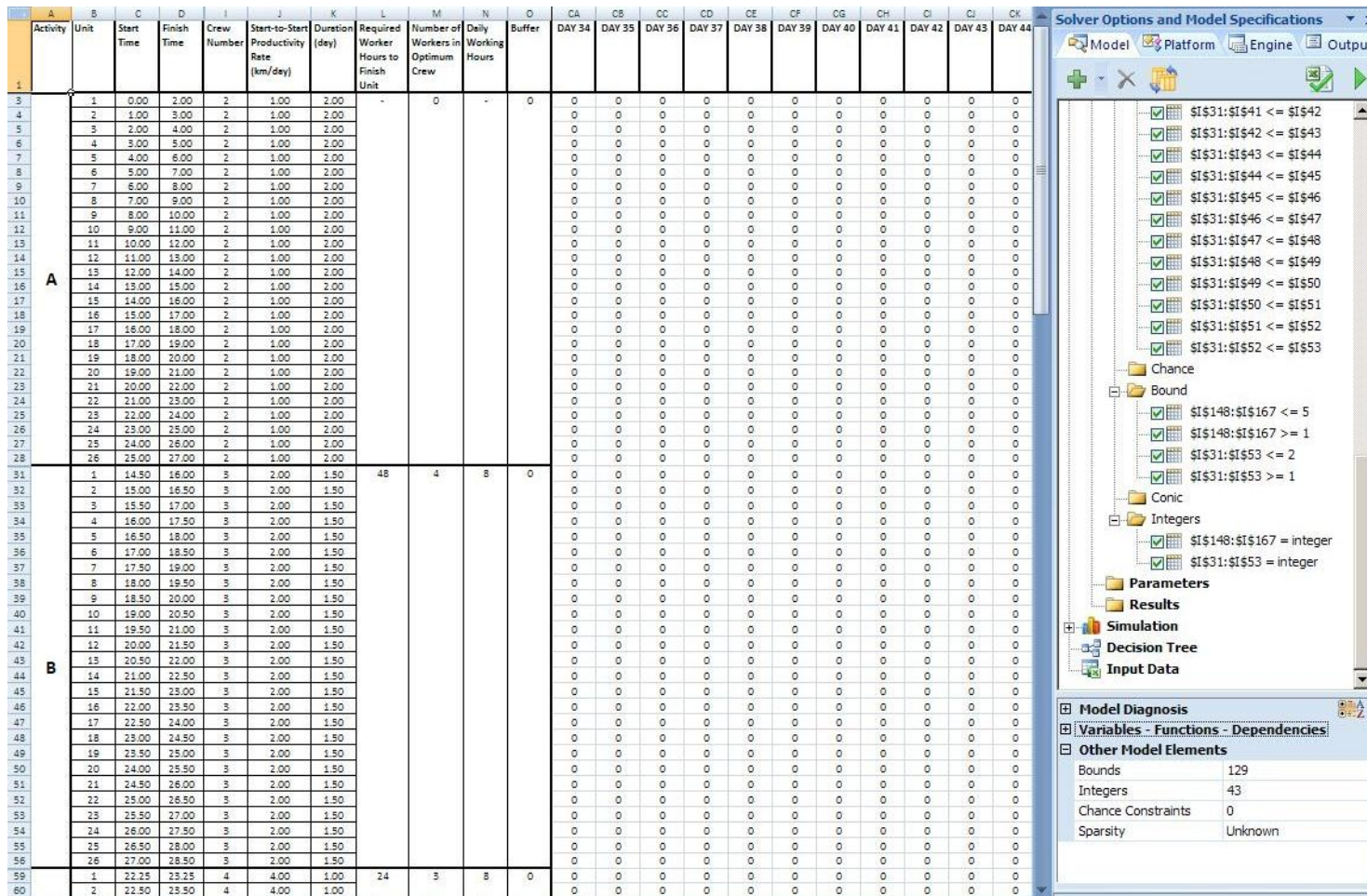


Figure A.28 : Excel sheet of the model for Activity A and B (Scenario 2 / Day 34 - 44)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 45	DAY 46	DAY 47	DAY 48	DAY 49	DAY 50	DAY 51	DAY 52	DAY 53	DAY 54	DAY 55				
3	A	1	0.00	2.00	2	1.00	2.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
4		2	1.00	3.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
5		3	2.00	4.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
6		4	3.00	5.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
7		5	4.00	6.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
8		6	5.00	7.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
9		7	6.00	8.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
10		8	7.00	9.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
11		9	8.00	10.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
12		10	9.00	11.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
13		11	10.00	12.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
14		12	11.00	13.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
15		13	12.00	14.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
16		14	13.00	15.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
17		15	14.00	16.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
18		16	15.00	17.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
19		17	16.00	18.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
20		18	17.00	19.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
21		19	18.00	20.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
22		20	19.00	21.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
23		21	20.00	22.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
24		22	21.00	23.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
25		23	22.00	24.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
26		24	23.00	25.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
27		25	24.00	26.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
28		26	25.00	27.00	2	1.00	2.00					0	0	0	0	0	0	0	0	0	0	0	0			
31	B	1	14.50	16.00	3	2.00	1.50	48	4	8	0	0	0	0	0	0	0	0	0	0	0	0	0			
32		2	15.00	16.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
33		3	15.50	17.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
34		4	16.00	17.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
35		5	16.50	18.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
36		6	17.00	18.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
37		7	17.50	19.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
38		8	18.00	19.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
39		9	18.50	20.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
40		10	19.00	20.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
41		11	19.50	21.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
42		12	20.00	21.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
43		13	20.50	22.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
44		14	21.00	22.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
45		15	21.50	23.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
46		16	22.00	23.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
47		17	22.50	24.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
48		18	23.00	24.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
49		19	23.50	25.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
50		20	24.00	25.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
51		21	24.50	26.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
52		22	25.00	26.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
53		23	25.50	27.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
54		24	26.00	27.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
55		25	26.50	28.00	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
56		26	27.00	28.50	3	2.00	1.50					0	0	0	0	0	0	0	0	0	0	0				
59	1	22.25	23.25	4	4.00	1.00	24	3	8	0	0	0	0	0	0	0	0	0	0	0	0	0				
60	2	22.50	23.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0				

Solver Options and Model Specifications

ModelPlatformEngineOutput

Chance

Bound

Conic

Integers

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds

Integers

Chance Constraints

Sparsity

129

43

0

Unknown

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds	129
Integers	43
Chance Constraints	0
Sparsity	Unknown

Figure A.29 : Excel sheet of the model for Activity A and B (Scenario 2 / Day 45 - 55)

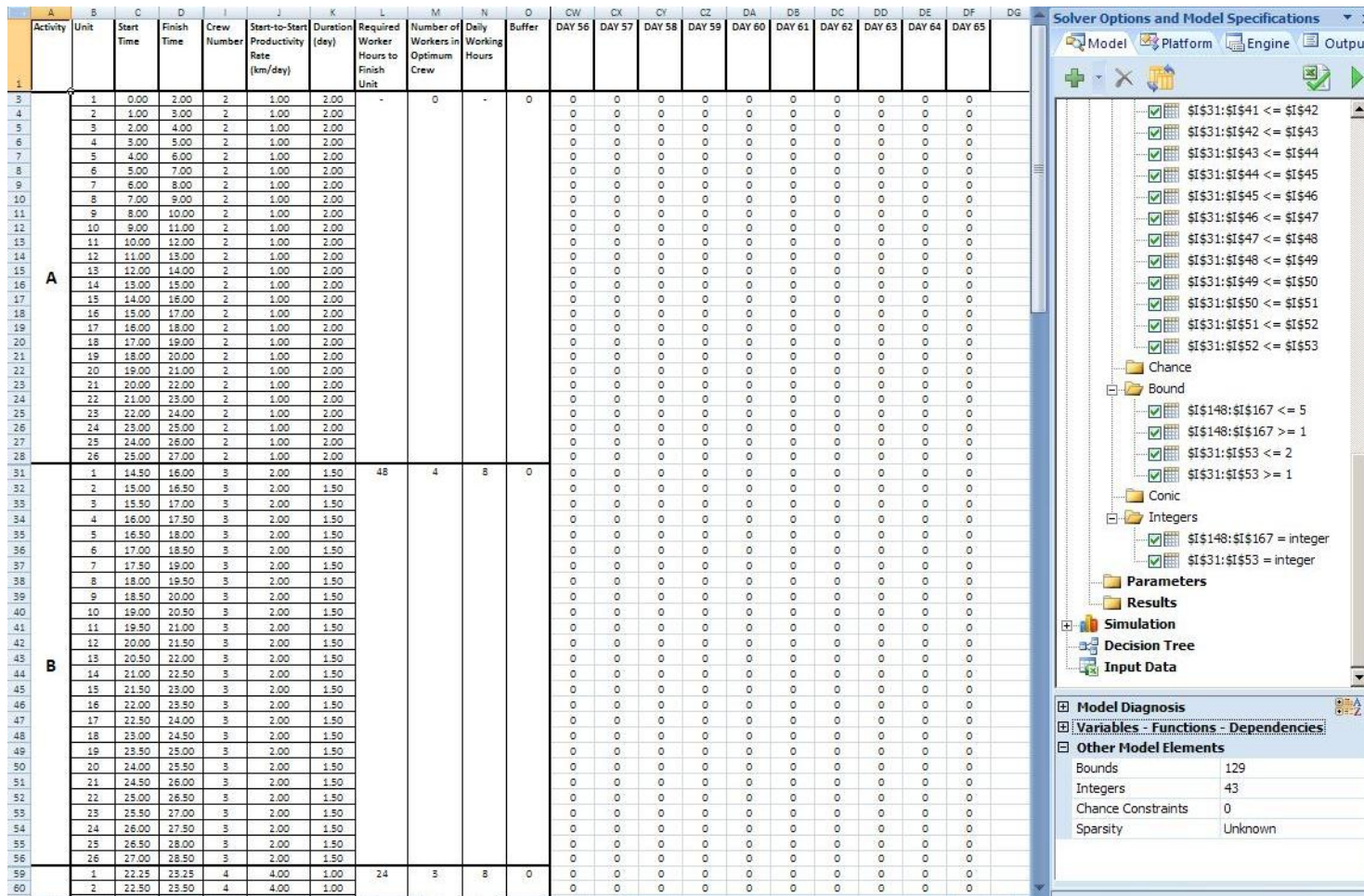


Figure A.30 : Excel sheet of the model for Activity A and B (Scenario 2 / Day 56 - 65)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7	DAY 8	DAY 9	DAY 10	DAY 11				
59	C	1	22.25	23.25	4	4.00	1.00	24	3	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
60		2	22.50	23.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
61		3	22.75	23.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
62		4	23.00	24.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
63		5	23.25	24.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
64		6	23.50	24.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
65		7	23.75	24.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
66		8	24.00	25.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
67		9	24.25	25.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
68		10	24.50	25.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
69		11	24.75	25.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
70		12	25.00	26.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
71		13	25.25	26.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
72		14	25.50	26.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
73		15	25.75	26.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
74		16	26.00	27.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
75		17	26.25	27.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
76		18	26.50	27.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
77		19	26.75	27.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
78		20	27.00	28.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
79		21	27.25	28.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
80		22	27.50	28.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
81		23	27.75	28.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
82		24	28.00	29.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
83		25	28.25	29.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
84		26	28.50	29.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
88	D	1	23.25	24.25	2	2.00	1.00	40	5	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
89		2	23.75	24.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
90		3	24.25	25.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
91		4	24.75	25.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
92		5	25.25	26.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
93		6	25.75	26.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
94		7	26.25	27.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
95		8	26.75	27.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
96		9	27.25	28.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
97		10	27.75	28.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
98		11	28.25	29.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
99		12	28.75	29.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
100		13	29.25	30.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
101		14	29.75	30.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
102		15	30.25	31.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
103		16	30.75	31.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
104		17	31.25	32.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
105		18	31.75	32.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
106		19	32.25	33.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
107		20	32.75	33.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
108		21	33.25	34.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
109		22	33.75	34.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
110		23	34.25	35.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
111		24	34.75	35.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
112		25	35.25	36.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
113		26	35.75	36.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
115		1	30.50	31.50	4	4.00	1.00		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		
116		2	30.75	31.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
117		3	31.00	32.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
118		4	31.25	32.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		

Solver Options and Model Specifications

ModelPlatformEngineOutput

Sensitivity

Optimization

Objective

Variables

Normal

Recourse

Constraints

Normal

\$AS\$196 (Min)

\$I\$148:\$I\$167

\$I\$31:\$I\$53

Recourse

Normal

\$D\$167 <= \$C\$194

\$D\$3 <= \$C\$31

\$I\$149:\$I\$167 <= \$I\$148

\$I\$150:\$I\$167 <= \$I\$149

\$I\$151:\$I\$167 <= \$I\$150

\$I\$152:\$I\$167 <= \$I\$151

\$I\$153:\$I\$167 <= \$I\$152

\$I\$154:\$I\$167 <= \$I\$153

\$I\$155:\$I\$167 <= \$I\$154

\$I\$156:\$I\$167 <= \$I\$155

\$I\$157:\$I\$167 <= \$I\$156

\$I\$158:\$I\$167 <= \$I\$157

\$I\$159:\$I\$167 <= \$I\$158

\$I\$160:\$I\$167 <= \$I\$159

\$I\$161:\$I\$167 <= \$I\$160

\$I\$162:\$I\$167 <= \$I\$161

Model Diagnosis

Variables - Functions - Dependencies

Vars

Fcns

Dpns

All

43

446

N/A

Smooth

N/A

N/A

N/A

Linear

N/A

N/A

N/A

Recourse

0

N/A

N/A

Uncertain

0

0

N/A

Other Model Elements

Solver Options and Model Specifications

Model Platform Engine Output

Sensitivity

Optimization

Objective

\$A\$196 (Min)

Variables

Normal

☒ \$I\$148:\$I\$167
 ☒ \$I\$31:\$I\$53

Recourse

Constraints

Normal

☒ \$D\$167 <= \$C\$194
 ☒ \$D\$3 <= \$C\$31
 ☒ \$I\$149:\$I\$167 <= \$I\$148
 ☒ \$I\$150:\$I\$167 <= \$I\$149
 ☒ \$I\$151:\$I\$167 <= \$I\$150
 ☒ \$I\$152:\$I\$167 <= \$I\$151
 ☒ \$I\$153:\$I\$167 <= \$I\$152
 ☒ \$I\$154:\$I\$167 <= \$I\$153
 ☒ \$I\$155:\$I\$167 <= \$I\$154
 ☒ \$I\$156:\$I\$167 <= \$I\$155
 ☒ \$I\$157:\$I\$167 <= \$I\$156
 ☒ \$I\$158:\$I\$167 <= \$I\$157
 ☒ \$I\$159:\$I\$167 <= \$I\$158
 ☒ \$I\$160:\$I\$167 <= \$I\$159
 ☒ \$I\$161:\$I\$167 <= \$I\$160
 ☒ \$I\$162:\$I\$167 <= \$I\$161

Model Diagnosis

Variables - Functions - Dependencies

	Vars	Fcns	Dpns
All	43	446	N/A
Smooth	N/A	N/A	N/A
Linear	N/A	N/A	N/A
Recourse	0	N/A	N/A
Uncertain	0	0	N/A

Other Model Elements

Figure A.31 : Excel sheet of the model for Activity C and D (Scenario 2 / Day 1 - 11)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DM	DN	DO	DP	DQ	DR	DS	DT	DU	DV	DW	DX	DY	DZ	EA	EB	EC	ED	EE	EF	EG	EH	EI	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES	ET	EU	EV	EW	EX	EY	EZ	FA	FB	FC	FD	FE	FF	FG	FH	FI	FJ	FK	FL	FM	FN	FO	FP	FQ	FR	FS	FT	FU	FV	FW	FX	FY	FZ	GA	GB	GC	GD	GE	GF	GG	GH	GI	GJ	GK	GL	GM	GN	GO	GP	GQ	GR	GS	GT	GU	GV	GW	GX	GY	GZ	HA	HB	HC	HD	HE	HF	HG	HH	HI	HJ	HK	HL	HM	HN	HO	HP	HQ	HR	HS	HT	HU	HV	HW	HX	HY	HZ	IA	IB	IC	ID	IE	IF	IG	IH	II	IJ	IK	IL	IM	IN	IO	IP	IQ	IR	IS	IT	IU	IV	IW	IX	IY	IZ	JA	JB	JC	JD	JE	JF	JG	JH	JI	IJ	JK	KL	KM	KN	KO	KP	KQ	KR	KS	KT	KU	KV	KW	KX	KY	KZ	LA	LB	LC	LD	LE	LF	LG	LH	LI	LJ	LK	LM	LN	LO	LP	LQ	LR	LS	LT	LU	LV	LW	LX	LY	LZ	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	ML	MM	MN	MO	MP	MQ	MR	MS	MT	MU	MV	MW	MX	MY	MZ	NA	NB	NC	ND	NE	NF	NG	NH	NI	NJ	NK	NL	NM	NN	NO	NP	NQ	NR	NS	NT	NU	NV	NW	NX	NY	NZ	OA	OB	OC	OD	OE	OF	OG	OH	OI	OJ	OK	OL	OM	ON	OO	OP	OQ	OR	OS	OT	OU	OV	OW	OX	OY	OZ	PA	PB	PC	PD	PE	PF	PG	PH	PI	PJ	PK	PL	PM	PN	PO	PP	PQ	PR	PS	PT	PU	PV	PW	PX	PY	PZ	QA	QB	QC	QD	QE	QF	QG	QH	QI	QJ	QK	QL	QM	QN	QO	QP	QQ	QR	QS	QT	QU	QV	QW	QX	QY	QZ	RA	RB	RC	RD	RE	RF	RG	RH	RI	RJ	RK	RL	RM	RN	RO	RP	RQ	RR	RS	RT	RU	RV	RW	RX	RY	RZ	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ	SK	SL	SM	SN	SO	SP	SQ	SR	SS	ST	SU	SV	SW	SX	SY	SZ	TA	TB	TC	TD	TE	TF	TG	TH	TI	TJ	TK	TL	TM	TN	TO	TP	TQ	TR	TS	TT	TU	TV	TW	TX	TY	TZ	UA	UB	UC	UD	UE	UF	UG	UH	UI	UJ	UK	UL	UM	UN	UO	UP	UQ	UR	US	UT	UU	UV	UW	UX	UY	UZ	VA	VB	VC	VD	VE	VF	VG	VH	VI	VJ	VK	VL	VM	VN	VO	VP	VQ	VR	VS	VT	VU	VV	VW	VX	VY	VZ	WA	WB	WC	WD	WE	WF	WG	WH	WI	WJ	WK	WL	WM	WN	WO	WP	WQ	WR	WS	WT	WU	WV	WW	WX	WY	WZ	XA	XB	XC	XD	XE	XF	XG	XH	XI	XJ	XK	XL	XM	XN	XO	XP	XQ	XR	XS	XT	XU	XV	XW	XX	XY	XZ	YA	YB	YC	YD	YE	YF	YG	YH	YI	YJ	YK	YL	YM	YN	YO	YP	YQ	YR	YS	YT	YU	YV	YW	YX	YY	YZ	ZA	ZB	ZC	ZD	ZE	ZF	ZG	ZH	ZI	ZJ	ZK	ZL	ZM	ZN	ZO	ZP	ZQ	ZR	ZS	ZT	ZU	ZV	ZW	ZX	ZY	ZZ
Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 12	DAY 13	DAY 14	DAY 15	DAY 16	DAY 17	DAY 18	DAY 19	DAY 20	DAY 21	DAY 22																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
1																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
59	C	1	22.25	23.25	4	4.00	1.00	24	3	8	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
60		2	22.50	23.50	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
61		3	22.75	23.75	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
62		4	23.00	24.00	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
63		5	23.25	24.25	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
64		6	23.50	24.50	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
65		7	23.75	24.75	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
66		8	24.00	25.00	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
67		9	24.25	25.25	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
68		10	24.50	25.50	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
69		11	24.75	25.75	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
70		12	25.00	26.00	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
71		13	25.25	26.25	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
72		14	25.50	26.50	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
73		15	25.75	26.75	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
74		16	26.00	27.00	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
75		17	26.25	27.25	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
76		18	26.50	27.50	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
77		19	26.75	27.75	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
78		20	27.00	28.00	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
79		21	27.25	28.25	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
80		22	27.50	28.50	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
81		23	27.75	28.75	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
82		24	28.00	29.00	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
83		25	28.25	29.25	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
84		26	28.50	29.50	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
88	D	1	23.25	24.25	2	2.00	1.00	40	5	8	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
89		2	23.75	24.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
90		3	24.25	25.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
91		4	24.75	25.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
92		5	25.25	26.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
93		6	25.75	26.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
94		7	26.25	27.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
95		8	26.75	27.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
96		9	27.25	28.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
97		10	27.75	28.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
98		11	28.25	29.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
99		12	28.75	29.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
100		13	29.25	30.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
101		14	29.75	30.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
102		15	30.25	31.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
103		16	30.75	31.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
104		17	31.25	32.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
105		18	31.75	32.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
106		19	32.25	33.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
107		20	32.75	33.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
108		21	33.25	34.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
109		22	33.75	34.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
110		23	34.25	35.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
111		24	34.75	35.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
112		25	35.25	36.25	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
113		26	35.75	36.75	2	2.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
115	1	30.50	31.50	4	4.00	1.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
116	2	30.75	31.75	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
117	3	31.00	32.00	4	4.00	1.00	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	

Figure A.32 : Excel sheet of the model for Activity C and D (Scenario 2 / Day 12 - 22)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 23	DAY 24	DAY 25	DAY 26	DAY 27	DAY 28	DAY 29	DAY 30	DAY 31	DAY 32	DAY 33				
59	C	1	22.25	23.25	4	4.00	1.00	24	3	8	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	
60		2	22.50	23.50	4	4.00	1.00					2	2	0	0	0	0	0	0	0	0	0	0	0	0	
61		3	22.75	23.75	4	4.00	1.00					1	2	0	0	0	0	0	0	0	0	0	0	0	0	
62		4	23.00	24.00	4	4.00	1.00					0	3	0	0	0	0	0	0	0	0	0	0	0	0	
63		5	23.25	24.25	4	4.00	1.00					0	2	1	0	0	0	0	0	0	0	0	0	0	0	
64		6	23.50	24.50	4	4.00	1.00					0	2	2	0	0	0	0	0	0	0	0	0	0	0	
65		7	23.75	24.75	4	4.00	1.00					0	1	2	0	0	0	0	0	0	0	0	0	0	0	
66		8	24.00	25.00	4	4.00	1.00					0	0	3	0	0	0	0	0	0	0	0	0	0	0	
67		9	24.25	25.25	4	4.00	1.00					0	0	2	1	0	0	0	0	0	0	0	0	0	0	
68		10	24.50	25.50	4	4.00	1.00					0	0	2	2	0	0	0	0	0	0	0	0	0	0	
69		11	24.75	25.75	4	4.00	1.00					0	0	1	2	0	0	0	0	0	0	0	0	0	0	
70		12	25.00	26.00	4	4.00	1.00					0	0	0	3	0	0	0	0	0	0	0	0	0	0	
71		13	25.25	26.25	4	4.00	1.00					0	0	0	2	1	0	0	0	0	0	0	0	0	0	
72		14	25.50	26.50	4	4.00	1.00					0	0	0	2	2	0	0	0	0	0	0	0	0	0	
73		15	25.75	26.75	4	4.00	1.00					0	0	0	1	2	0	0	0	0	0	0	0	0	0	
74		16	26.00	27.00	4	4.00	1.00					0	0	0	0	3	0	0	0	0	0	0	0	0	0	
75		17	26.25	27.25	4	4.00	1.00					0	0	0	0	2	1	0	0	0	0	0	0	0	0	
76		18	26.50	27.50	4	4.00	1.00					0	0	0	0	2	2	0	0	0	0	0	0	0	0	
77		19	26.75	27.75	4	4.00	1.00					0	0	0	0	1	2	0	0	0	0	0	0	0	0	
78		20	27.00	28.00	4	4.00	1.00					0	0	0	0	0	3	0	0	0	0	0	0	0	0	
79		21	27.25	28.25	4	4.00	1.00					0	0	0	0	0	2	1	0	0	0	0	0	0	0	
80		22	27.50	28.50	4	4.00	1.00					0	0	0	0	0	2	2	0	0	0	0	0	0	0	
81		23	27.75	28.75	4	4.00	1.00					0	0	0	0	0	1	2	0	0	0	0	0	0	0	
82		24	28.00	29.00	4	4.00	1.00					0	0	0	0	0	0	3	0	0	0	0	0	0	0	
83		25	28.25	29.25	4	4.00	1.00					0	0	0	0	0	0	2	1	0	0	0	0	0	0	
84		26	28.50	29.50	4	4.00	1.00					0	0	0	0	0	0	2	2	0	0	0	0	0	0	
88	D	1	23.25	24.25	2	2.00	1.00	40	5	8	0	0	4	1	0	0	0	0	0	0	0	0	0	0	0	
89		2	23.75	24.75	2	2.00	1.00					0	1	4	0	0	0	0	0	0	0	0	0	0	0	
90		3	24.25	25.25	2	2.00	1.00					0	0	4	1	0	0	0	0	0	0	0	0	0	0	
91		4	24.75	25.75	2	2.00	1.00					0	0	1	4	0	0	0	0	0	0	0	0	0	0	
92		5	25.25	26.25	2	2.00	1.00					0	0	0	4	1	0	0	0	0	0	0	0	0	0	
93		6	25.75	26.75	2	2.00	1.00					0	0	0	1	4	0	0	0	0	0	0	0	0	0	
94		7	26.25	27.25	2	2.00	1.00					0	0	0	0	4	1	0	0	0	0	0	0	0	0	
95		8	26.75	27.75	2	2.00	1.00					0	0	0	0	1	4	0	0	0	0	0	0	0	0	
96		9	27.25	28.25	2	2.00	1.00					0	0	0	0	0	4	1	0	0	0	0	0	0	0	
97		10	27.75	28.75	2	2.00	1.00					0	0	0	0	0	1	4	0	0	0	0	0	0	0	
98		11	28.25	29.25	2	2.00	1.00					0	0	0	0	0	0	4	1	0	0	0	0	0	0	
99		12	28.75	29.75	2	2.00	1.00					0	0	0	0	0	0	1	4	0	0	0	0	0	0	
100		13	29.25	30.25	2	2.00	1.00					0	0	0	0	0	0	0	4	1	0	0	0	0	0	
101		14	29.75	30.75	2	2.00	1.00					0	0	0	0	0	0	0	1	4	0	0	0	0	0	
102		15	30.25	31.25	2	2.00	1.00					0	0	0	0	0	0	0	0	4	1	0	0	0	0	
103		16	30.75	31.75	2	2.00	1.00					0	0	0	0	0	0	0	0	1	4	0	0	0	0	
104		17	31.25	32.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	4	1	0	0	0	
105		18	31.75	32.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	4	1	0	0	
106		19	32.25	33.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	4	1	0	
107		20	32.75	33.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	4	1	
108		21	33.25	34.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	4	
109		22	33.75	34.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
110		23	34.25	35.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
111		24	34.75	35.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
112		25	35.25	36.25	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
113		26	35.75	36.75	2	2.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
115		1	30.50	31.50	4	4.00	1.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
116		2	30.75	31.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
117		3	31.00	32.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	
118		4	31.25	32.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Solver Options and Model Specifications

ModelPlatformEngineOutput

\$I\$31:\$I\$41 <= \$I\$42

\$I\$31:\$I\$42 <= \$I\$43

\$I\$31:\$I\$43 <= \$I\$44

\$I\$31:\$I\$44 <= \$I\$45

\$I\$31:\$I\$45 <= \$I\$46

\$I\$31:\$I\$46 <= \$I\$47

\$I\$31:\$I\$47 <= \$I\$48

\$I\$31:\$I\$48 <= \$I\$49

\$I\$31:\$I\$49 <= \$I\$50

\$I\$31:\$I\$50 <= \$I\$51

\$I\$31:\$I\$51 <= \$I\$52

\$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

\$I\$148:\$I\$167 <= 5

\$I\$148:\$I\$167 >= 1

\$I\$31:\$I\$53 <= 2

\$I\$31:\$I\$53 >= 1

Conic

Integers

\$I\$148:\$I\$167 = integer

\$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds129

Integers43

Chance Constraints0

SparsityUnknown

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds	129
Integers	43
Chance Constraints	0
Sparsity	Unknown

Figure A.33 : Excel sheet of the model for Activity C and D (Scenario 2 / Day 23 - 33)

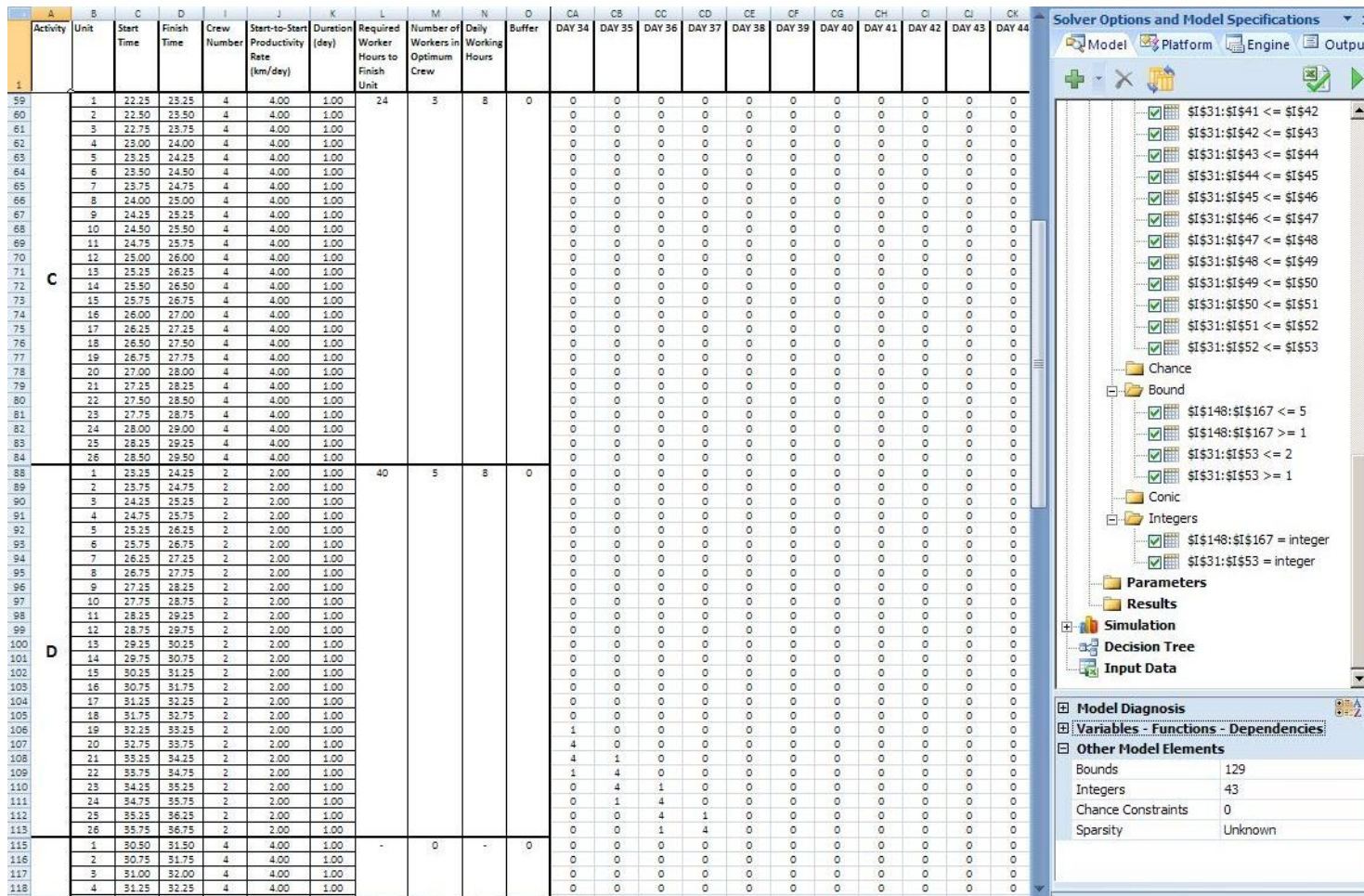


Figure A.34 : Excel sheet of the model for Activity C and D (Scenario 2 / Day 34 - 44)

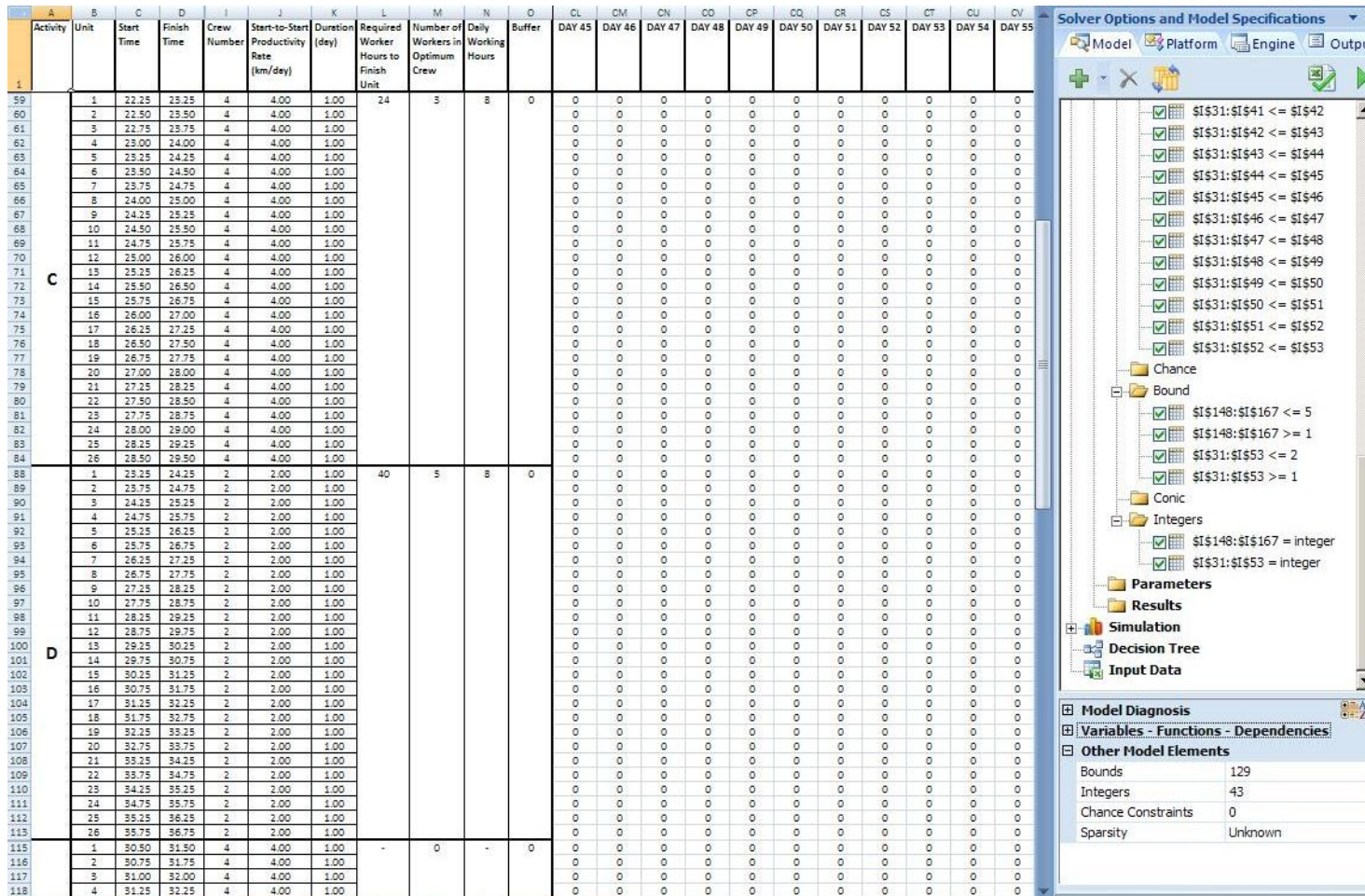


Figure A.35 : Excel sheet of the model for Activity C and D (Scenario 2 / Day 45 - 55)

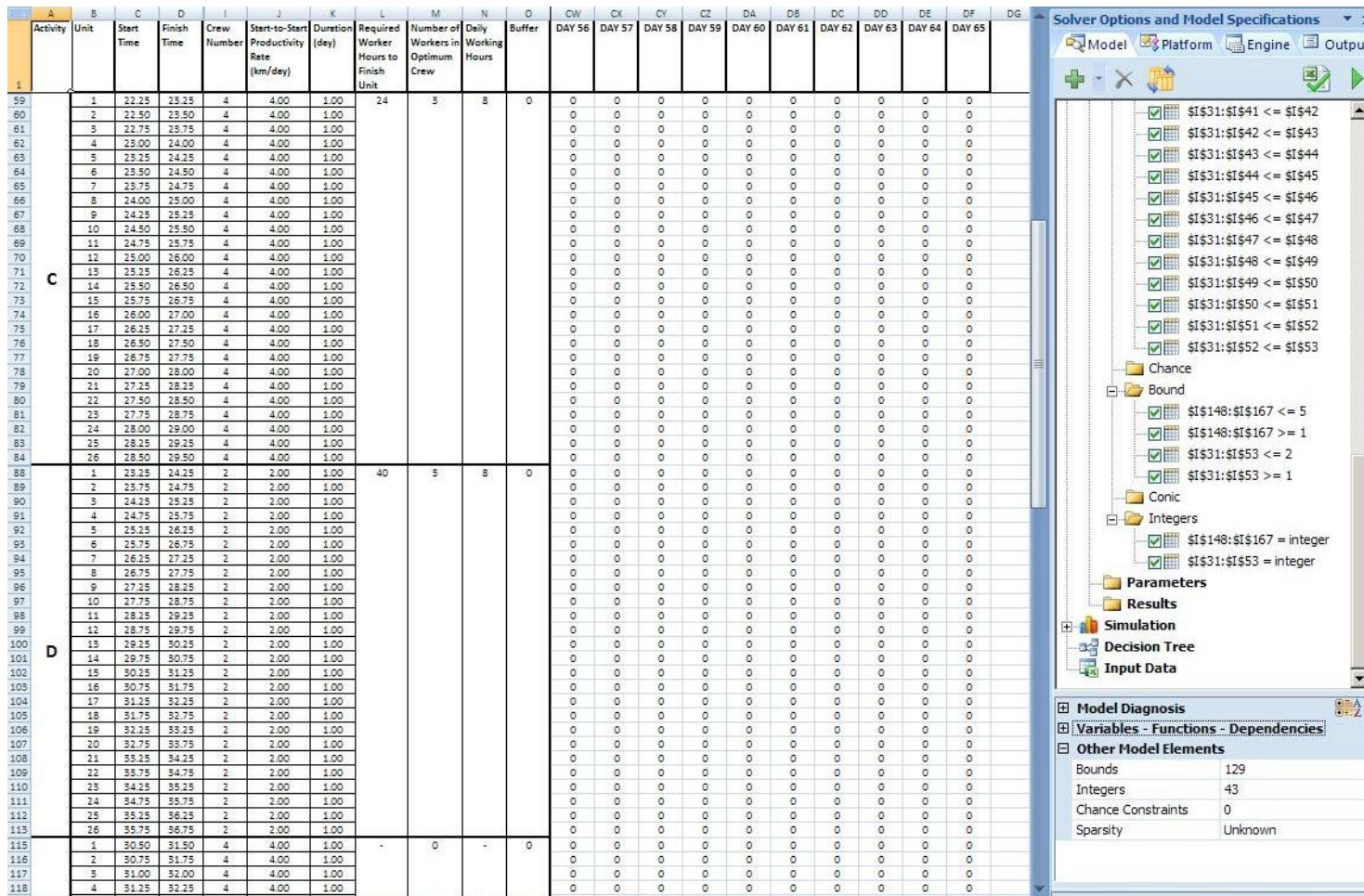


Figure A.36 : Excel sheet of the model for Activity C and D (Scenario 2 / Day 56 - 65)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7	DAY 8	DAY 9	DAY 10	DAY 11				
115	E	1	30.50	31.50	4	4.00	1.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
116		2	30.75	31.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
117		3	31.00	32.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
118		4	31.25	32.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
119		5	31.50	32.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
120		6	31.75	32.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
121		7	32.00	33.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
122		8	32.25	33.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
123		9	32.50	33.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
124		10	32.75	33.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
125		11	33.00	34.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
126		12	33.25	34.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
127		13	33.50	34.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
128		14	33.75	34.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
129		15	34.00	35.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
130		16	34.25	35.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
131		17	34.50	35.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
132		18	34.75	35.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
133		19	35.00	36.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
134		20	35.25	36.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
135		21	35.50	36.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
136		22	35.75	36.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
137		23	36.00	37.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
138		24	36.25	37.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
139		25	36.50	37.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
140		26	36.75	37.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
142	F	1	31.50	32.50	3	3.00	1.00	24	3	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
143		2	31.83	32.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
144		3	32.17	33.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
145		4	32.50	33.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
146		5	32.83	33.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
147		6	33.17	34.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
148		7	33.50	34.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
149		8	33.83	34.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
150		9	34.17	35.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
151		10	34.50	35.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
152		11	34.83	35.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
153		12	35.17	36.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
154		13	35.50	36.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
155		14	35.83	36.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
156		15	36.17	37.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
157		16	36.50	37.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
158		17	36.83	37.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
159		18	37.17	38.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
160		19	37.50	38.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
161		20	37.83	38.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
162		21	38.17	39.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
163		22	38.50	39.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
164		23	38.83	39.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
165		24	39.17	40.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
166		25	39.50	40.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
167		26	39.83	40.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0	0	0		
169		1	32.50	34.00	2	1.33	1.50	36	3	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
170		2	33.25	34.75	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
171		3	34.00	35.50	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		
172		4	34.75	36.25	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0	0	0		

Solver Options and Model Specifications

ModelPlatformEngineOutput

Sensitivity

Optimization

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Variables

Constraints

Objective

Solver Options and Model Specifications

Model Platform Engine Output

Sensitivity

Optimization

Objective

\$A\$196 (Min)

Variables

Normal

☒ \$I\$148:\$I\$167
 ☒ \$I\$31:\$I\$53

Recourse

Constraints

Normal

☒ \$D\$167 <= \$C\$194
 ☒ \$D\$3 <= \$C\$31
 ☒ \$I\$149:\$I\$167 <= \$I\$148
 ☒ \$I\$150:\$I\$167 <= \$I\$149
 ☒ \$I\$151:\$I\$167 <= \$I\$150
 ☒ \$I\$152:\$I\$167 <= \$I\$151
 ☒ \$I\$153:\$I\$167 <= \$I\$152
 ☒ \$I\$154:\$I\$167 <= \$I\$153
 ☒ \$I\$155:\$I\$167 <= \$I\$154
 ☒ \$I\$156:\$I\$167 <= \$I\$155
 ☒ \$I\$157:\$I\$167 <= \$I\$156
 ☒ \$I\$158:\$I\$167 <= \$I\$157
 ☒ \$I\$159:\$I\$167 <= \$I\$158
 ☒ \$I\$160:\$I\$167 <= \$I\$159
 ☒ \$I\$161:\$I\$167 <= \$I\$160
 ☒ \$I\$162:\$I\$167 <= \$I\$161

Model Diagnosis

Variables - Functions - Dependencies

	Vars	Fcns	Dpns
All	43	446	N/A
Smooth	N/A	N/A	N/A
Linear	N/A	N/A	N/A
Recourse	0	N/A	N/A
Uncertain	0	0	N/A

Other Model Elements

Figure A.37 : Excel sheet of the model for Activity E and F (Scenario 2 / Day 1 - 11)

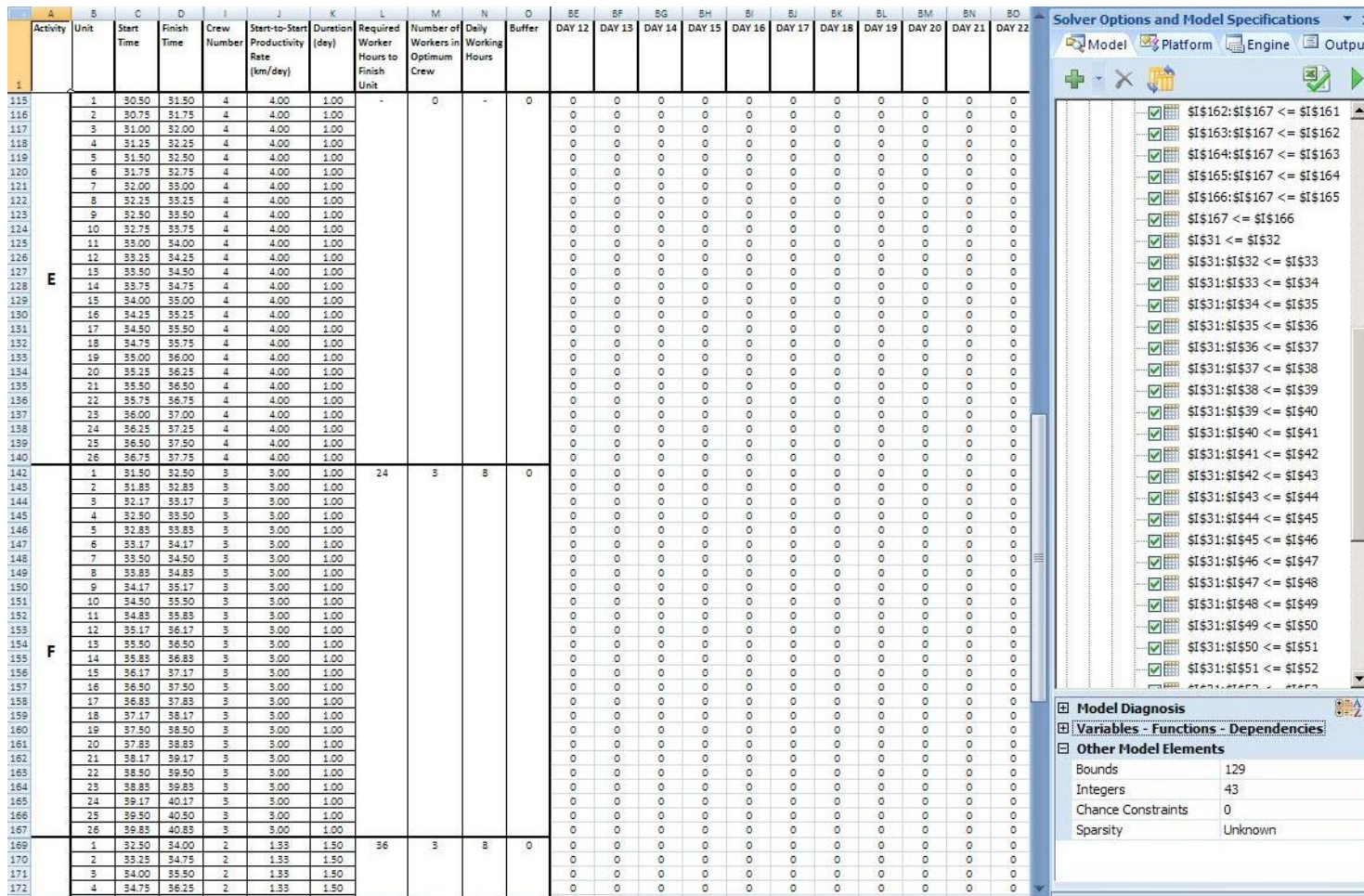


Figure A.38 : Excel sheet of the model for Activity E and F (Scenario 2 / Day 12 - 22)

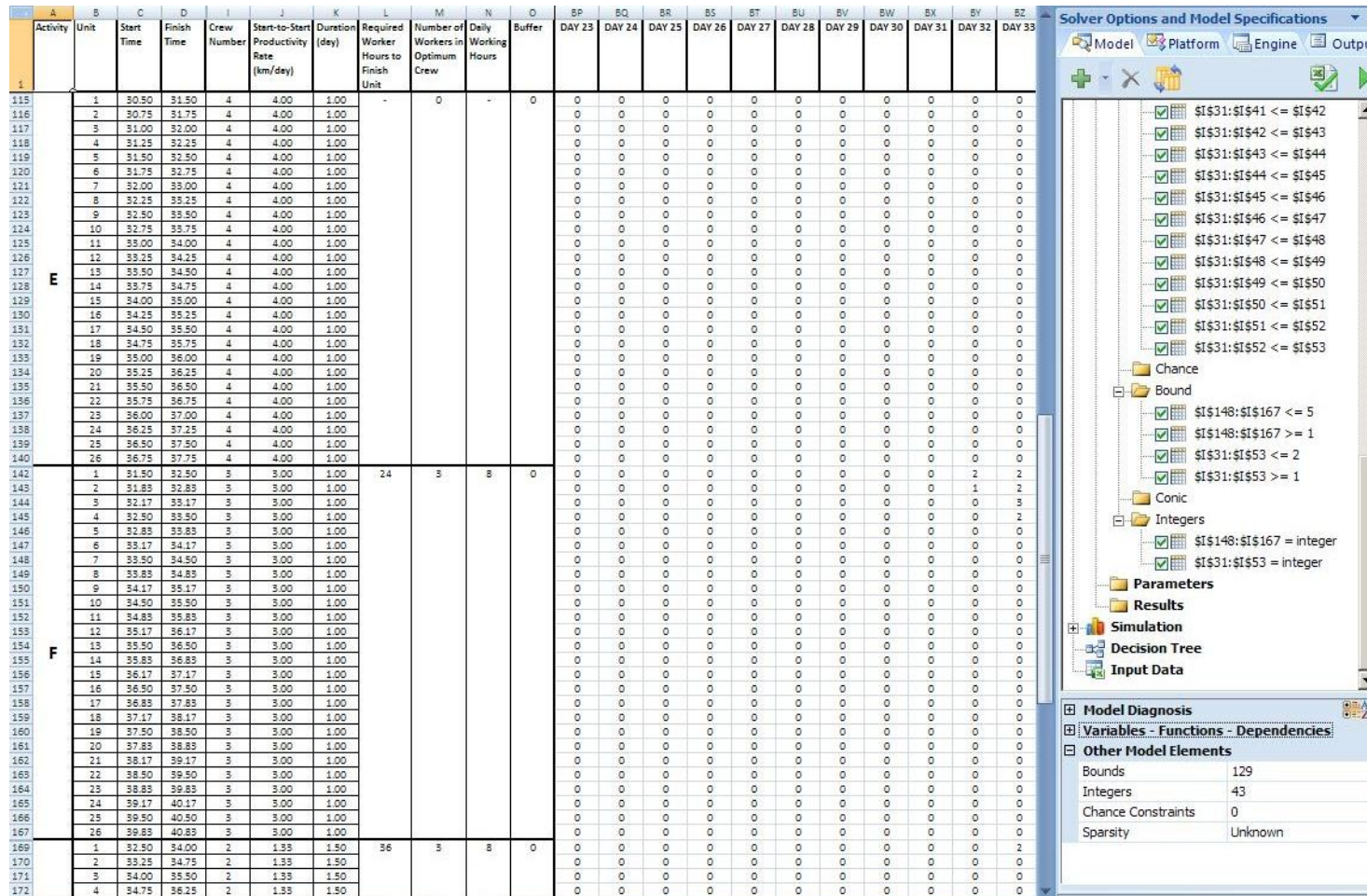


Figure A.39 : Excel sheet of the model for Activity E and F (Scenario 2 / Day 23 - 33)

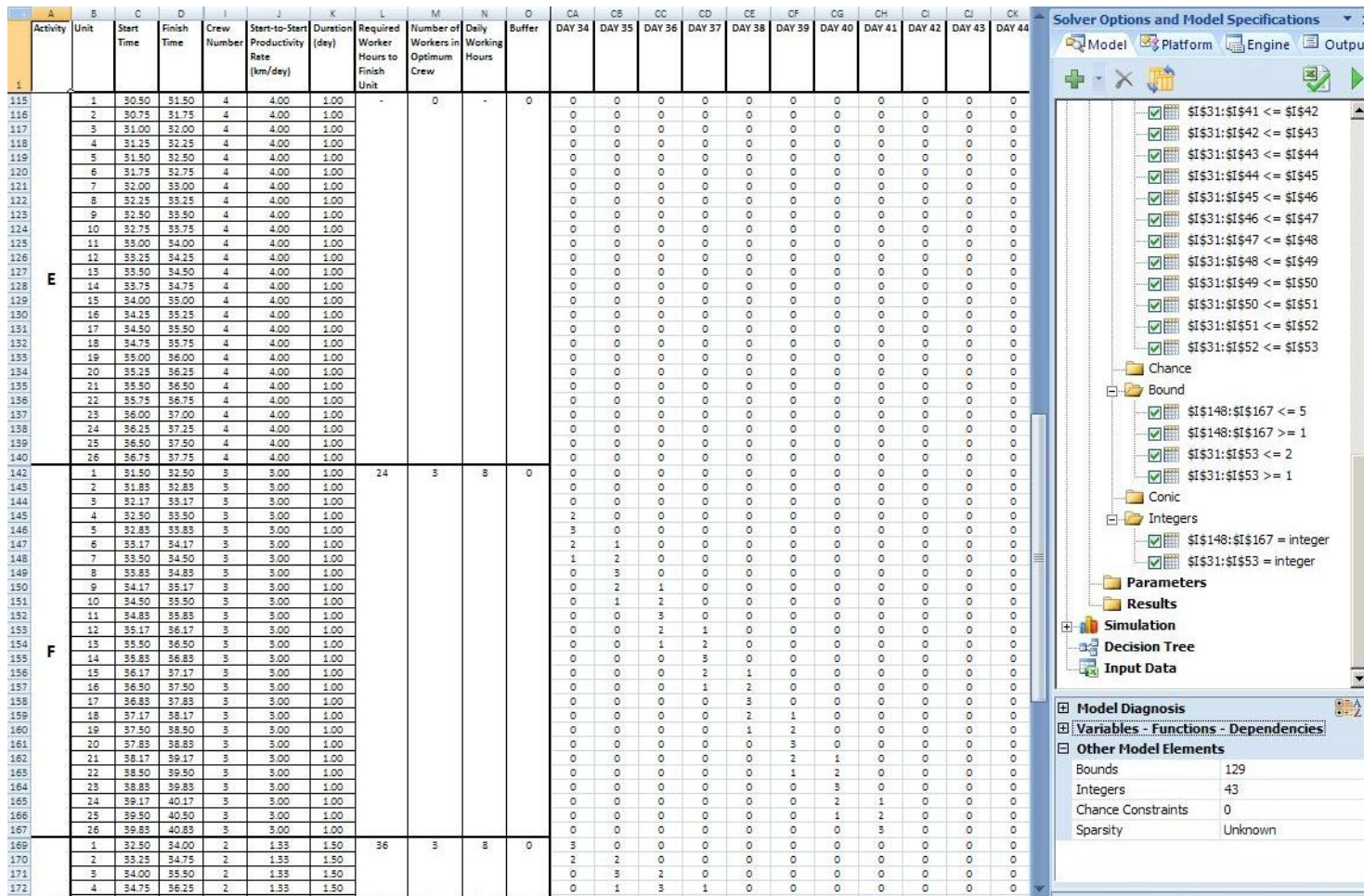


Figure A.40 : Excel sheet of the model for Activity E and F (Scenario 2 / Day 34 - 44)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
	Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 45	DAY 46	DAY 47	DAY 48	DAY 49	DAY 50	DAY 51	DAY 52	DAY 53	DAY 54	DAY 55
115	E	1	30.50	31.50	4	4.00	1.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0
116		2	30.75	31.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
117		3	31.00	32.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
118		4	31.25	32.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
119		5	31.50	32.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
120		6	31.75	32.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
121		7	32.00	33.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
122		8	32.25	33.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
123		9	32.50	33.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
124		10	32.75	33.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
125		11	33.00	34.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
126		12	33.25	34.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
127		13	33.50	34.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
128		14	33.75	34.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
129		15	34.00	35.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
130		16	34.25	35.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
131		17	34.50	35.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
132		18	34.75	35.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
133		19	35.00	36.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
134		20	35.25	36.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
135		21	35.50	36.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
136		22	35.75	36.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
137		23	36.00	37.00	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
138		24	36.25	37.25	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
139		25	36.50	37.50	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
140		26	36.75	37.75	4	4.00	1.00					0	0	0	0	0	0	0	0	0	0	0
142	F	1	31.50	32.50	3	3.00	1.00	24	3	8	0	0	0	0	0	0	0	0	0	0	0	0
143		2	31.83	32.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
144		3	32.17	33.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
145		4	32.50	33.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
146		5	32.83	33.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
147		6	33.17	34.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
148		7	33.50	34.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
149		8	33.83	34.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
150		9	34.17	35.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
151		10	34.50	35.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
152		11	34.83	35.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
153		12	35.17	36.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
154		13	35.50	36.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
155		14	35.83	36.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
156		15	36.17	37.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
157		16	36.50	37.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
158		17	36.83	37.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
159		18	37.17	38.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
160		19	37.50	38.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
161		20	37.83	38.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
162		21	38.17	39.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
163		22	38.50	39.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
164		23	38.83	39.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
165		24	39.17	40.17	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
166		25	39.50	40.50	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
167		26	39.83	40.83	3	3.00	1.00					0	0	0	0	0	0	0	0	0	0	0
169		1	32.50	34.00	2	1.33	1.50	36	3	8	0	0	0	0	0	0	0	0	0	0	0	0
170		2	33.25	34.75	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0
171		3	34.00	35.50	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0
172		4	34.75	36.25	2	1.33	1.50					0	0	0	0	0	0	0	0	0	0	0

Solver Options and Model Specifications

Model Platform Engine Output

☒ \$I\$31:\$I\$41 <= \$I\$42
☒ \$I\$31:\$I\$42 <= \$I\$43
☒ \$I\$31:\$I\$43 <= \$I\$44
☒ \$I\$31:\$I\$44 <= \$I\$45
☒ \$I\$31:\$I\$45 <= \$I\$46
☒ \$I\$31:\$I\$46 <= \$I\$47
☒ \$I\$31:\$I\$47 <= \$I\$48
☒ \$I\$31:\$I\$48 <= \$I\$49
☒ \$I\$31:\$I\$49 <= \$I\$50
☒ \$I\$31:\$I\$50 <= \$I\$51
☒ \$I\$31:\$I\$51 <= \$I\$52
☒ \$I\$31:\$I\$52 <= \$I\$53

Chance

Bound

☒ \$I\$148:\$I\$167 <= 5
☒ \$I\$148:\$I\$167 >= 1
☒ \$I\$31:\$I\$53 <= 2
☒ \$I\$31:\$I\$53 >= 1

Conic

Integers

☒ \$I\$148:\$I\$167 = integer
☒ \$I\$31:\$I\$53 = integer

Parameters

Results

Simulation

Decision Tree

Input Data

Model Diagnosis

Variables - Functions - Dependencies

Other Model Elements

Bounds	129
Integers	43
Chance Constraints	0
Sparsity	Unknown

Figure A.41 : Excel sheet of the model for Activity E and F (Scenario 2 / Day 45 - 55)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DM	DN	DO	DP	DQ	DR	DS	DT	DU	DV	DW	DX	DY	DZ	EA	EB	EC	ED	EE	EF	EG	EH	EI	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES	ET	EU	EV	EW	EX	EY	EZ	FA	FB	FC	FD	FE	FF	FG	FH	FI	FJ	FK	FL	FM	FN	FO	FP	FQ	FR	FS	FT	FU	FV	FW	FX	FY	FZ	GA	GB	GC	GD	GE	GF	GG	GH	GI	GJ	GK	GL	GM	GN	GO	GP	GQ	GR	GS	GT	GU	GV	GW	GX	GY	GZ	HA	HB	HC	HD	HE	HF	HG	HH	HI	HJ	HK	HL	HM	HN	HO	HP	HQ	HR	HS	HT	HU	HV	HW	HX	HY	HZ	IA	IB	IC	ID	IE	IF	IG	IH	II	IJ	IK	IL	IM	IN	IO	IP	IQ	IR	IS	IT	IU	IV	IW	IX	IY	IZ	JA	JB	JC	JD	JE	JF	JG	JH	JI	IJ	JK	KL	KM	KN	KO	KP	KQ	KR	KS	KT	KU	KV	KW	KX	KY	KZ	LA	LB	LC	LD	LE	LF	LG	LH	LI	LJ	LK	LM	LN	LO	LP	LQ	LR	LS	LT	LU	LV	LW	LX	LY	LZ	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	ML	MN	MO	MP	MQ	MR	MS	MT	MU	MV	MW	MX	MY	MZ	NA	NB	NC	ND	NE	NF	NG	NH	NI	NJ	NK	NL	NM	NO	NP	NQ	NR	NS	NT	NU	NV	NW	NX	NY	NZ	OA	OB	OC	OD	OE	OF	OG	OH	OI	OJ	OK	OL	OM	ON	OO	OP	OQ	OR	OS	OT	OU	OV	OW	OX	OY	OZ	PA	PB	PC	PD	PE	PF	PG	PH	PI	PJ	PK	PL	PM	PN	PO	PP	PQ	PR	PS	PT	PU	PV	PW	PX	PY	PZ	QA	QB	QC	QD	QE	QF	QG	QH	QI	QJ	QK	QL	QM	QN	QO	QP	QQ	QR	QS	QT	QU	QV	QW	QX	QY	QZ	RA	RB	RC	RD	RE	RF	RG	RH	RI	RJ	RK	RL	RM	RN	RO	RP	RQ	RR	RS	RT	RU	RV	RW	RX	RY	RZ	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ	SK	SL	SM	SN	SO	SP	SQ	SR	SS	ST	SU	SV	SW	SX	SY	SZ	TA	TB	TC	TD	TE	TF	TG	TH	TI	TJ	TK	TL	TM	TN	TO	TP	TQ	TR	TS	TT	TU	TV	TW	TX	TY	TZ	UA	UB	UC	UD	UE	UF	UG	UH	UI	UJ	UK	UL	UM	UN	UO	UP	UQ	UR	US	UT	UU	UV	UW	UX	UY	UZ	VA	VB	VC	VD	VE	VF	VG	VH	VI	VJ	VK	VL	VM	VN	VO	VP	VQ	VR	VS	VT	VU	VV	VW	VX	VY	VZ	WA	WB	WC	WD	WE	WF	WG	WH	WI	WJ	WK	WL	WM	WN	WO	WP	WQ	WR	WS	WT	WU	WV	WW	WX	WY	WZ	XA	XB	XC	XD	XE	XF	XG	XH	XI	XJ	XK	XL	XM	XN	XO	XP	XQ	XR	XS	XT	XU	XV	XW	XX	XY	XZ	YA	YB	YC	YD	YE	YF	YG	YH	YI	YJ	YK	YL	YM	YN	YO	YP	YQ	YR	YS	YT	YU	YV	YW	YX	YY	YZ	ZA	ZB	ZC	ZD	ZE	ZF	ZG	ZH	ZI	ZJ	ZK	ZL	ZM	ZN	ZO	ZP	ZQ	ZR	ZS	ZT	ZU	ZV	ZW	ZX	ZY	ZZ
Activity	Unit	Start Time	Finish Time	Crew Number	Start-to-Start Productivity Rate (km/day)	Duration (day)	Required Worker Hours to Finish Unit	Number of Workers in Optimum Crew	Daily Working Hours	Buffer	DAY 56	DAY 57	DAY 58	DAY 59	DAY 60	DAY 61	DAY 62	DAY 63	DAY 64	DAY 65	DG																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
E	1	30.50	31.50	4	4.00	1.00	-	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0																																																																																																																																																																																																																																								

Figure A.42 : Excel sheet of the model for Activity E and F (Scenario 2 / Day 56 - 65)

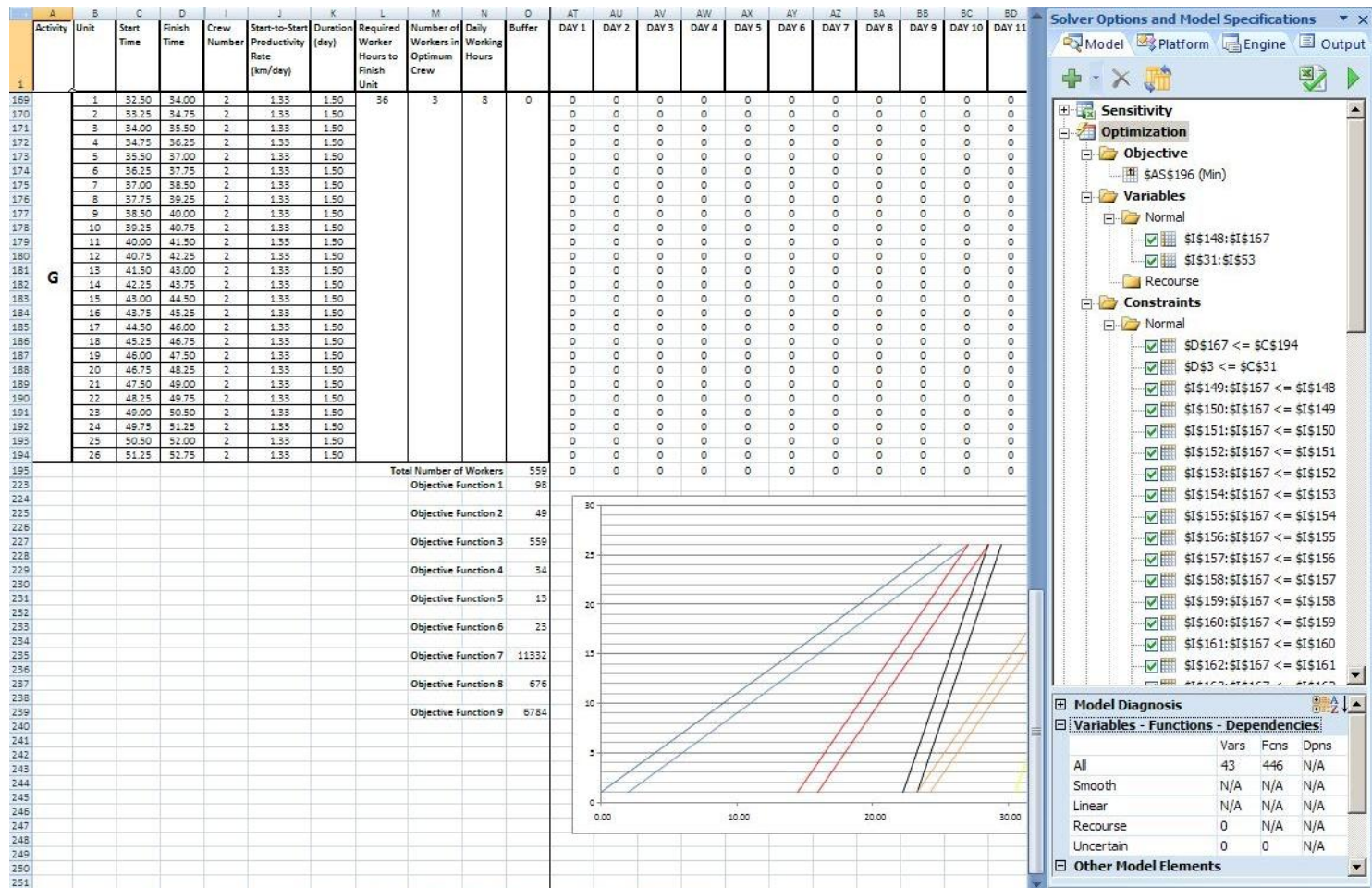


Figure A.43 : Excel sheet of the model for Activity G (Scenario 2 / Day 1 - 11)

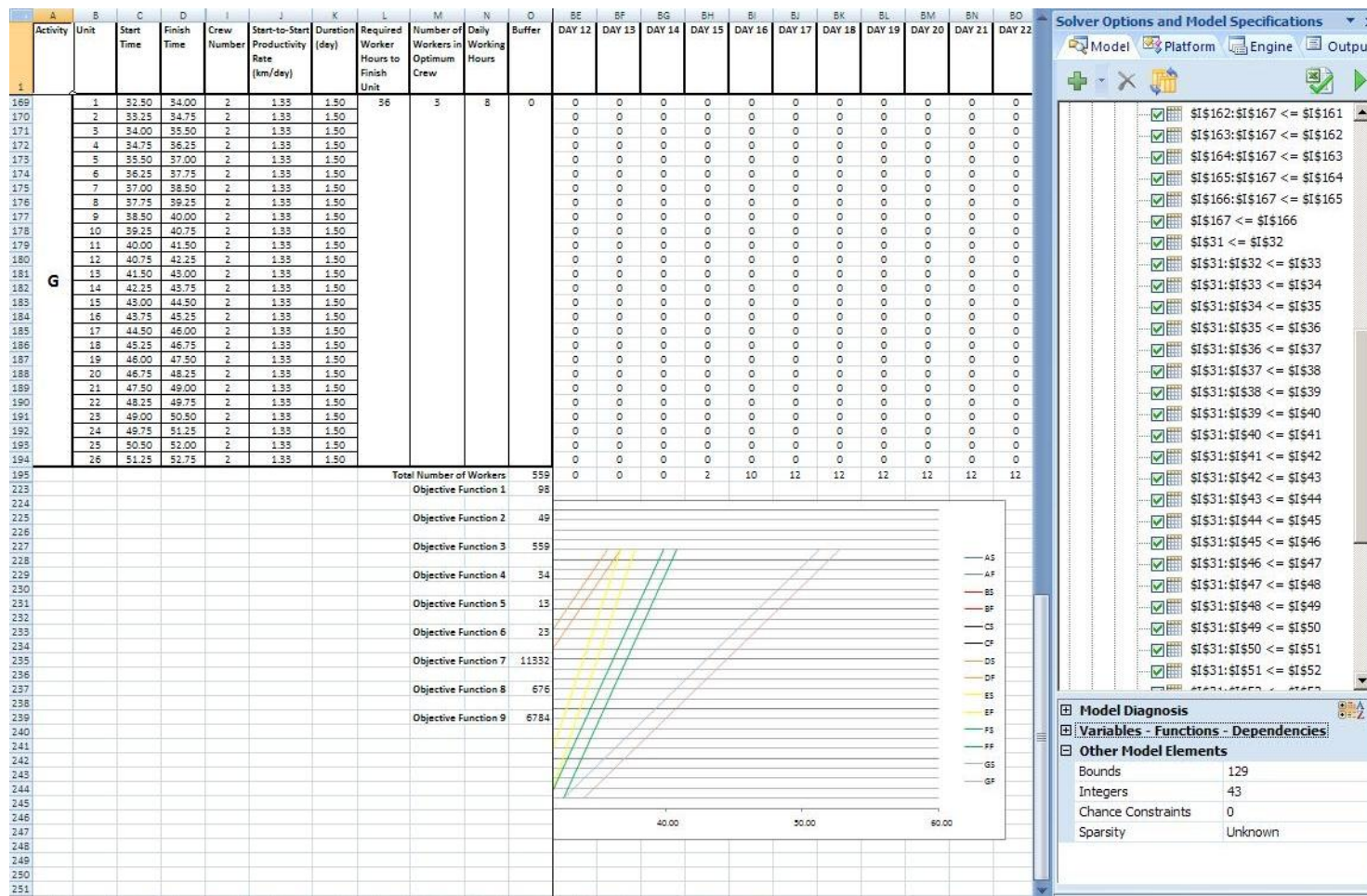


Figure A.44 : Excel sheet of the model for Activity G (Scenario 2 / Day 12 - 22)

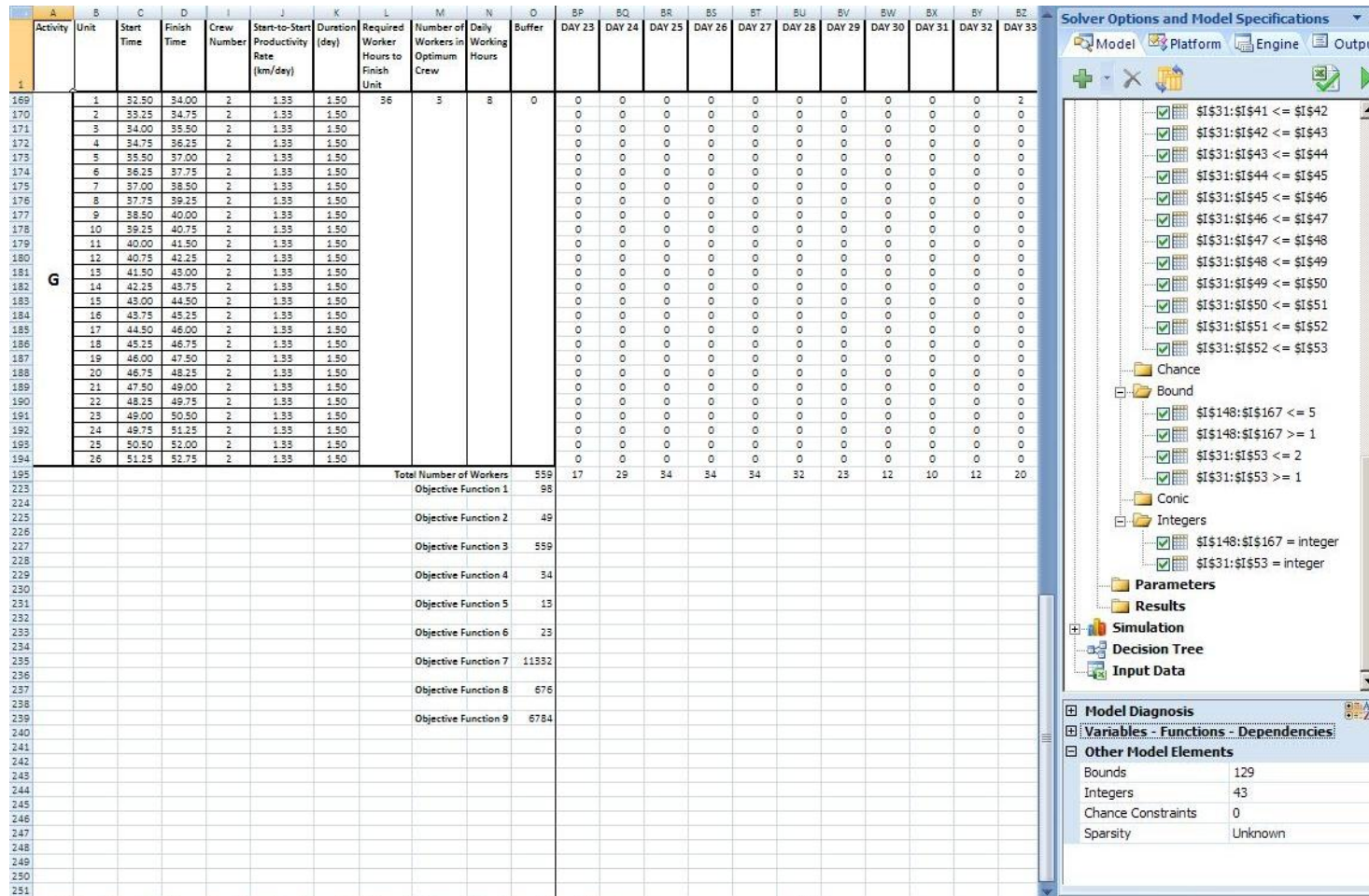


Figure A.45 : Excel sheet of the model for Activity G (Scenario 2 / Day 23 - 33)

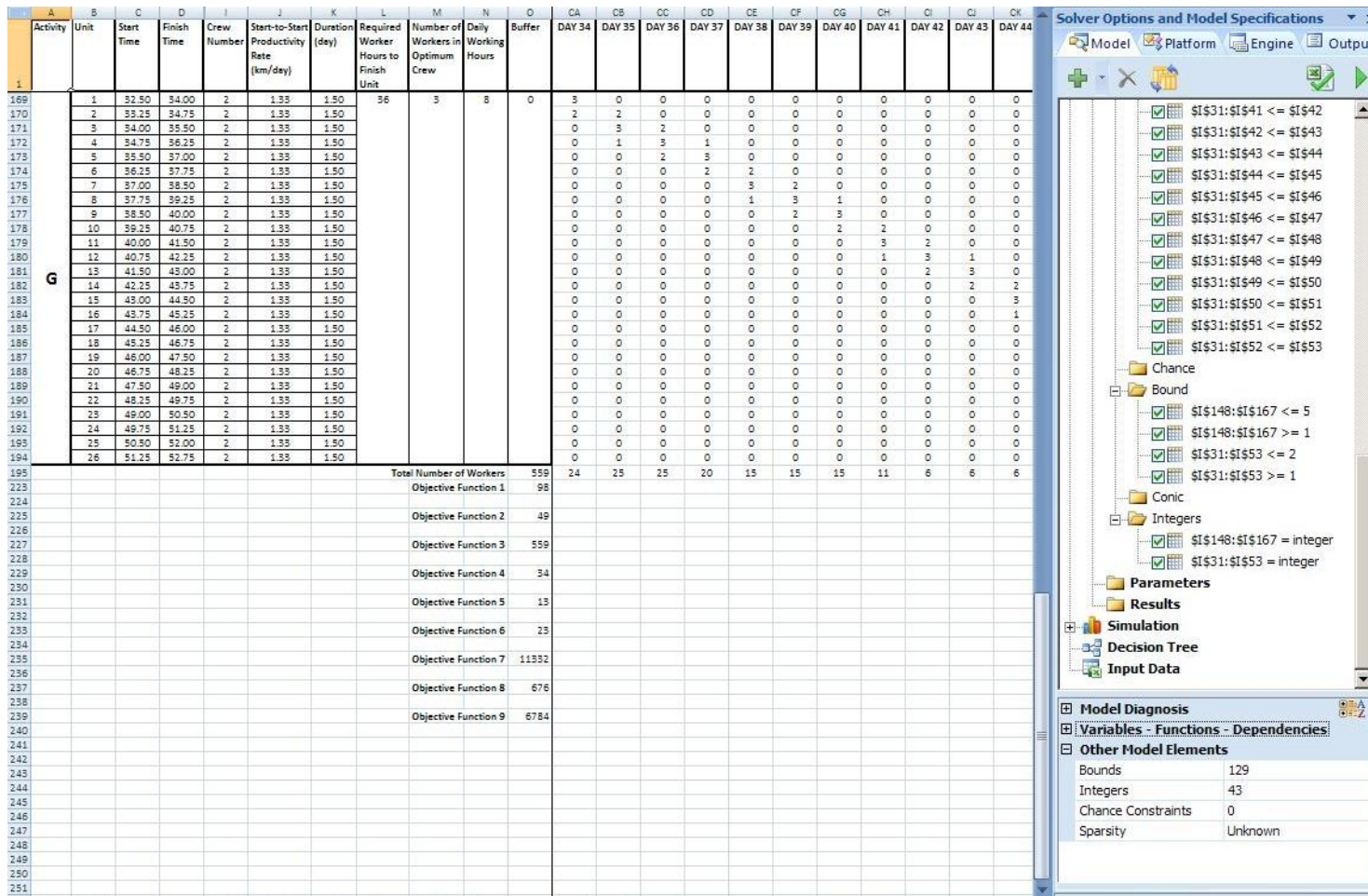


Figure A.46 : Excel sheet of the model for Activity G (Scenario 2 / Day 34 - 44)

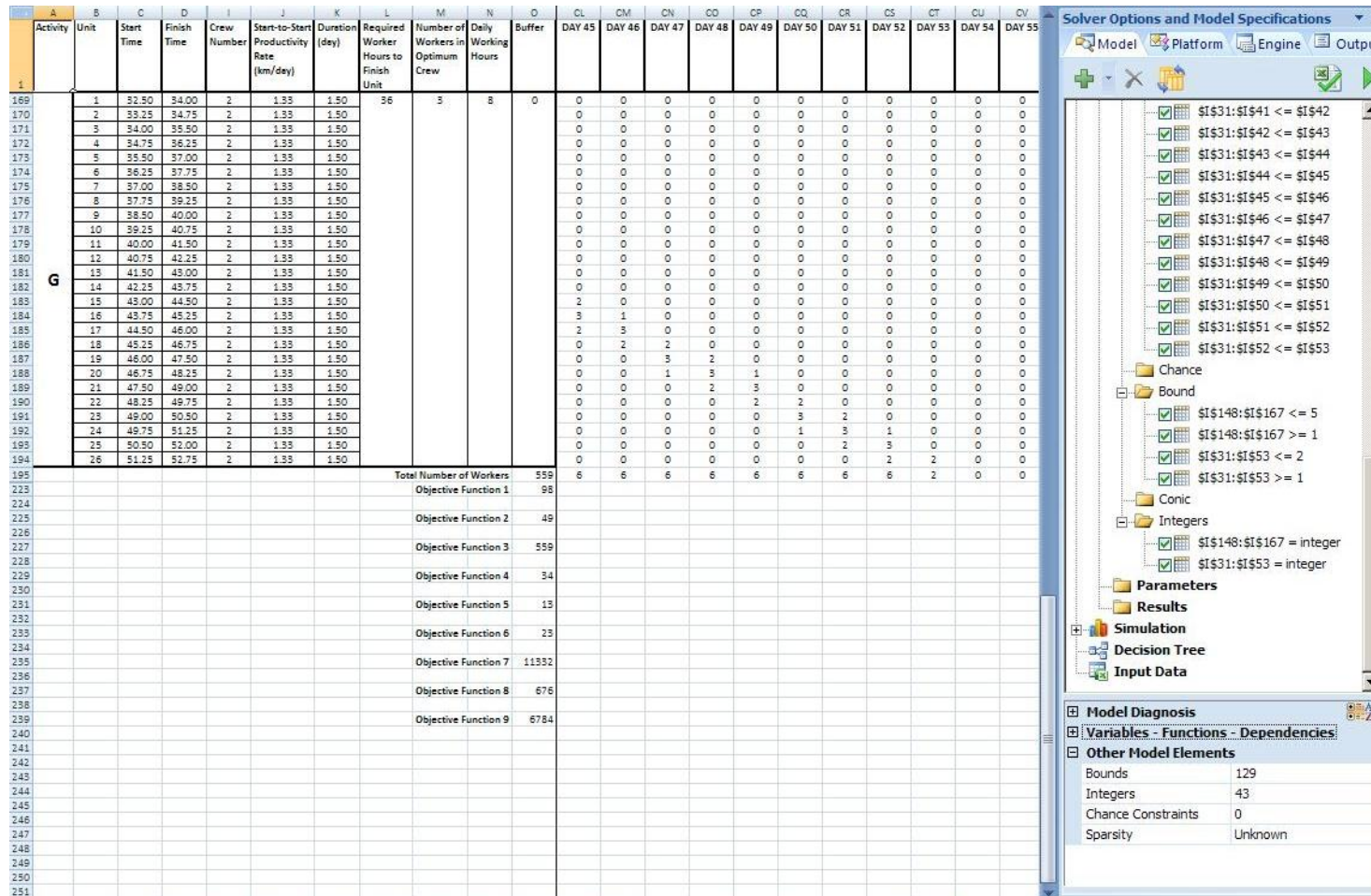


Figure A.47 : Excel sheet of the model for Activity G (Scenario 2 / Day 45 - 55)

CURRICULUM VITAE

Name Surname: Atilla DAMCI

B.Sc.: Civil Engineering - YTÜ (2003)

M.Sc.: Real Estate Development - İTÜ (2006)

List of Publications and Patents:

- Ersoy M.A., **DAMCI A.**, "Identification of Location Selection Criteria for Shopping Centres: Case of Forum Istanbul", 2007, s. Volume 1 / 19-22., International Conference on Construction and Real Estate Management, Bristol, UK, 21.08.2007 - 22.08.2007
- Polat G., **DAMCI A.**, "Need for Qualified Workforce in Industrialized Building Systems: Case of the Turkish Precast Concrete Industry", 2007, Built Environment Education Annual Conference (Beecon 2007), University of Westminster, Central London, UK, 12.09.2007 - 13.09.2007
- Polat G., **DAMCI A.**, "Türk İnşaat Sektöründe Prefabrik Betonarme Yapı Sistemlerinin Kullanımını Etkileyen Faktörler", 2007, 4. İnşaat Yönetimi Kongresi, İstanbul, 30.10.2007 - 31.10.2007
- Polat G., **DAMCI A.**, "Supplier Selection Criteria in the Turkish Precast Concrete Industry", 2008, s. 499-506, 8th International Congress on Advances in Civil Engineering, Famagusta, Turkish Republic of North Cyprus, 15.09.2008 - 17.09.2008
- **DAMCI A.**, Polat G., Ciraci M., "Need for Education in the Design/Build Project Delivery System in Turkey", 2008, s. 537-544, 8th International Congress on Advances in Civil Engineering, Famagusta, Turkish Republic of North Cyprus, 15.09.2008 - 17.09.2008
- Polat G., Buyuksaracoglu Y., **DAMCI A.**, "Scheduling Asphalt Highway Construction Operations Using the Combination of Line-of-Balance and Discrete Event Simulation Techniques", 12/2009, 2009 IEEE International Conference on Industrial Engineering and Engin, Hong Kong, 08.12.2009 - 11.12.2009
- Polat G., **DAMCI A.**, "Mühendislik ve Tasarım Hizmeti Sunan Firmalarda Bilgi Teknolojilerinin Kullanımı", 10/2009, 5.Yapı işletmesi/Yapım Yönetimi Kongresi, Eskişehir, 22.10.2009 - 23.10.2009
- **DAMCI A.**, Polat G., "Resource Leveling of Railway Track Construction Operations Using the Linear Scheduling and Genetic Algorithm Techniques", Proc. 8th International Conference on Construction and Real Estate Management, Brisbane, Australia, 105-110, 2010

- Polat, G., **DAMCI A.**, M. Düzcan, “Uluslararası İnşaat Projelerinde Risk Priminin Çoklu Regresyon Yöntemi ile Belirlenmesi”, 1. Proje ve Yapım Yönetimi Kongresi, 584-595, Ankara, 2010.
- **DAMCI A.**, Polat G., T. Baysal, “Resource Leveling of an Industrial Building Using Genetic Algorithm Technique,” Proc. International Balkans Conference on Challenges of Civil Engineering, Tirana, Albania, 2011
- Polat, G., **DAMCI A.**, Tatar, Y., “Barriers and Benefits of Total Quality Management in the Construction Industry: Evidence from Turkish Contractors,” Proc. 7th Research/Expert Conference with International Participations “Quality 2011”, Neum, Bosnia and Herzegovina, 2011.