ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

RESOURCE LEVELING OF A LINEAR CONSTRUCTION PROJECT USING BRANCH AND BOUND ALGORITHM

M.Sc. THESIS

Resulali Emre ÖRGÜT

Department of Civil Engineering

Construction Management Programme

JANUARY 2012

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

RESOURCE LEVELING OF A LINEAR CONSTRUCTION PROJECT USING BRANCH AND BOUND ALGORITHM

M.Sc. THESIS

Resulali Emre ÖRGÜT
501101164

Department of Civil Engineering

Construction Management Programme

Thesis Advisor: Assoc. Prof. Dr. Gül POLAT TATAR

JANUARY 2012

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

DOĞRUSAL BİR İNŞAAT PROJESİNİN DAL VE SINIR ALGORİTMASI KULLANILARAK KAYNAK DENGELEMESİ

YÜKSEK LİSANS TEZİ

Resulali Emre ÖRGÜT
501101164

İnşaat Mühendisliği Anabilim Dalı

Yapı İşletmesi Programı

Tez Danışmanı: Doç. Dr. Gül POLAT TATAR

OCAK 2012

Resulali Emre ÖRGÜT, a **M.Sc.** student of ITU **Graduate School of Science, Engineering and Technology** student ID 501101164, successfully defended the **thesis** entitled "**RESOURCE LEVELING OF A LINEAR CONSTRUCTION PROJECT USING BRANCH AND BOUND ALGORITHM**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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

Jury Members : **Assoc. Prof. Dr. Uğur MÜNGEN** ....
İstanbul Technical University

Assist. Prof. Dr. Beliz ÖZORHON ....
Boğaziçi University

Date of Submission : 19 December 2012
Date of Defense : 26 January 2012

To my grandparents
İhsan, Sebahat, İbrahim and Nadire

FOREWORD

I'd like to thank to Assoc. Prof. Gul POLAT TATAR for her illumunating knowledge, my father Civ. Eng. Melih ÖRGÜT for sharing his valuable vast of experience, İrem ŞENGÜL for her most precious help and contribution in case study and optimization process, Yahya BÜYÜKSARAÇOĞLU for providing real life project data of the case study, Dr. Erinç ALBEY and Dr. Hakan KARAGUL for their guidance and help in most difficult times, last but not least my mother Demet ÖRGÜT, my brother Mehmet ÖRGÜT and my family for their great support not only on every stage of my study but also throughout my entire life.

January 2012

Resulali Emre ÖRGÜT
Civil Engineer

TABLE OF CONTENTS

Page

FOREWORD .... **ix**
TABLE OF CONTENTS .... **xi**
ABBREVIATIONS .... **xv**
LIST OF TABLES .... **xvii**
LIST OF FIGURES .... **xix**
SUMMARY .... **xxi**
ÖZET .... **xxiii**
1. INTRODUCTION **1**
1.1 Background of the Study 1
1.2 Objectives of the Thesis 1
1.3 Research Methodology 2
1.4 Scope 2
2. PLANNING IN CONSTRUCTION MANAGEMENT **5**
2.1 Construction Management 5
2.2 Planning 5
2.2.1 Role and importance of planning in construction management 6
2.2.2 Factors interacting with planning 7
3. PLANNING AND SCHEDULING TECHNIQUES **9**
3.1 Construction Project Types 10
3.1.1 Linear projects 10
3.1.2 Non-linear Projects 11
3.2 Classical Planning Techniques 11
3.2.1 Critical path method (CPM) 12
3.2.2 Program evaluation and review technique (PERT) 12
3.2.3 Defects of classical techniques and need for a new approach 13
3.3 Alternative Planning Techniques 13
3.3.1 Line of balance (LoB) 13
3.3.2 Location-based planning (LBP) 14
3.3.2.1 VICO Control 15
4. RESOURCE MANAGEMENT IN CONSTRUCTION PLANNING **17**
4.1 Resource-Based Planning 17
4.2 Resource Optimization 18
4.2.1 Limitations 18
4.2.1.1 Time-limited resource scheduling 18
4.2.1.2 Resource-limited resource scheduling 19
4.2.2 Basic methods 19
4.2.2.1 Serial method 19
4.2.2.2 Parallel method 19
4.2.3 Resource optimization approaches 19
4.2.3.1 Aggregation 19
4.2.3.2 Cumulation 21

4.2.3.3 Allocation 23
4.2.3.4 Leveling 23
5. MATHEMATICAL MODELING 27
5.1 Integer Programming Models 28
5.2 Branch & Bound (B&B) Method 29
5.2.1 Linear programming relaxations of integer programming problems 29
5.2.2 The theory behind B&B method 30
5.2.2.1 An illustrative example 31
6. CASE STUDY 35
6.1 Project Information 35
6.1.1 Tasks and quantities 36
6.1.2 Location breakdown structure 38
6.2 Construction Methodology 39
6.2.1 Production rates 39
6.2.1.1 Subbase and plantmix layers 39
6.2.1.2 Binder and wearing Layers 41
6.2.1.3 Drainage 43
6.2.2 Precedence relations 43
6.2.2.1 Activity orders 43
6.2.2.2 Location orders 44
6.3 Deciding On The Planning System To Be Employed 44
6.4 Preparing the Initial Plan Using LBS and VICO Control 45
6.4.1 LBS 45
6.4.2 Tasks 48
6.4.3 Production rates 48
6.4.4 Bill of quantities 49
6.4.5 Resources 52
6.4.6 Dependencies 53
6.4.7 Durations and schedule 53
6.5 Start date calculations 55
6.5.1 Earliest start dates 55
6.5.2 Backward pass and latest start calculation with total floats 57
6.5.3 Backward pass and latest start date calculation with free floats 60
6.5.4 Completing initial location-based plan and data set 63
6.6 Resource Leveling Process 64
6.6.1 Objective Functions 64
6.6.1.1 Linear Objectives 65
6.6.1.2 Non-linear objectives 65
6.6.2 Working with OPL 66
6.6.3 Transforming data set for integer programming 67
6.6.4 First mathematical optimization model 67
6.6.4.1 Model analysis 68
6.6.4.2 Data input 71
6.6.4.3 Problems 71
6.6.5 Second mathematical optimization model 72
6.6.5.1 New precedence definitions 72
6.6.5.2 New absolute value definitions 75
6.6.6 Solutions 76
6.6.6.1 Solutions with total float 76
6.6.6.2 Solutions with free float 80

7. RESULTS & DISCUSSIONS **101**
8. CONCLUSIONS **113**
REFERENCES **115**
CURRICULUM VITAE **119**

ABBREVIATIONS

ABP	**:** Activity-Based Planning
ADM	**:** Arrow Diagramming Method
B&B	**:** Branch and Bound
BOQ	**:** Bill of Quantities
CM	**:** Construction Management
CMAA	**:** Construction Management Association of America
CPM	**:** Critical Path Method
IP	**:** Integer Programming
LoB	**:** Line of Balance
LBP	**:** Location-Based Planning
LBS	**:** Location Breakdown Structure
LP	**:** Linear Programming
OPL	**:** Optimization Programming Language
PERT	**:** Program Evaluation and Review Technique
PDM	**:** Precedence Diagram Method
RBP	**:** Resource-Based Planning
RLRS	**:** Resource-Limited Resource Scheduling
TLRS	**:** Time-Limited Resource Scheduling
VC	**:** VICO Control
WBS	**:** Work Breakdown Structure

LIST OF TABLES

Page

Table 4.1: Aggregation and cumulation of resources by earliest and latest start dates 21
Table 4.2: Resource leveling criteria 26
Table 6.1: Total quantities of asphalt highway construction works 37
Table 6.2: LBS with distance information 38
Table 6.3: Activity codes and activities distributed over locations 43
Table 6.4: Activity order for subbase activity over locations 43
Table 6.5: Location order for activities over Location 1 44
Table 6.6: LBS and location quantities of the project 46
Table 6.7: Calculated production rates to be used in VC 49
Table 6.8: Total quantities of the activites 50
Table 6.9: Complete schedule with activity earliest time and durations 55
Table 6.10: Complete data set calculated with total floats 58
Table 6.11: Complete data set calculated with free floats 61
Table 6.12: Resource leveling criteria and objective function formulations 64
Table 6.13: Sample data set with decimal digits 67
Table 6.14: Sample data set multiplied with 10 67
Table 6.15: Precedence matrix 73
Table 6.16: Precedence list 74
Table 6.17: Start dates – Objective 4 / Total Float 77
Table 6.18: Activity start date statistics – Objective 4 / Total Float 80
Table 6.19: Start dates – Objective 1 / Free Float 81
Table 6.20: Activity start date statistics – Objective 1 / Free Float 84
Table 6.21: Start dates – Objective 2 / Free Float 84
Table 6.22: Activity start date statistics – Objective 2 / Free Float 87
Table 6.23: Start dates – Objective 3 / Free Float 88
Table 6.24: Activity start date statistics – Objective 3 / Free Float 90
Table 6.25: Start dates – Objective 4 / Free Float 91
Table 6.26: Activity start date statistics – Objective 4 / Free Float 94
Table 6.27: Start dates – Objective 5 / Free Float 94
Table 6.28: Activity start date statistics – Objective 5 / Free Float 97
Table 6.29: Start dates – Objective 6 / Free Float 98
Table 6.30: Activity start date statistics – Objective 6 / Free Float 100
Table 7.1: Evaluation of the solutions in terms of objective metrics 110
Table 7.2: Improvements provided by leveled solutions 112

LIST OF FIGURES

Page

Figure 3.1: Alternative emphases in construction planning..................................... 10
Figure 4.1: Resource unit aggregation chart derived from a bar chart 20
Figure 4.2: Resource unit aggregation chart showing resource requirements associated with earliest and latest start along with highlighted resource unit requirements for critical path activities............................ 21
Figure 4.3: Early and late cumulative resource profiles showing the resource envelope 22
Figure 4.4: Resource demand compared to resource availability 24
Figure 5.1.: An example enumeration tree... 31
Figure 5.2: The enumeration tree for the illustrative example................................. 34
Figure 6.1: Highway cross-sections.. 36
Figure 6.2: Tasks in the order of production.. 37
Figure 6.3: Layer sections... 37
Figure 6.4: Mobile asphalt plant 42
Figure 6.5: Asphalt laying and compacting 42
Figure 6.6: Laddering of activities in accordance with activity and location orders.................................... 44
Figure 6.7: Adding locations to the project.. 46
Figure 6.8: Quantity adjusted locations over the project 47
Figure 6.9: Roughly drawn tasks in flowline view 48
Figure 6.10: Activities in BOQ screen.. 49
Figure 6.11: Activities with undistributed quantities.. 50
Figure 6.12: Quantity distribution for subbase layer 51
Figure 6.13: Quantity distribution view for activities... 51
Figure 6.14: Identifying locations without quantities 52
Figure 6.15: Resource registration 52
Figure 6.16: Allocated resources to the activities... 53
Figure 6.17: Dependency generating between activities 53
Figure 6.18: Location-based schedule on flowline view 53
Figure 6.19: Task editing in order to obtain earliest start dates................................ 54
Figure 6.20: Location-based schedule with activities starting as early as possible.. 54
Figure 6.21: An exemplary figure for representing the feasible region of a nonlinear program 66
Figure 6.22: Solution statistics – Objective 4 / Total Float 77
Figure 6.23: Solution statistics – Objective 1 / Free Float....................................... 81
Figure 6.24: Solution statistics – Objective 2 / Free Float....................................... 84
Figure 6.25: Solution statistics – Objective 3 / Free Float....................................... 87
Figure 6.26: Solution statistics – Objective 4 / Free Float....................................... 91
Figure 6.27: Solution statistics – Objective 5 / Free Float....................................... 94
Figure 6.28: Solution statistics – Objective 6 / Free Float....................................... 97

Figure 7.1: Resource histogram for earliest start dates 101
Figure 7.2: Resource histogram for latest start dates (total float) 101
Figure 7.3: Resource histogram for latest start dates (free float) 102
Figure 7.4: Resource histogram – Objective 4 / Total Float 102
Figure 7.5: Resource requirement – Objective 4 / Total Float 103
Figure 7.6: Resource histogram – Objective 1 / Free Float 103
Figure 7.7: Resource requirement – Objective 1 / Free Float 104
Figure 7.8: Resource histogram – Objective 2 / Free Float 104
Figure 7.9: Resource requirement – Objective 2 / Free Float 105
Figure 7.10: Resource histogram – Objective 3 / Free Float 105
Figure 7.11: Resource requirement – Objective 3 / Free Float 106
Figure 7.12: Resource histogram – Objective 4 / Free Float 106
Figure 7.13: Resource requirement – Objective 4 / Free Float 107
Figure 7.14: Resource histogram – Objective 5 / Free Float 107
Figure 7.15: Resource requirement – Objective 5 / Free Float 108
Figure 7.16: Resource histogram – Objective 6 / Free Float 108
Figure 7.17: Resource requirement – Objective 6 / Free Float 109

RESOURCE LEVELING OF A LINEAR CONSTRUCTION PROJECT USING BRANCH AND BOUND ALGORITHM

SUMMARY

This research mainly aims to level resource utilization of a 9.7 km long asphalt highway project that was constructed in Sakarya using branch and bound (B&B) algorithm. In this study, the number of trucks utilized throughout the project was aimed to be leveled. Actual data of bill of quantities, resources (i.e., equipment), and production rates were obtained from the records of the contractor of this real life highway project.

Leveling is a kind of resource allocation, which aims to spread resource utilization rates throughout the schedule in order to achieve a uniform level of resource usage (Kenley and Seppänen, 2010). The main purpose of leveling process is to smooth the resource histogram, which means elimination of peaks and valleys in resource utilization histograms. Besides, resource leveling also deals with resource over-allocation, which means that it is also the process that guarantees resource usage remains in available limits. using algorithms and advanced planning techniques for such complicated issues may bring about better results. Furthermore, one of the most important facts about the leveling process is that project's time limitations should also be considered along with resource constraints. Because it is important to keep total project completion time as it is, while dealing with resource utilization to create the most balanced and evenly distributed usage.

The studied project consists of four different layers, which include: sub-base, plant-mix, binder and wearing. In addition to the production of these layers, drainage pipes were installed after the completion of the sub-base layer. The highway project in question was highly linear and repetitive in nature, location-based planning (LBP) system was found to be appropriate for establishing the initial construction plan. The above-mentioned layers of the highway, along with the drainage, were constructed in the same order but with different quantities throughout the entire project. Quantities of the each task were calculated in detail, by taking the roof slope of the highway into consideration. Production rates for the activities differ since the numbers and productivities of the equipments and crews working on that task are different. Therefore, production rates of the activities were calculated separately based on the information taken from the company.

Using these data, a location-based schedule was developed considering both resource and time constraints and precedence relations between activities via VICO Control (VC) software program. VC software provided the durations and the earliest start dates of the activities. Latest start dates were then manually calculated by making backward pass as it is the case in Critical Path Method (CPM). Having determined the earliest and latest start dates of the activities and precedence relationships between the activities, resource leveling problem was formulated as a binary integer mathematical program.

In the mathematical formulation of the resource leveling problem, the objective function of minimizing the maximum daily resource usage was solved using B&B algorithm via Optimization Programming Language (OPL) software program considering the constraints of earliest and latest start dates of the activities and the precedence relationships between the activities. OPL is a modeling tool used for solving different linear programming, integer programming and combinatorial optimization problems. The leveled resource histogram was then compared with the initial resource histogram prepared based on the earliest start schedule.

This research proposed a mathematical model for leveling resources of a linear construction project, namely a highway construction project, scheduled with location-based planning technique. Mixed-integer programming with branch and bound algorithm was used to level resources for different objective functions. In the case study, proposed model was examined in detail and all steps to accomplish the development of a new model was represented. Different resource histograms derived from the solutions of various objective functions, are compared and examined. Two data set obtained from different project floats was used in proposed model with different objective functions. Since, all of the objective functions with total floats could not give solution due to excessive memory usage, it is hard to deliver a comparison and/or analysis regarding the effect of total floats. However, a detailed examination was available for data set with free floats in different objective functions hence, best solution for free float data set was shown from various evaluation aspects.

Besides, it is shown that, LBP offers better layout for resource leveling than CPM due to easier project control and less complexity. In addition, proposed model emerges as a reliable resource leveling tool, since it takess many aspects of project into consideration such as production rates, exact durations and complete precedence relations without breaking project order logic.

In conclusion, this study is contributed to the field by proposing a mathematical model with branch and bound algorithm for resource leveling of linear construction projects. This contribution can be expanded by considering provided future work areas and more.

DOĞRUSAL BİR İNŞAAT PROJESİNİN DAL VE SINIR ALGORİTMASI KULLANILARAK KAYNAK DENGELEMESİ

ÖZET

Her inşaat projesi, inşaat sektörünü doğası gereği, kendine özgü ve tektir. İnşaat endüstrisi ürünlerinin yalnızca yerellik, karmaşıklık ve yüksek üretim maliyetleri gibi özellikleri değil; hava durumu, tedarik sorunları ve kalite gereksinimleri gibi üretim sureci etmenleri de bu uzunluğu yaratır. Her inşaat projesinin farklı olması, projeye özgü önlemler ve metotların kullanılmasını gerektirir. Bu gereksinim, projeye uygun yapı işletmesi uygulamalarının da önemini artırır. Amerikan Yapı İşletmesi Birliği'ne (Construction Management Association of America) göre, yapı işletmesi, kalite, maliyet, zaman ve kapsam yönetimi gibi proje hedeflerine ulaşmak için planlama, tasarım, yapım ve yapım sonrası aşamaları boyunca inşaat projeleri ve programlarına uygulanan bir hizmetler bütünüdür (CMAA, 2011). "Zaman, maliyet, kalite ve kapsam" gibi unsurlar, bir inşaat projesinde en temel unsurlar olarak görünmektedir. Yapı işletmesinin birincil odağı, projeyi başarıyla tamamlamak için bu etmenlerin en iyileştirilmesidir. Bahsi gecen en iyileştirme sureci planlama, organizasyon, yönetim ve kontrolü içeren 4 temel adımdan oluşur (Newitt, 2009). Adımlar önemlerine göre sıralanmışlardır. Bir projenin organizasyon, yönetim ve kontrol işlevleri, düzgün, mantıklı ve iyi hazırlanmış bir plan olmadan yeterli düzeyde yerine getirilemez.

Genel olarak planlama, projeye dahil olan tüm tarafları bir fikirden proje bitişine tatmin edici bir şekilde yönlendirme sureci seklinde tanımlanabilir (Adeli ve Karim, 2001). Bu rehberlik, planlamayı, belirsizliklere çokça tabi olan inşaat sektörü için gerekli ve hatta hayati kılar. Ayrıca planlama, aktivitelerin sadece surelerini değil, kaynak ve finansal gereksinimlerini de göz önünde bulundurarak, aktiviteleri önceden belirlenmiş bir zaman dilimine yayma isidir. Genel inanış, yapım isleri için planlama surecinde odak noktasının zaman olduğu seklindedir. Oysa. Sadece zamana odaklanmak, proje hedeflerinin diğer önemli elemanlarını göz ardı edilmesi ve aralarındaki dengenin de bozulması gibi sonuçlar doğurur. Planlamanın en önemli amacı tüm proje unsurlarını bir arada değerlendirmek olduğu kadar, onları dengelemektir de.

Kaynakların etkili ve verimli kullanımı, başarılı proje yönetimi ve haliyle proje planlaması için çok önemlidir. Akılda tutulması gereken bir başka husus da, planlama surecinde kritik olan aktivite surelerinin, o aktiviteyi tamamlamak için gerekli olan kaynakların uygunluk durumuna göre tespit edilmesidir (Hinze, 2008). Önde gelen kaynak maddeleri; yapı malzemeleri, isçilik, ekipman, yükleniciler, alt yükleniciler ve tabii ki paradır. Günümüz dünyasında kaynaklar sinirlidir ve kaynak kısıtlarını dikkate almamak, planlamayı gerçekçilikten uzaklaştırır. Öte yandan, kaynak kısıtlarını dikkate almak ve kaynak akışını planlamak, proje planlarını sadece gerçekçi yapmakla kalmaz, uygulanmalarını da kolaylaştırır.

Genel olarak inşaat projelerinde kullanılan iki tur planlama vardır. Bunlar aktivite tabanlı planlama (ATP) ve mahal tabanlı planlama (MTP) dır. Bir projede her bir ayrı is paketine aktivite adi verilir (Callahan ve diğ., 1992). ATP sistemleri, planlamaya daha gelenekselci bir yaklaşım olarak değerlendirilebilirler (Kenley, 2004). Bu sistemler yapılacak isin birimine odaklanırlar. Burada is, birbirine zaman yönünden bağlı aktiviteler olarak; aktiviteler ise, gerçekleştikleri mahalden bağımsız olarak değerlendirilirler. 1950'lerde ortaya çıktıklarından beri, Kritik Yol Metodu (KYM) ve Program Değerlendirme ve Gözden geçirme Tekniği (PDGT) gibi ATP araçları dünyanın her yerindeki yapı işletmesi profesyonelleri ve şirketleri tarafından sıklıkla tercih edilmiştir. O zamanlardan bugüne, inşaat projeleri daha karmaşık hale geldikçe ve inşaat endüstrisinin gereksinimleri arttıkça, bu metotlar gereksinimleri karşılayamaz hale gelmişlerdir. Bazı araştırmacılar, KYM'na dayanan ATO metodolojisinin, projeyi en erken zamanda tamamlamak uğruna kaynakların verimli kullanımını feda ettiğini fark etmişlerdir (Arditi et al., 2002). Dahası, ATP tekniklerinin sinirsiz kaynak varsayımına dayandığı da bilinmektedir. Su açıkça görülmüştür ki, aslen inşaat sektörü için değil de askeri endüstri için geliştirilmiş olan ATP teknikleri inşaat sektörünün karakteristiklerine tam olarak uymamaktadır (Kenley ve Seppänen, 2010).

Kaynakların daha iyi ve verimli yönetimi arayışına MTP sistemleri cevap olmuştur. MTP kaynakların mahaller arasında engelsiz akışı sayesinden eniyi proje suresini sağlar (Kenley ve Seppänen, 2010). Tıpkı ATP ve KYM arasında olduğu gibi, MTP de Denge Diyagramları (DD) metodunun temellerine dayanır. İnşaat projelerinin doğaları gereği tekrara dayalı olduğu gerçeğinden (Lumsden, 1968) yola çıkarak, MTP'nin de sunabileceği doğrusal bir planlama sistemi daha uygundur (Harris ve Ioannau, 1998; Arditi ve diğ., 2001). MTP, sürekli is akışını doğrusal planlama tekniği ve kaynakların dengeli kullanımı vasıtasıyla planlamak ve kontrol etmek için kaynak tabanlı bir yönetim sistemidir (Fırat ve diğ., 2009). ATP ve MTP arasındaki bir başka önemli farklılık da KYM aktivite surelerini girdi olarak tanımlarken, eniyi aktivite surelerinin MTP planlama surecinin çıktısı olmalarıdır. Her bir aktivite için, kaynak gereksinimleri ve metrajlar MTP'ye girilerek aktivite sureleri hesaplanır (Kenley ve Seppänen, 2010).

Bu çalışma aslen, Sakarya'da inşa edilmiş 9,7 km uzunluğunda bir asfalt karayolu projesinin kaynak kullanımının Dal ve Sinir (D&S) algoritması kullanılarak dengelenmesini amaçlamaktadır. Bu çalışmada, proje boyunca kullanılan kamyon sayılarının dengelenmesi hedeflenmiştir. Gerçek metraj, kaynak, ekipman ve üretim miktarı verileri, bu karayolu projesinin gerçek yüklenicisinin kayıtlarından alınmıştır.

Dengeleme, kaynakların benzer düzeylerde kullanımını sağlamak amacıyla kaynak kullanım oranlarını proje takvimi boyunca yaymayı hedefleyen bir çeşit kaynak atamasıdır (Kenley ve Seppänen, 2010). Kaynaklama surecinin asil amacı kaynakların çoklu dağılım grafiğini düzgünleştirmektir ki bu grafikteki tepe ve vadilerin ortadan kaldırılması anlamına gelir. Ayrıca, dengelem sureciyle ilgili en önemli unsurlardan biri de projenin zaman sınırlamalarının, kaynak kısıtları ile birlikte değerlendirilmesi gerekliliğidir. Çünkü kaynak kullanımını en dengeli ve eşit dağılmış hale getirmekle ilgilenirken toplam proje suresini de olduğu gibi muhafaza etmek önemlidir.

İncelenen proje dört katmandan oluşmaktadır; alt-temel, plan-mix, binder ve aşınma tabakaları. Bu katmanların üretimine ilaveten, alt-temel tabakası tamamlandıktan sonra drenaj boruları da yerleştirilmiştir. İncelenen karayolu projesi yüksek oranda doğrusal ve tekrar eden bir yapıdadır. Bu yüzden de MTP sisteminin başlangıç planlarının oluşturmak için uygun olduğuna karar verilmiştir. Karayolunun yukarıda bahsi gecen katmanları ve drenaj sistemi, projenin her mahali boyunca ayni sırada fakat farklı miktarlarda inşa edilmişlerdir. Her bir aktivitenin metrajı tüm detaylar göz önünde bulundurularak hesaplanmıştır. Ekipman sayıları ve verimlilikleri her aktivitede farklılık gösterdiğinden aktivitelerin üretim oranları da farklıdır. Bu yüzden de, her aktivitenin üretim oranı firmadan alınan bilgiler doğrultusunda ayrı ayrı hesaplanmıştır.

Bu veriler kullanılıp, kaynak ve zaman kısıtları ile aktiviteler arasındaki öncelik sıraları göz önünde bulundurularak VICO Control (VC) yazılımında mahal tabanlı bir plan oluşturulmuştur. VC yazılımı aktivite surelerini ve en erken başlama zamanlarını vermiştir. Daha sonra, en geç başlama zamanları KYM'nda olduğu gibi geriye doğru hesaplama yapılarak elle bulunmuştur. En erken ve en geç başlama zamanları ile aktiviteler arasındaki öncelik sıraları belirlendiğinden, kaynak dengeleme problemi bir ikili tamsayı matematiksel programı olarak formülize edilmiştir. Kaynak dengeleme probleminin matematiksel formülasyonda, farklı hedef fonksiyonları, aktivitelerin en erken ve en geç başlama zamanları ve aktiviteler arasındaki öncelik sıraları göz önünde bulundurulup, D&S algoritması kullanılarak OPL adi verilen bir yazılımda çözülmüştür. Sonrasında, kaynakların dengelenen çoklu dağılım grafikleri, başlangıçta en erken başlangıç zamanlarına göre hazırlanan grafikler ile karşılaştırılmıştır.

Bu çalışma MTP tekniği ile planlanmış doğrusal inşaat projelerinde kaynakların dengelenmesi için bir matematiksel model önermektedir. Farklı hedef fonksiyonlar için kaynak dengelemesi amacıyla D&S algoritması kullanılmıştır. Vaka çalışmasında, önerilen model detaylı olarak incelenmiş ve yeni bir model geliştirmede kullanılan tüm adımlar gösterilmiştir. Çeşitli hedef fonksiyonların çözümlenmesinden farklı çoklu kaynak dağılım grafikleri elde edilmiş ve bunlar karşılaştırmalı olarak incelenmiştir. Çalışmada, farklı proje bolluklarından elde edilen iki veri seti, farklı hedef fonksiyonlar ile önerilen modelde kullanılmışlardır. Toplam bollukları kullanan veri setleri ile denenen hedef fonksiyonları aşırı hafıza kullanımına bağlı olarak çözüm vermediğinden, toplam bollukların etkisi üzerine bir karşılaştırma ve/veya analiz yapmak mümkün olamamıştır. Ancak, serbest bollukları kullanan veri setleri için farklı hedef fonksiyonlarda detaylı bir inceleme yapılabilmiş, serbest bolluk veri seti için en iyi sonuç çeşitli değerlendirme açılarından gösterilmiştir.

İlaveten görülmüştür ki, MTP daha kolay proje kontrolü ve daha az karmaşıklık içerdiğinden kaynak dengeleme için KYM'na nazaran daha iyi sonuçlar sunmaktadır. Ayrıca, önerilen model, üretim oranları, gerçek aktivite sureleri ve proje sıralama mantığını bozmayan eksiksiz öncelik ilişkileri gibi birçok proje etmeninin göz önünde bulundurduğundan, güvenilir bir kaynak dengeleme aracı olarak ortaya çıkmaktadır.

Sonuç olarak, bu çalışma, kendi ilgili alanına, doğrusal inşaat projelerinin kaynak dengelemesinde dal ve sinir algoritmasının kullanan bir matematiksel model önererek katkıda bulunmaktadır. Bu katkı ileriki çalışmalar ile daha da geliştirilip genişletilebilir.

1. INTRODUCTION

1.1 Background of the Study

In order to fulfill main project objectives such as completing a project on time and within budget, all necessary resources (i.e. crews, equipment, materials, money etc.) for a construction projects should be planned and managed not only properly but also efficiently. Resource planning is of crucial effect on successful project execution, since there is not any real construction project and site that has unlimited resources. Managing and controlling resources cannot be thought apart from the selection of the convenient planning and scheduling technique for the conditions of the project. With the right scheduling and planning method, any project can be managed productively, which is mainly based on effective utilization of resources.

Since each construction project consists of different characteristics, same management, planning and control approaches cannot be used in every project. Therefore, linear scheduling techniques seem to be more appropriate for linear projects. However, there are limited numbers of studies that deal with resource optimization procedures working with linear scheduling techniques.

1.2 Objectives of the Thesis

This study will concentrate on resource leveling of a linear project by using mathematical models. The objectives are:

I. Developing a resource leveling model using branch and bound algorithm for a highway construction project scheduled according to location-based scheduling method.

II. Determining and analyzing the effects of using different objective functions in modeling.

III. Determining and analyzing the impact of considering different type of floats on resources and leveling process.

1.3 Research Methodology

The methodology of this study mainly involves the following steps:

1. Literature study on not only planning and scheduling techniques but also resource management approaches,
2. Obtaining actual data of a real life linear construction project that represent common properties and problems,
3. Identification of linear activities and their resource utilization rates,
4. Calculation of the production rates of each activity,
5. Scheduling the project with location-based planning approach considering precedence relations and resource limitations,
6. Implementation of the mathematical model prepared with integer programming,
7. Analysis of the effects of changing objective function in the mathematical model on different start date intervals calculated in accordance with different project floats.
8. Verification and validation of the model.

1.4 Scope

In this thesis, a mathematical model was formulated with integer programming and branch and bound algorithm for leveling resources of a linear project scheduled using location-based planning method. The format of the study is as below described order.

This chapter describes and states the problem, the objectives of the thesis and the research methodology.

Chapter 2 explains briefly what construction management and planning are and the role and importance of planning in construction management discipline.

Chapter 3 first deals with construction project types, then by explaining currently available planning techniques in the order of their historical development, mentions the importance of choosing appropriate planning technique suitable for the conditions of the project.

Chapter 4 describes resource management approaches used in planning. It mainly focuses on optimization approaches for resources and analyzes resource leveling and objective function criteria in-depth.

Chapter 5 is all about mathematical modeling not in all manners of the topic but for the necessary background information about integer programming and branch and bound method, which are used for the case study.

Chapter 6 starts with the information about the studied project and continues with the detailed analysis of the linear activities, production rates and precedence relations that are used in scheduling process. Later, by emphasizing the main characteristics of the project, selection of the location-based planning methods for scheduling are validated. Moreover, using previously delivered information of the project, an initial construction plan is prepared by location-based scheduling. Continued with start date calculations, latest start dates are calculated with both total and free floats to be used in the mathematical model and resource leveling process. Objective functions, modeling software and developed optimization models are examined in detail and solutions are presented.

Analysis and discussions on the results of the proposed model are mentioned in Chapter 7 with explanatory graphs and resource histograms.

Summary of the research results and recommendations for the future work are placed in Chapter 8 as conclusions.

2. PLANNING IN CONSTRUCTION MANAGEMENT

2.1 Construction Management

Every construction project is idiosyncratic and unique to itself due to the nature of construction industry. Not only locality, complexity and high production costs of construction industry products (i.e. buildings, airports, hospitals coastal structures etc.) but also production process factors such as weather conditions, procurement, and quality create this uniqueness. Since, every construction project is different, particular precautions and methods are required. This requisite increases the importance and necessity of Construction Management (CM) day after day.

According to the Construction Management Association America (CMAA), Construction Management is a professional management practice consisting of an array of services applied to construction projects and programs through the planning, design, construction and post construction phases for achieving project objectives including the management of quality, cost, time and scope (CMAA, 2011). Looking at this explanation it is conspicuous that elements like “time, cost, quality and scope” are indicating factors. The primary focus of CM is to optimize these factors and blend them together to successfully complete projects.

Furthermore, mentioned optimization process consists of 4 major steps, which are Planning, Organization, Management and Control (Newitt, 2009). This order also represents the level of significance of these steps. Organization, management and control tasks for a project cannot be completely fulfilled without a proper, ratiocinated and well-prepared plan.

2.2 Planning

In general, planning can be defined as a process of guiding all parties involved in a project from an idea to the completion, in a satisfactory way (Adeli & Karim, 2001). This guidance makes planning essential, and even vital, for construction industry, which consists of many uncertainties and unknown variables.

In addition, planning is the action of spreading activities over a pre-defined time period, while considering their not only durations but also resource and finance necessities. It is a decision-making support tool prepared for controlling the work plan, detecting deviations from original program and reporting them to the owner/employer with its cause.

As a concept, main purpose and scope of planning is to:

- determine a road map to follow while design and construction phases of a project,
- calculate optimum time, resource and cost values for production,
- compare and contrast actual and planned schedule data for activities,
- establish communication between headquarters and work sites,
- inform administrators with periodic reporting,
- collect and store design and production data to create an archive,
- analyze productivity using the archived data (Kuruoğlu & Özvek, 2009).

It is noticeable that planning is a substantial element of CM and it is important to consider its magnitude at length.

2.2.1 Role and importance of planning in construction management

It is widely assumed that the focus is time when it comes to planning process for construction works. However, focusing only on time brings such consequences as ignoring other important elements of the project objectives and the deterioration of the balance between them. The most important goal of planning and in particular construction management, is to not only consider all of the project elements together but also bring them into balance.

Besides, making a good plan for construction is a tough task because, there are many ways and options to complete a project. Experiences can be useful while planning a construction project; however, due to the previously mentioned uniqueness of each project, a new plan must be developed for every new construction.

Hendrickson & Au (1989) emphasize the significance of planning for construction projects:

“An example from a roadway rehabilitation project in Pittsburgh, PA can serve to illustrate the importance of good construction planning and the effect of technology choice. In this project, the decks on overpass bridges as well as the pavement on the highway itself were to be replaced. The initial construction plan was to work outward from each end of the overpass bridges while the highway surface was replaced below the bridges. As a result, access of equipment and concrete trucks to the overpass bridges was a considerable problem. However, the highway work could be staged so that each overpass bridge was accessible from below at prescribed times. By pumping concrete up to the overpass bridge deck from the highway below, costs were reduced and the work was accomplished much more quickly” (Hendrikson & Au, 1989).

Moreover, the need for controlling project elements requires planning in order to manage construction projects. Therefore, a decent construction plan is expected to:

- reduce total construction time,
- increase profit margin by reducing costs particularly labor,
- provide continuous work flow,
- multiply productivity,
- fulfill the needs of the employer,
- increase the communication between workers (Kuruoğlu & Özvek, 2009).

It is more than obvious that planning has a major role in CM and it is of great significance for construction projects to succeed.

2.2.2 Factors interacting with planning

It is previously mentioned that due to unique properties of each project, a new plan should be established for every time a new work starts. Even if the plans change from one project to another, steps for solid planning are generally same:

- Choice of technology and construction method

- Defining work tasks and quantities
- Estimating resource requirements for activities
- Estimating activity durations
- Defining precedence relationships among activities
- Defining interactions and work flow between crews (Hendrikson & Au, 1989; Polat et al., 2008).

Besides, no matter how a plan is well thought and prepared, there are many project management factors effective on the performance of the established plan. Still, factors such as, *previous experience of project group on similar projects, design details, efficiency of project execution plan, constructability, planning budget and update frequency* are more noteworthy among others (Kog, et al., 1999).

Planning is also a very tough job to do. As Sherlock Holmes noted:

"Most people, if you describe a train of events to them, will tell you what the result would be. They can put those events together in their minds, and argue from them that something will come to pass. There are few people, however, who, if you told them a result, would be able to evolve from their own inner consciousness what the steps were which led up to that result. This power is what I mean when I talk of reasoning backward" (Doyle, 1930).

Like in detective stories, main character, a planner for construction cases, knowing the outcome, must think and find the way that leads to that particular consequence.

3. PLANNING AND SCHEDULING TECHNIQUES

There are always different ways to do things. Men can put on their ties in many different styles. Women also may have different ways for shaping their hair. Each one of these methods of doing things are acceptable and it cannot easily be said that one is superior to another. It is a matter of selection, yet conditions of the current environment or situation should be evaluated for the choice. Windsor style tie knotting may be more appropriate for official events as well as short hair may not be suitable for women with round faces. Deciding on which planning system to be used works the same way.

In developing a construction plan, it is common to adopt a primary emphasis on either cost control or on schedule control as illustrated in Figure 3.1 (Hendrickson & Au, 1989). Some projects are primarily divided into expense categories with associated costs. In these cases, construction planning is either cost or expense oriented. Within the categories of expenditure, a distinction is made between costs incurred directly in the performance of an activity and indirectly for the accomplishment of the project. For example, borrowing expenses for project financing and overhead items are commonly treated as indirect costs. For other projects, scheduling of activities over time is critical and emphasized in the planning process. In this case, the planner insures that the proper precedence among activities is maintained and that efficient scheduling of the available resources prevails. Traditional scheduling procedures emphasize the maintenance of task precedences (resulting in critical path scheduling procedures) or efficient use of resources over time (resulting in job shop scheduling procedures) (Hendrickson & Au, 1989). Finally, most complex projects require consideration of both cost and scheduling over time, so that planning, monitoring and record keeping must consider both dimensions. In these cases, the integration of schedule and budget information is a major concern.

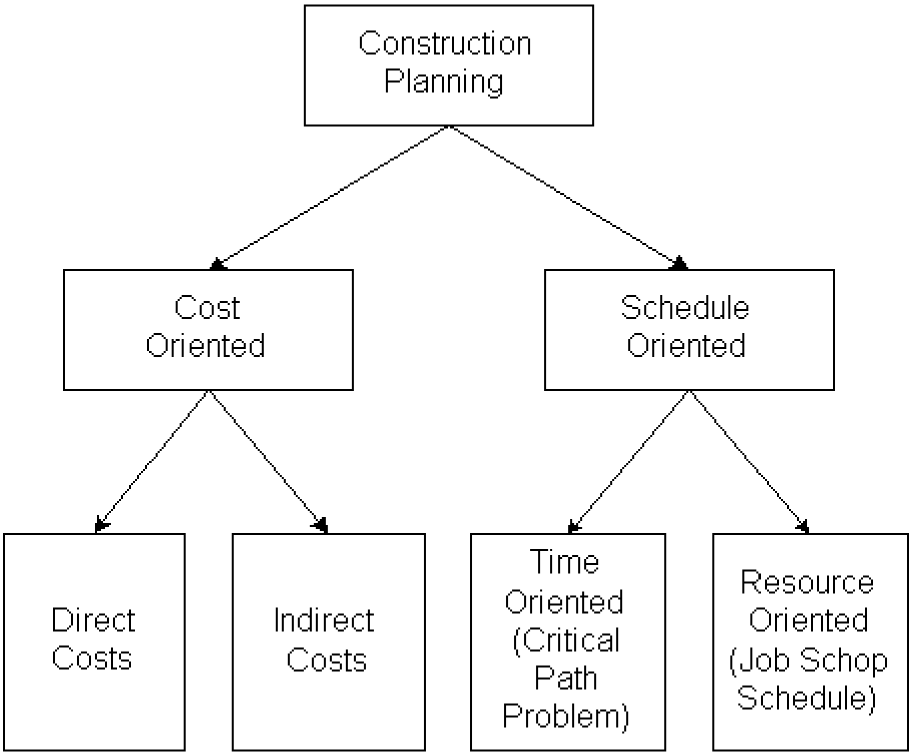


Figure 3.1: Alternative emphases in construction planning (Hendrickson & Au, 1989).

Since, there are several options for planning a project, finding the most suitable system is a tough task to complete. In order to achieve in planning process, becoming familiar with construction project types is essential.

3.1 Construction Project Types

There are many kinds of construction works and these projects can be classified in too many different groups. However, there is also a generally accepted grouping for construction works and divides them into two groups: linear projects and non-linear projects.

3.1.1 Linear projects

Linear projects are both highly repetitive in nature and composed of same types of activities throughout the project. Highway, railway, pipeline, tunnel, high-rise building projects can be given as examples for linear projects and most of the construction projects fall into this group. These projects provide smooth flow of crews and equipment if well planned.

3.1.2 Non-linear Projects

Non-linear projects are of discrete and special production and activities in different sections of the project. It is hard to talk about repeating tasks in non-linear projects. Hospitals, coastal structures, museums are good non-linear project examples.

3.2 Classical Planning Techniques

In a project, each discrete work package is called activity (Callahan et al., 1992). Activity-based planning (ABP) systems can be identified as more traditional approach to planning (Kenley, 2004). These systems focus on the unit of work to be done. Work is considered as series of activities bonded each other only time-wise and activities are evaluated independent from the locations they occur.

According to Kenley & Seppänen (2010), an ideal activity-based schedule is expected to have following properties:

- dominated by discrete locations,
- consisting prefabricated components mostly,
- not allowing simultaneous work to be done and highly sequential,
- having only critical path, chosen from many,
- managing resource time-wise and independent from locations.

However, these characteristics do not well match with the specialties of the construction industry. For instance, instead of prefabricated components, construction works are mostly performed on-site and in contrast to sequential work, projects consist of continuous and repetitive activities mostly.

Despite all of these shortages, dominance of the ABP methods may be the result of the following factors:

- Early publication,
- Absence of alternative methods for many years,
- The acceptance of ABP methods as a requirement for US government projects (Kenley & Seppänen, 2010).

There are two mainstream ABP techniques: Critical Path Method and Program Evaluation and Review Technique.

3.2.1 Critical path method (CPM)

Development of the CPM is dated back to 1950's thanks to the simultaneous studies conducted in both Europe and North America (Kenley & Seppänen, 2010). CPM is based on network diagrams that show entire project as arrows and nodes. CPM uses Work Breakdown Structure (WBS) in order to break entire project down into small packages, increase detail level and make it more manageable and measurable. The main constraint of a schedule is resource in general, however CPM calculation techniques are time-based.

After the network is established forward and backward pass calculations are done in order to reveal the critical path by obtaining earliest and latest activity start dates. Start dates are used to calculate activity floats that are the available time for activities to be done without creating any delays in the total project time. Floats are also used as a measurement of criticality (Callahan et al., 1992). If the maximum time available for a job equals its duration, the job is called critical (Kenley & Seppänen, 2010).

CPM depends on the limitless resource availability assumption, which is the weakest point of CPM, since resources are generally limited in construction projects. Even if the required resources for a project can be provided completely, these necessities cannot be satisfied in a lump but over a certain time period.

3.2.2 Program evaluation and review technique (PERT)

PERT is very similar to CPM, but with a different strategic purpose, and it had specific functionality for the incorporation of variation in job duration as a distribution (Kenley & Seppänen, 2010). The PERT system was designed to be a method to assess a particular schedule, which had been developed by other techniques and which encompassed thousands of activities extending years into the future (Malcolm et al., 1959). PERT is particularly successful in handling multiple project situations, since it is a probabilistic method and construction projects are of various uncertain events and situations. Uncertainity of the project elements makes not only projects hard to predetermine but also PERT a very suitable tool.

3.2.3 Defects of classical techniques and need for a new approach

ABP tools, such as CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique) have been dominantly preferred by construction management professionals and companies around the globe since their introduction in 1950's. Through the years, as the construction, projects have become more complex and the necessities of the industry have increased, these world-renowned methods failed to meet the requirements. Some researchers have realized that CPM based ABP methodology sacrifices efficient use of resources in favor of earliest completion (Arditi et al., 2002a). Furthermore, it is known that ABP techniques are based on limitless resource assumption. Therefore, it has been studied to manage resource requirements and keep resources leveled in a new method called Critical Chain Project Management (CCPM) (Goldratt, 1997). However, due to the birth defects of CPM, on which CCPM also founded, this novel technique could not be the cure. Even when cost driven, or with resource optimization, there is no focus on continuity in ABP way of thinking. It has been clearly seen that ABP techniques, which are not originally developed for building industry but in the military/industrial environment, does not well match the character of construction projects (Kenley & Seppänen, 2010).

3.3 Alternative Planning Techniques

As the shortages of ABP techniques come clear, researches for alternative methods are increased throughout the years and focused on weak sides of ABP techniques and CPM. New systems, considering resource limitations and location orders, are developed.

3.3.1 Line of balance (LoB)

LoB is originally a production scheduling technique, but has found application in construction (Kenley & Seppänen, 2010). Lumsden (1968) defines this method, which was already in use in the UK housing industry. LoB relies on the relationship between quantity of units delivered and the rate of unit production and this is considered as a linear relationship. The technique was originally designed to be a way to handle repetitive construction, where a CPM sub-network, or other logical sub-component, could be modeling as a whole and the effective rate of production of the sub-component indicated as a LoB as the repetitive units repeat. Slope of a line, representing an activity of a task, gives the production rate.

LoB uses time buffers as a risk management strategy. Time buffers provide a margin for error and ensuring that one trade does not interfere with another. The essential function of the time buffer is to minimize the effect of disturbances between adjacent stages such that the planned smooth working of each stage is maintained and full benefits are gained from repetitive working (Lumsden, 1968).

3.3.2 Location-based planning (LBP)

In pursuit of better for the efficient management of resources, location-based planning system emerged as the answer. LBP provides optimum project time by smooth continuous flow of resources through locations (Kenley & Seppänen, 2010). Just like the relation between ABP and CPM, LBP depends on the fundamentals of Line-of-Balance (LoB) method. On the ground that construction projects are in repetitive nature (Lumsden, 1968), a linear scheduling system, which LoB and LBP can offer, is more suitable (Harris et al., 1998; Arditi et al., 2001). To wit, LBP is a resource-based management system tool for planning and controlling continuous workflow by both linear scheduling technique and leveled used of resources (Firat et al., 2009). Another important difference between ABP and LBP is that CPM identifies activity durations as input data whereas optimum activity durations are outputs of planning process of LBP. For each task, resource needs and quantities along with production rates are inserted as input data to LBP and activity durations are calculated (Kenley & Seppänen, 2010).

Although LoB and LBP offers better solutions for construction projects, due to the lack of commercial software it cannot be used and known as much as CPM based ABP methods. For this reason, there have been some studies in North America and four products are developed with the fundamentals of LoB: SYRUS (System for Repetitive Unit Scheduling) (Arditi & Psarros, 1987), RUSS (Repetitive Unit Scheduling System) (Arditi et al., 2001), CHRISS (Computerized High Rise Integrated Scheduling System) (Arditi et al., 2002b) and ALISS (Advanced Linear Scheduling System) (Tokdemir et al., 2006). Besides, LoB method had been better developed in Finland and it had been named Advanced Line-of-Balance (Kiiras, 1989; Kankainen & Sandvik, 1993). ALoB has become primarily used scheduling method in Finland since these advancements. However, most important contribution is the development of commercial software products: DynaRoad and VICO Control (Kankainen & Seppänen, 2003).

3.3.2.1 VICO Control

VICO Control (VC) is the first location-based planning software in construction industry and differs from others with its advanced properties as a scheduling tool. VC allows planners to control risks and increase productivity by workflows. VC produces activity durations as an output using quantities, production rates and precedence relations between activities. It allows planner to see "what-if" scenarios before and throughout the project and simplifies planning process. VC allows seizing a project from different point of views, since it includes Gantt charts, network diagrams and flowline views for every planned project and enables synchronized work on these three views.

VC is used in the case study and will be investigated in detail later.

4. RESOURCE MANAGEMENT IN CONSTRUCTION PLANNING

Effective and efficient use of resources is of utmost importance for successful CM and project planning. Another point to bear in mind is that, activity durations, which are highly attached importance during planning, are defined according to the availability of necessary resources to complete that task (Hinze, 2008). Major items of these resources include construction materials, labor, equipment, contractors, sub-contractors and money of course. In today's world, resources are not limitless and construction projects are subject to limited resources problem like any major economic job. Not taking resource limitations into consideration, makes the plan estranged from reality. On the other hand, evaluating resource limitations and planning resource flows makes plans not only more genuine but also easier to execute.

4.1 Resource-Based Planning

Resource-Based Planning (RBP) is tool to use when both necessary resources for a project are limited and there is a competition between activities for same restricted number of resources (Hendrikson & Au, 1989). Actually, these activities are disposed to delay, because they are obliged to wait until the necessary resources become available. Due to the fact that resources are limited and demand for these resources is high, waiting time may longer than expected. Moreover, waiting creates increases in costs, decrease in productivity and delays at the end of the project (Hendrickson & Au, 1989).

Rules for planning with limited resources can be abridged as (Hinze, 2008):

- An activity should start as soon as its predecessor finishes.
- If there are activities using the same resources more than one, then the one with the earliest late start time should have priority.

- If late start times are the same, then the one with the lowest total float should have priority.

- If total float are same, then the one with the biggest consumption of limited resource should have priority.

- If resource consumptions are the same, then the one has already started should have priority.

- If choosing an activity according to all of the above rules is not possible, then first activity in the time order should have the priority.

4.2 Resource Optimization

In order to consider project risks, resources should always be planned and used efficiently. According to the Kelley (1961), there are three main principles of resource optimization:

1. The logic of the schedule remains valid.

2. There are limits on available resources, which are not exceeded.

3. The duration of the project is minimized.

4.2.1 Limitations

The principles defined by Kelley (1961), also shapes the two primary limitations of resource optimization: *time-limited resource scheduling (TLRS)* and *resource-limited resource scheduling (RLRS)*.

4.2.1.1 Time-limited resource scheduling

In TLRS, main priority of the scheduling process is not to exceed total project duration or milestone (if any). Available resources are used to their maximum if necessary in order to adjust the schedule to the time limitations. However, planner uses activity floats to not only level resource consumption but also create a balanced and flexible plan (Kenley & Seppänen, 2009).

4.2.1.2 Resource-limited resource scheduling

In RLRS, matching resource constraints and keeping consumption within these limits is indispensable. Even the project completing date can be deferred in order to stay in resource limits.

4.2.2 Basic methods

Kelley (1961) also offered two basic approaches for resource optimization. These two methods are expanded later by other researchers and lead resource planning to the different optimization methods.

4.2.2.1 Serial method

Serial method orders activities that the one with the earliest late start date comes first. The action assumes that none of the activities would be interrupted and all predecessors are completed. Resources are assigned to activities aiming to use available free floats (Griffis & Farr, 2000; Kenley & Seppänen, 2009).

4.2.2.2 Parallel method

Unlike the serial method, activities can start at the same time in parallel method. Besides, if resource consumption comes to the limits and resources are not adequate, activities can be paused until necessary resources are released from other activities (Griffis & Farr, 2000).

4.2.3 Resource optimization approaches

In due course, five methods developed over the Kelley basic methodology. These methods are *aggregation, cumulation, allocation*, *smoothing and leveling.*

4.2.3.1 Aggregation

Resource aggregation is simply the calculation of the required resources of activities on a periodical basis. The desired period can be chosen as an hourly, daily or weekly period, depending on the resource-time relation units.

If bar charts are selected for planning, the resource aggregation is simple. For every given bar chart, there can only be a specific resource aggregation graph as a resource histogram. An example can be seen in Figure 4.1 below. The total number of resource units for each time period can be summed and a resource aggregation or load chart can be drawn as in the example (Url – 1).

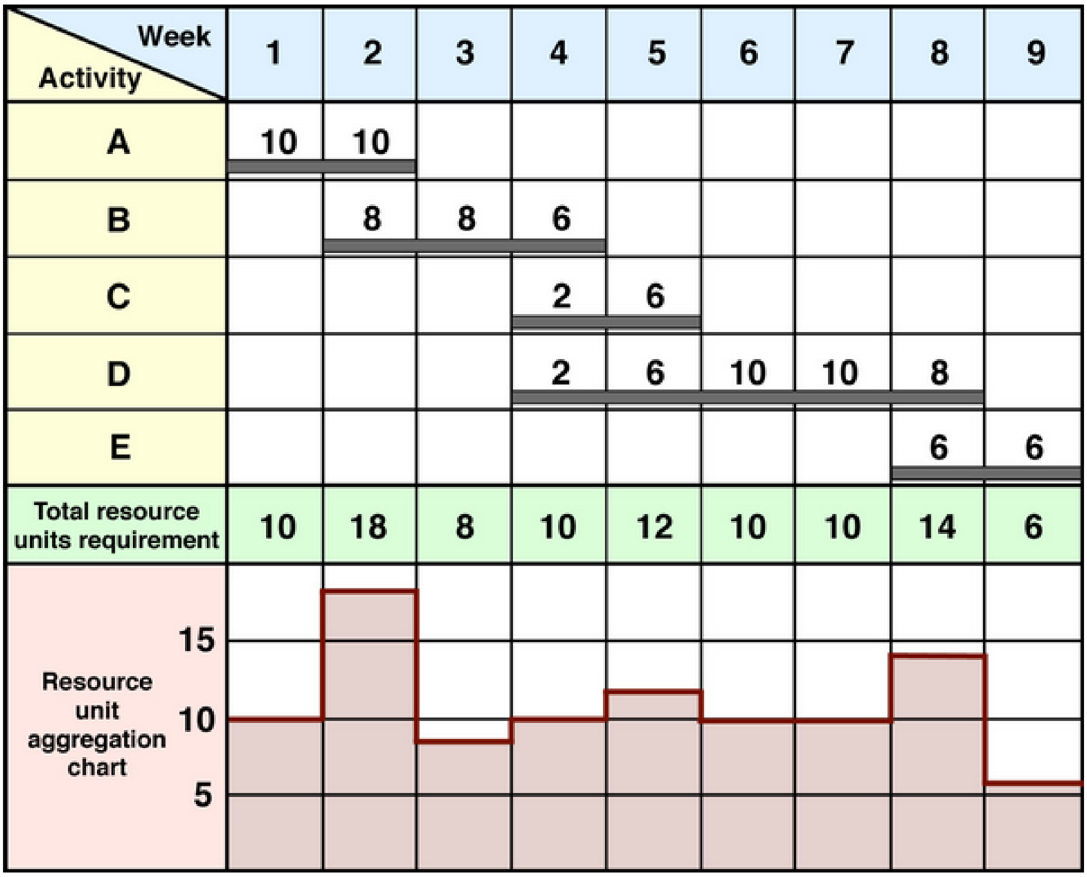


Figure 4.1: Resource unit aggregation chart derived from a bar chart (Url – 1).

On the other hand, if network diagrams were preferred for planning, resource aggregation process would be more complex to complete. Due to the fact that networks are not time-scaled planning tools, establishing relationships between activities on the network and their resource needs is a task that cannot be achieved directly. For this reason, a table containing resource utilization, earliest and latest start times of every activity should be prepared in order to draw resource aggregation graph. The resource usage rates for earliest and latest start times of activities differ and this differentiation can be identified on resource histogram and necessary adjustments can be made. An example can be seen in Figure 4.2 below, containing earliest and latest activity starts and critical activities (Url – 1).

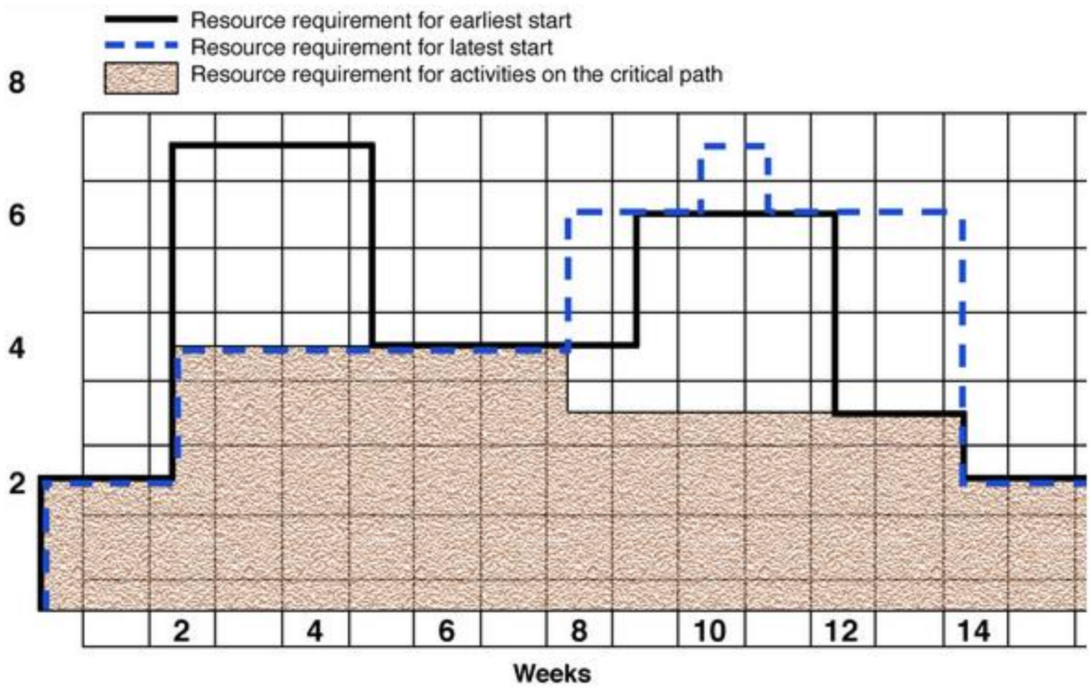


Figure 4.2: Resource unit aggregation chart showing resource requirements associated with earliest and latest start along with highlighted resource unit requirements for critical path activities (Url – 1).

4.2.3.2 Cumulation

Slightly different from aggregation, cumulative total number of resource requirement or usage is calculated progressively throughout the every period for resource cumulation. On the other hand, similar to the aggregation method, cumulation graphs can also prepared for both earliest and latest start dates (Kenley & Seppänen, 2010).

Table 4.1: Aggregation and cumulation of resources by earliest and latest start dates (Kenley & Seppänen, 2010).

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Earliest Start															
Aggregate	4	4	8	5	4	4	2	2	2	2	2	2	1	1	1	1
Cumulative	4	8	16	21	25	29	31	33	35	37	39	41	42	43	44	45
	Latest Start															
Aggregate	1	4	5	5	1	1	4	4	4	4	2	2	2	2	2	2
Cumulative	1	5	10	15	16	17	21	25	29	33	35	37	39	41	43	45

There are number of reasons for using resource cumulation (Kenley & Seppänen, 2010):

- This method enables strict stock control of non-renewable resources. By seeing the cumulation of non-renewable resource utilization and comparing cumulative usage amounts with stock values, it is easier to manage resource deliveries and keeping work stability.

- The actual resource utilization data can be checked using the resource envelope shown in Figure 4.3. The resource envelope is the area between earliest and latest start cumulation graphs. Project's resource usage is expected to occur inside this area and this graph makes it easier to control resource utilization throughout the project.

- Resource cumulation charts may be used for earned value analysis of either resources or money, since money can also be accepted as a special type of resource. Cash flow and cumulative cash flow charts can also be identified as resource cumulation graphs.

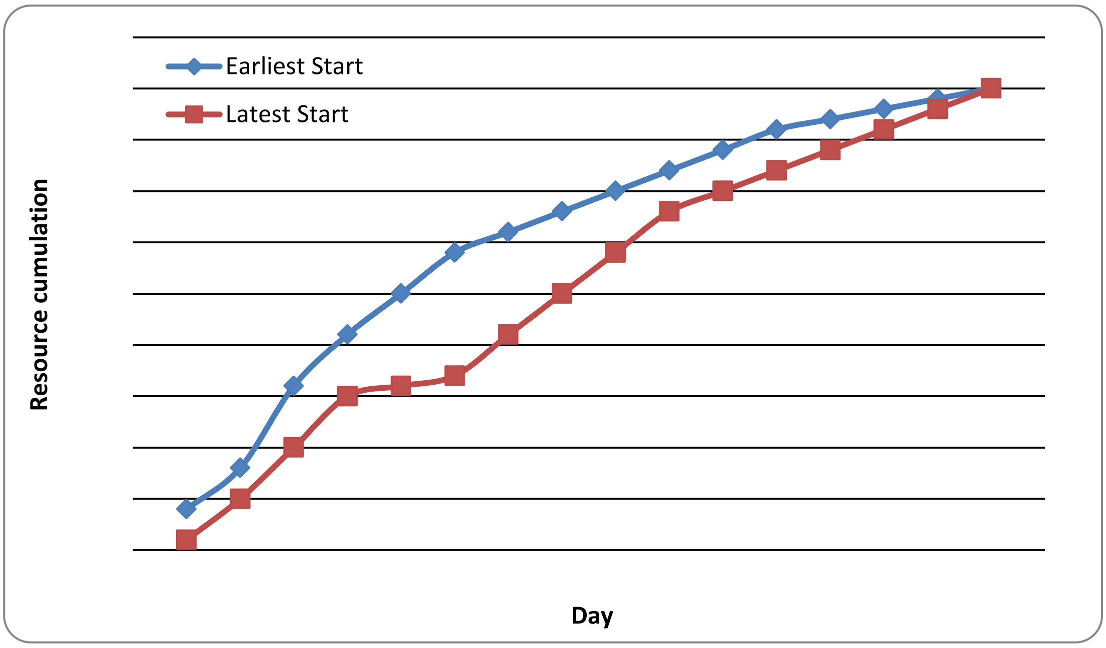


Figure 4.3: Early and late cumulative resource profiles showing the resource envelope (Kenley & Seppänen, 2010).

4.2.3.3 Allocation

Resource allocation, also called resource loading, is the process of assigning available resources to the activities of the project (Url - 1). Allocation does not have to follow a constant pattern and this action may take place in several different ways, since there are many options for deciding activity and/or resource orders. There may be some activities using same type of resources but also different kinds of resources may be needed to accomplish one task. Allocation decisions depend on several discrete factors such as availability of resources, costs, stock status, delivery time etc.; on the other hand, results of each option should be evaluated.

Basically, resource allocation operation is executed by previously mentioned Serial and Parallel methods of Kelley (1961). However, describing the resource allocation methodology in detail may be useful. As a basis, Forman & Selly (2002) offer a five-step methodology for determining the resource allocation strategy:

1. Determining and/or creating different options
2. Determining the purposes of the project and also allocation process
3. Identifying the objectives and sub-objectives
4. Evaluating every possible alternative's results to each of the lowest level sub-objectives
5. Deciding on the best combination considering every possible effect on the environment and the project

A systematic methodology like above-mentioned one should be followed in order to rationally allocate resources throughout the project.

4.2.3.4 Leveling

Leveling is a kind of resource allocation, which aims to spread resource utilization rates throughout the schedule in order to get a uniform level of resource usage (Kenley & Seppänen, 2010). Main purpose of leveling process is to sleek the resource histogram which means elimination of peaks and troughs in resource utilization. To make it more clear, leveling process can be liken to the game of

Tetris. The aim of the game is to create slick levels by moving and rotating downthrown blocks in different shapes. A player aiming filling layers for smoother surfaces controls the movements of the block. Gordon and Tulip (1997) identify smoothing cycle as a four-step process, which has to be repeated until all resources are allocated to activities:

1. Schedule activities are of criticality.
2. Find the most important activity within the remaining unscheduled activities.
3. Schedule this activity in most suitable time and place.
4. Adjust the earliest and latest start dates of the remaining activities considering both the last scheduled activity and resource utilization impacts.

Besides, resource leveling also deals with resource over-allocation, which means it is also the process that guarantees resource usage remains in available limits (Url – 1).

As it is seen in Figure 4.4, bar chart are time scaled which makes them more advantageous than network diagrams for not only detecting over-allocations but also leveling resources, since resource leveling must be evaluated within a time frame.

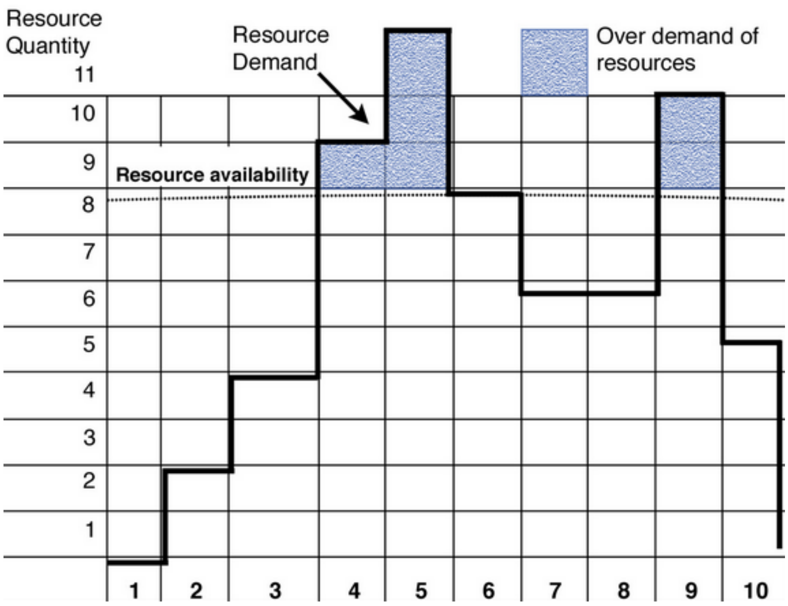


Figure 4.4: Resource demand compared to resource availability (Url – 1).

Resource over-demand problems can be solved by several actions while using bar charts, such as (1) delaying the start of certain activities, (2) splitting task to satisfy resource limits or (3) extending activity durations to reduce resource demands (Url – 1; Url – 2). However, one shortage of bar charts as a leveling tool is that they cannot display interdependencies of activities. Therefore, actions like delaying, splitting or extending activities cannot be possible due to precedence relations between activities. Accordingly, using algorithms and more advanced planning techniques than graphic methods for such complicated issues may result better in advance.

Furthermore, one of the most important facts about the leveling process is that project's time limitations should also be considered along with resource constraints. Because it is important to keep total project completion time as it is, while dealing with resource utilization to create most balanced and evenly distributed usage. If these actions create any changes in completion duration of the project then it would be allocation not leveling. It is always have to be kept in mind that leveling is to change activity orders in accordance with precedence relations, in order to make resource usage rates leveled within the same total project time.

Resource Leveling Criteria

Leveling resource utilization of a project was defined in many different ways by some researchers. This diversity stems from the variation of the selected leveling criteria that shapes the objective of the study and the leveling process.

According to Wagner et al. (1964), Popescu (1976) and Mattila (1997), there are nine different criteria for resource leveling as shown in Table 3.2. First six of these are suitable for linear programming methods and can be formulated with linear equations, whereas the remaining three are non-linear objectives and use quadratic equations.

Table 4.2: Resource leveling criteria

Objective No.	Leveling Criteria
1	Minimization of the sum of the absolute deviations in daily resource usage
2	Minimization of the sum of only the increases in daily resource usage from one day to the next
3	Minimization of the sum of the absolute deviations between daily resource usage and the average resource usage
4	Minimization of the maximum daily resource usage
5	Minimization of the maximum deviation in daily resource usage
6	Minimization of the maximum absolute deviation between daily resource usage and the average resource usage
7	Minimization of the sum of the square of daily resource usage
8	Minimization of the sum of the square of the deviations in daily resource usage
9	Minimization of the sum of the square of the deviations between daily resource usage and the average resource usage

5. MATHEMATICAL MODELING

A mathematical model is formulated in order to represent a system to solve a specific problem. Mathematical concepts, variables and equations are used to create the model. The values that are known and input to the model are called parameters. The variables, which determine the solution of the problem and are to be determined, are called decision variables. The equations for various descriptions in the model are called constraints. Finally, the function that represents the main purpose of the proposed model is called the objective function (Wolsey, 1998).

The area that is captured by the constraints of a mathematical model is called the feasible region of the model. Any solution that satisfies all of the constraints of a mathematical model is included in this region and any such solution is called a feasible solution. Among such feasible solutions, the solution that gives the best objective function value (if the problem has an objective function with minimization, the best value would be the minimum value and vice versa), is called the optimum solution to the problem. The corresponding objective function value is called the optimum value of the objective function.

There are many types of mathematical models used in various applications. Some examples to these models are linear programming models, nonlinear programming models, integer programming models, dynamic programming models and stochastic models. There are many advantages and disadvantages to using mathematical models (Wolsey, 1998). The greatest advantage is that they are easy to formulate and usually easy to solve. There are many software packages developed to solve mathematical models. In this study, Optimization Programming Language (OPL) is used for this purpose. On the other hand, as the name “model” suggests, they are merely representations of the real system so they can never grasp the details and probabilistic nature of the system completely. Because of this reason, the solutions that are obtained from the mathematical models give the closest approximations to real life situations; however, it is important to keep in mind that they are not perfect answers to the problems that are faced in real life.

5.1 Integer Programming Models

In order to stay within the scope of this study, the focus will be on Integer Programming models and solution techniques. The difference between Linear Programming (LP) models and Integer Programming (IP) models is that in LP models, the decision variables represent continuous, real numbers whereas in IP models, the decision variables take integer values (Wolsey, 1998). Examples of a Linear Programming Model (Formulation 1) and Integer Programming Model (Formulation 2) are given as follows:

Formulation 1 – Linear Programming Model:

$$minimize\ x_1 + 2x_2 \quad \textbf{(5.1)}$$

$$x_1 + x_2 \geq 1 \quad \textbf{(5.2)}$$

$$x_1 \in R^+ \quad \textbf{(5.3)}$$

$$x_2 \in R^+ \quad \textbf{(5.4)}$$

Formulation 2 – Integer Programming Model:

$$minimize\ x_1 + 2x_2 \quad \textbf{(5.5)}$$

$$x_1 + x_2 \geq 1 \quad \textbf{(5.6)}$$

$$x_1 \in Z^+ \quad \textbf{(5.7)}$$

$$x_2 \in Z^+ \quad \textbf{(5.8)}$$

In these models, the variables x_1 and x_2 are the decision variables. Expressions 5.1 and 5.5 represent the objective functions for formulations 1 and 2 respectively. The rest of the equations are the constraints for these models. When these models are examined, it is noticed that the only differences are observed between equations 5.3 & 5.7 and 5.4 & 5.8. The symbol, R^+ used in constraints 5.3 and 5.4 represent the set of positive real numbers whereas; Z^+, used in constraints 5.7 and 5.8, represent the set of positive integers. Constraints 5.7 and 5.8 are usually referred to as the integrality constraints whereas constraints 5.3 and 5.4 are usually called the nonnegativity constraints (Wolsey, 1998).

An example of a Binary Integer Programming model is as the following:

Formulation 3 – Binary Integer Programming Model:

$$minimize\ x_1 + 2x_2 \quad \textbf{(5.9)}$$

$$x_1 + x_2 \geq 1 \quad \textbf{(5.10)}$$

$$x_1 \in B \quad \textbf{(5.11)}$$

$$x_2 \in B \quad \textbf{(5.12)}$$

In formulation 3, constraints 5.11 and 5.12 are the binary integrality constraints and B represents set of binary variables (zero or one).

If, in a model, both integer and continuous decision variables are present, then that model is a Mixed Integer Programming (MIP) model. Moreover, if the decision variables in an IP model are binary variables; i.e. variables that can take a value of either zero or one, then, the model is called a Binary Integer Programming (BIP) model.

Among the different types of models, LP models are usually the easiest ones to solve. The reason for this is that the feasible regions of such problems form a polyhedron and it is easy to find the optimum value by only checking the corners (extreme points) of the feasible region. A very commonly used method for solving LP models is called the Simplex Method, which has the very simple idea of checking those corner points. On the other hand, the IP models are much difficult to solve since the feasible region is constrained by integer points and it is not enough to check the corner points to reach a feasible or optimal solution. For this reason, many heuristics and solution methods have been developed to solve IP models. The most commonly used method for solving Integer Programming models is called the Branch & Bound method and this method will be explained in the next section.

5.2 Branch & Bound (B&B) Method

5.2.1 Linear programming relaxations of integer programming problems

A Linear Programming (LP) Relaxation of an Integer Programming (IP) model is obtained by removing the integrality constraints from the IP and replacing them with nonnegativity constraints. In this context, formulation 1, given above, is the LP relaxation of formulation 2. If the problem is a Binary Integer Programming problem, the binary integrality constraints are replaced with [0,1] bounds. Hence, the LP relaxation of formulation 3 becomes:

Formulation 4 – Relaxation of Binary Integer Programming Model:

$$minimize\ x_1 + 2x_2 \quad \textbf{(5.13)}$$

$$x_1 + x_2 \geq 1 \quad \textbf{(5.14)}$$

$$0 \leq x_1 \leq 1 \quad \textbf{(5.15)}$$

$$0 \leq x_2 \leq 1 \quad \textbf{(5.16)}$$

It has been stated before that LP models are usually easier to solve than any type of IP models. Hence, the LP relaxation of an IP model can usually be solved in an easier and faster way than the corresponding IP models; however, it is not necessarily true that the optimal solution of the LP relaxation model is also optimal, or even feasible, for the IP model. However, this relaxation idea forms the basis of Branch and Bound method.

5.2.2 The theory behind B&B method

Any integer programming model can be solved by complete enumeration. Complete enumeration means generating all possible, feasible solutions for the model, calculating the objective function values for all those models, comparing them and picking the solution that gives the best objective function value (Wolsey, 1998). However, for large problems, the number of possible solution grows exponentially, hence, it becomes very difficult, if not impossible, to generate all those possible solutions. The next idea that comes to mind is that of a Partial Enumeration. Branch and Bound method uses the idea of Partial Enumeration by a “divide-and-conquer” approach. The basic idea is to divide the larger problem into a series of smaller problems and solve those smaller problems to obtain information about the original problem. This is usually represented via an enumeration tree. For example, if there are two binary variables in the model; say x_1 and x_2, the enumeration tree is as shown in Figure 5.1.

In Branch and Bound method, the name “Branch” comes from this enumeration tree approach. At each node, the LP relaxation of the IP problem is solved considering the variables that branching is made upon. For example, if Figure 5.1 is considered, S1 refers to the LP relaxation of the original IP problem with the additional constraint of the variable x_1 being equal to zero.

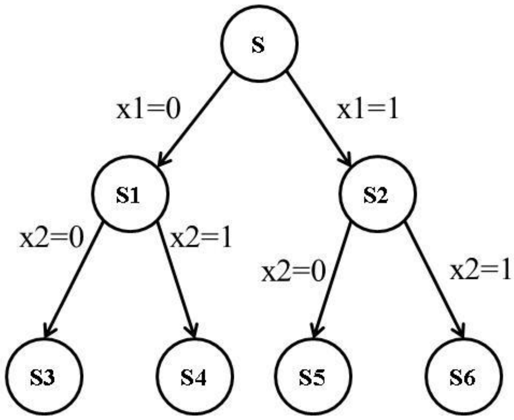


Figure 5.1.: An example enumeration tree.

Since Branch and Bound method only utilizes partial enumeration, the branches are stopped, or "fathomed" before the complete enumeration scheme is generated. This fathoming process occurs in one of the following three ways:

- Fathomed by optimality:

  If, at any node in the tree, the solution of the LP relaxation problem gives an integer solution, then, that solution is the optimal value of that specific branch. Hence, that branch can be fathomed. The corresponding value of the objective function is called the incumbent value. The incumbent is updated whenever a better solution is obtained.

- Fathomed by bound:

  If, at any node in the tree, the obtained value of the objective function for the LP relaxation is worse than that of a previously obtained feasible solution, then, there is no need to continue working on that branch; hence, the branch can be fathomed.

- Fathomed by infeasibility:

  If, at any node in the tree, the LP relaxation problem has no feasible solutions, then that branch can be fathomed.

These ideas will now be illustrated with an example.

5.2.2.1 An illustrative example

Consider the following Integer Programming Problem:

$$maximize\ x_1 + x_2 \quad \textbf{(5.17)}$$

$$x_1 + x_2 + x_3 \leq 1.5 \tag{5.18}$$

$$x_1 \in B \tag{5.19}$$

$$x_2 \in B \tag{5.20}$$

$$x_3 \in B \tag{5.21}$$

The corresponding LP relaxation, which is represented as problem S, is as follows.

$$\text{maximize } x_1 + x_2 \tag{5.22}$$

$$x_1 + x_2 + x_3 \leq 1.5 \tag{5.23}$$

$$0 \leq x_1 \leq 1 \tag{5.24}$$

$$0 \leq x_2 \leq 1 \tag{5.25}$$

$$0 \leq x_3 \leq 1 \qquad \textbf{(5.25)}$$

Hence, the series of LP relaxation problems along with the corresponding enumeration tree are as follows:

Problem S:

Optimal solution: x_1=1 x_2=0.5 x_3=0

Optimal value of the objective function: z=1.5

Problem S1: (x_1=0)

$$\text{maximize } x_2 \tag{5.26}$$

$$x_2 + x_3 \leq 1.5 \tag{5.27}$$

$$0 \leq x_2 \leq 1 \tag{5.28}$$

$$0 \leq x_3 \leq 1 \tag{5.29}$$

Optimal solution: x_1=0 x_2=1 x_3=0

Optimal value of the objective function: z=1

Fathom by optimality. Incumbent =1

Notice that x_3 can actually take any value between 0 and 0.5 since it does not affect the objective function. However, the value of zero is chosen for the sake of obtaining an optimal solution.

Problem S2: (x_1=1)

$$\text{maximize } 1 + x_2 \quad \textbf{(5.30)}$$

$$1 + x_2 + x_3 \leq 1.5 \quad \textbf{(5.31)}$$

$$0 \leq x_2 \leq 1 \quad \textbf{(5.32)}$$

$$0 \leq x_3 \leq 1 \quad \textbf{(5.33)}$$

Optimal solution: x_1=1 x_2=0.5 x_3=0

Optimal value of the objective function: z=1.5

Problem S3: (x_1=1 & x_2=0)

$$\text{maximize } 1 \quad \textbf{(5.34)}$$

$$x_3 \leq 0.5 \quad \textbf{(5.35)}$$

$$0 \leq x_3 \leq 1 \quad \textbf{(5.36)}$$

Optimal solution: x_1=1 x_2=0 x_3=0

Optimal value of the objective function: z=1

Fathom by optimality. Incumbent =1

Notice that x_3 can actually take any value between 0 and 0.5 since it does not affect the objective function. However, the value of zero is chosen for the sake of obtaining an optimal solution.

Problem S4: (x_1=1 & x_2=1)

$$\text{maximize } 2 \quad \textbf{(5.37)}$$

$$x_3 \leq -0.5 \quad \textbf{(5.38)}$$

$$0 \leq x_3 \leq 1 \quad \textbf{(5.39)}$$

Fathom by infeasibility; the problem has no feasible solution.

Since all the branches are fathomed, the best incumbent value and the corresponding solution are taken to be the optimal objective function and optimal solution to the original problem. In this problem, two branches gave the same incumbent values. Hence, an alternative optima have been obtained.

Optimal objective function value = 1

Optimal solutions: x_1=0 x_2=1 x_3=0 OR x_1=1 x_2=0 x_3=0

The corresponding enumeration tree is given in Figure 5.2.

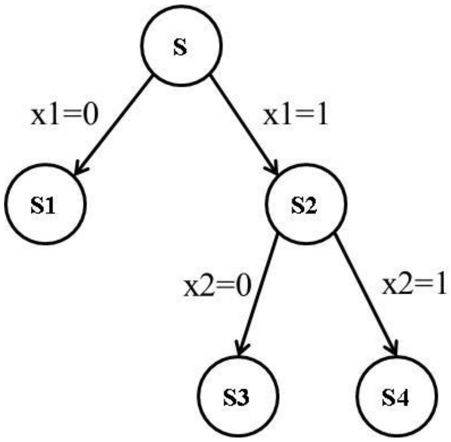


Figure 5.2: The enumeration tree for the illustrative example.

6. CASE STUDY

Previous chapters of the study dealt with general planning and resource management processes along with planning systems and resource leveling in depth. Construction project types and their relationship with appropriate planning systems were mentioned. In addition, the B&B algorithm as an optimization tool was also investigated.

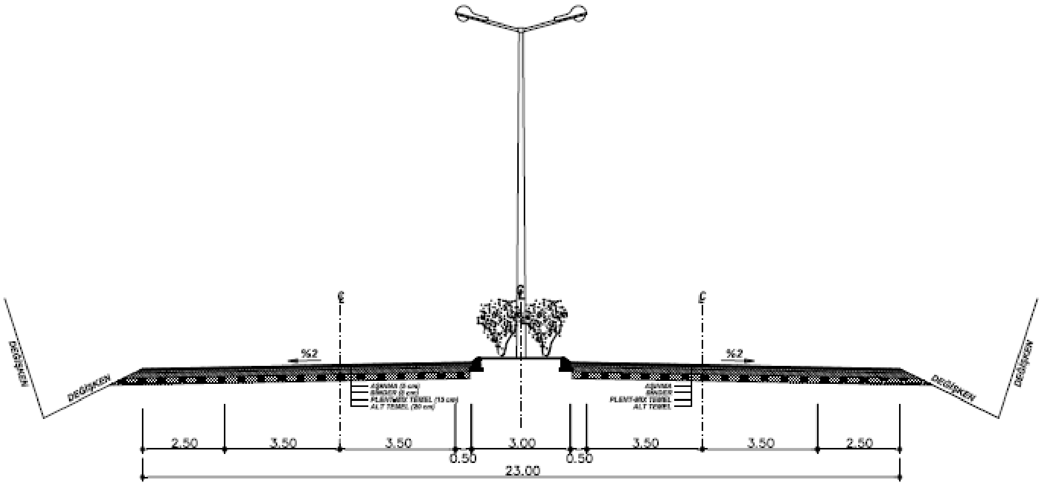
In this part of the study, using and blending in all the information previously described, an asphalt highway project will be examined from planning and resource leveling point of view in detail. Actual data of quantities, resources (i.e., equipment), and production rates were obtained from this real life highway project. Moreover, a location-based plan was established in accordance with precedence relations to obtain earliest start dates of activities. Later, latest start dates were calculated manually to use in optimization process and an integer-programming model is established and solved with B&B algorithm. In this study, the number of trucks utilized throughout the project was aimed to be leveled. Output of the model solution is analyzed and results were maintained.

6.1 Project Information

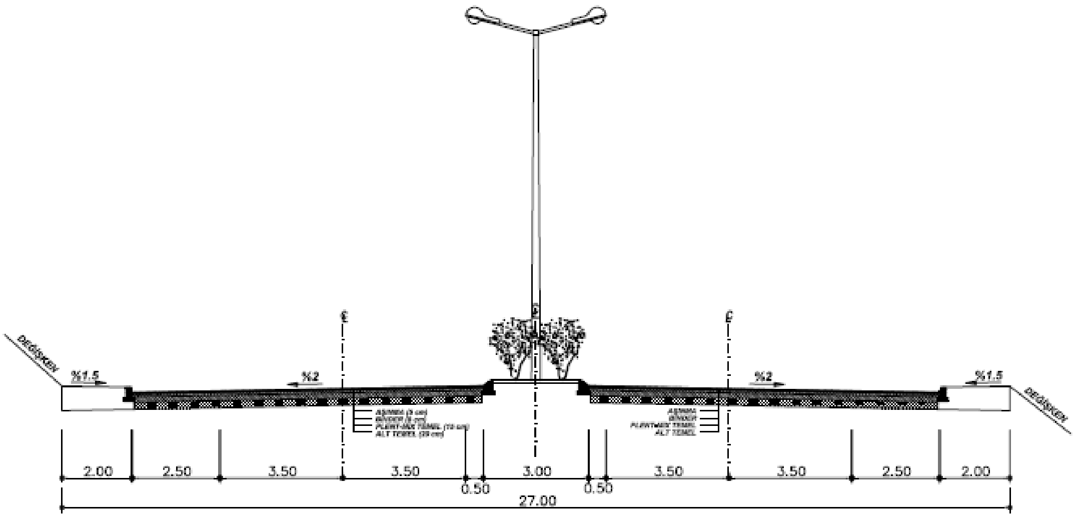
The project subject to case study is a 9.7 km long asphalt highway construction project and was built in Sakarya, Turkey, in 2011. Width of the highway is 23 m for the first 8.4 km and 27 m for the remaining 1.3 km as it can be seen in Figure 6.1.

There are two lanes on both directions of the highway, each 3.5 m wide and 2 x 3,5 = 7 m for one direction. In addition, width of 2.5 m highway is included as safety lanes on both sides, along with 2 m for pavement in 27 m wide section. Besides, there is a 4 m wide zone as refuge consisting lightning and planting.

In the following, activities constituent the highway project will be identified along with their total quantities in the project. Besides, the location breakdown structure of the real-life project will be explained.



(a)



(b)

Figure 6.1: Highway cross-sections for (a) 23 m width (b) 27 m width.

6.1.1 Tasks and quantities

Project consists of four different layers, which are:

I. Subbase II. Plantmix III. Binder IV. Wearing

In addition to production of these mentioned layers, drainage pipes were installed after the completion of subbase layer production. Therefore, these tasks follow the order shown in Figure 6.2.

Figure 6.2: Tasks in the order of production.

These layers are of various depths and the layer sections of the project are as in Figure 6.3.

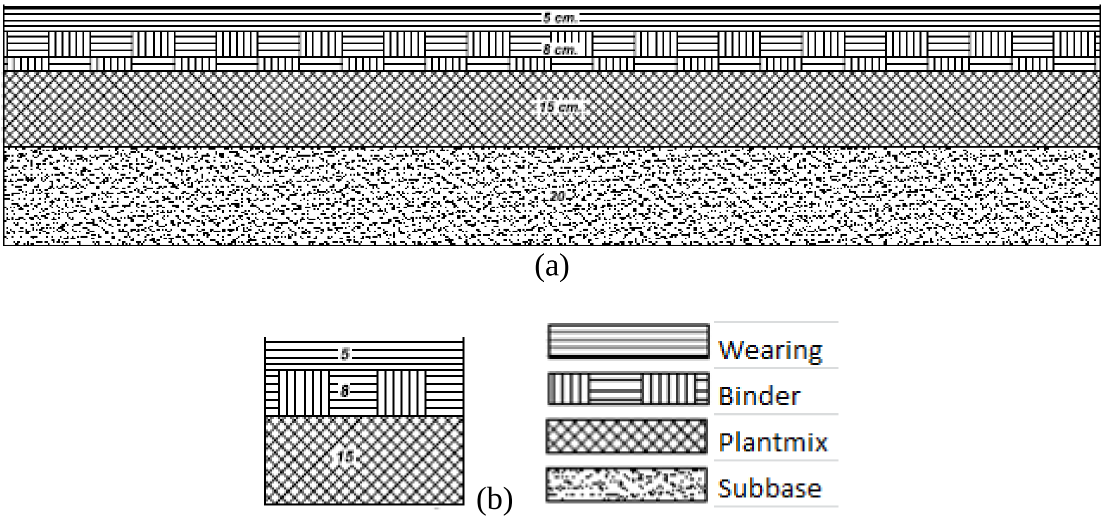


Figure 6.3: Layer sections (a) in first 8.4 km (b) in remaining 1.3 km.

Subbase layer production took place only in the first 8.4 km of the project. Other layers, plantmix, binder and wearing, along with drainage pipes installation, were conducted throughout the entire project.

Since the project is highway construction, it is highly linear and repetitive in nature. Above-mentioned layers of the highway, along with drainage, were constructed in same order but with different quantities throughout the entire project. Quantities of the each task were calculated in detail, by taking roof slope of the highway into consideration and total quantities of these activities are as in Table 6.1.

Table 6.1: Total quantities of asphalt highway construction works.

Activity Name	Quantity	Unit
Subbase layer	39.000,00	m3
Drainage pipes	5.415,00	m
Plantmix layer	30.500,00	m3
Binder layer	196.150,00	m2
Wearing layer	193.760,00	m2

6.1.2 Location breakdown structure

As it is mentioned in Chapter 3, by dividing complete project into smaller logical work groups, not only increased project control but also continuous work flow is aimed. For linear projects, especially for highway projects, as in this case study, breaking entire work package down into locations, preferably mostly equal and continuous stations, improves the sharpness of the planning process and makes it a far easier objective to achieve.

Project was conducted as sections of 500 m each and a location breakdown structure (LBS) was prepared in accordance with actual data obtained from the real-life project as shown in Table 6.2.

Table 6.2: LBS with distance information.

Location No.	Location distance (m)
1	0 - 500
2	500 - 1000
3	1000 - 1500
4	1500 - 2000
5	2000 - 2500
6	2500 - 3000
7	3000 - 3500
8	3500 - 4000
9	4000 - 4500
10	4500 - 5000
11	5000 - 5500
12	5500 - 6000
13	6000 - 6500
14	6500 - 7000
15	7000 - 7500
16	7500 - 8000
17	8000 - 8380
18	8380 - 8400
19	8400 - 8900
20	8900 - 9400
21	9400 - 9710

At 18th location there is the bridge construction works, therefore this location is limited with 20m in order to contain only bridge works. Remaining distance was again divided into 500 m sections and last location, 21th, had the remaining 310 m part only.

6.2 Construction Methodology

Previously mentioned layers of the highway project were constructed with different sets of equipment and crews, hence had different production rates. In accordance with tools and workers, production rates of each activity will be calculated in this section of the study.

Moreover, the precedence dependencies between tasks will also be analyzed in detail, due to the importance of these relations while creating solid plans.

6.2.1 Production rates

Production rate for each activity differs due to equipment and crews working on that task. Therefore, production rates of activities were calculated separately in accordance with the info taken form the company. Activities using same equipment and crews naturally have same production rates.

6.2.1.1 Subbase and plantmix layers

Subbase is the laid and compacted layer over the superstructure base resulted from cut or fills with completed thin grading, in accordance with the projects, profiles and cross-sections. Materials to be used in subbase layer production are sand, gravel, terrace gravel, deteriorated rock, slag, crushed stone etc. (RTGDH Technical Specification, 2006).

Plantmix layer is prepared by mixing materials such as crushed gravel, crushed slag, crushed stone, fine aggregate within the specified gradation limits in a way that at least three separate coarse and fine grain size groups with the appropriate amount of water gives gradation constantly. This prepared plantmix material, is laid and compacted in layers of one of more than once, over the completed, adjusted and given the necessary slope, subbase layer in accordance with defined projects, profiles and cross-sections (RTGDH Technical Specification, 2006).

Subbase and plantmix layer productions use same equipment and crews, as a result of this fact these two activities have same production rates.

Required Equipment:

- 1 Mechanical plant (400tons/hour)
- 1 Loader
- 1 Weighing machine

For laying and ramming:

- 1 Finisher
- 1 Pneumatic-tired roller
- 2 Iron drum rollers

For transportation:

- 16 Trucks

Required Crew:

- 1 Operator for plant
- 1 Operator assistant
- 1 Operator for loader
- 1 Oiler
- 1 Weighing personnel

For laying and compacting:

- 1 Operator for finisher
- 1 Operator for pneumatic-tired roller
- 2 Operators for iron drum rollers
- 5 Unskilled workers

For transportation:

- 16 Truck drivers

Laboratory Crew: 2 people

Surveyor Crew: 3 people

Production assumptions and averages:

1. There is a borrow pit 10 km away.
2. Trucks used in transportation, can make 8 trips a day to the disposal area.
3. Each truck can carry 25 $tons$ of load for a trip.

Production calculations:

$$Mechanical\ plant\ production\!: \ 400\,\frac{tons}{hour} \times 8\,\frac{hours}{day} = 3200\,\frac{ton}{day}$$

$$Number\ of\ trips\ for\ a\ day\!: 3200\,\frac{tons}{day} \div 25\,\frac{ton}{trip} = 128\,\frac{trips}{day}$$

$$Required\ number\ of\ trucks\!: 128\,\frac{trips}{day} \div 8\,\frac{trips}{truck} = 16\,\frac{trucks}{day}$$

$$1\ m^3\ Subbase = \ 1{,}8\ Tons$$

$$Daily\ subbase\ production\!: 3200\,\frac{tons}{day} \div 1{,}8\,\frac{tons}{m^3} = 1777{,}78\,\frac{m^3}{day}$$

$$1\ m^3\ Plantmix\ weighs\ 1{,}9\ Tons$$

$$Daily\ plantmix\ production: 3200\frac{tons}{day} \div 1{,}9\frac{tons}{m^3} = 1684{,}21\frac{m^3}{day}$$

6.2.1.2 Binder and wearing Layers

Binder and wearing layers are produced by mixing crushed and sieved coarse aggregate, fine aggregate and mineral filler with bituminous binder in an asphalt plant, within particular gradation limits according to the principles of mixture formula. This mixture is applied over sufficient bases, bituminous or concrete coatings as one or more layers in a hot state in accordance with defined projects, profiles and cross-sections (RTGDH Technical Specification, 2006).

Binder and wearing layer productions use same equipment and crews, as a result of this fact, these two activities have same production rates.

Required Equipment:

- 1 Asphalt plant (200 tons/hour)
- 1 Loader
- 1 Weighing machine

For laying and ramming:

- 1 Finisher
- 1 Pneumatic-tired roller
- 2 Iron drum rollers

For transportation:

- 8 Trucks

Required Crew:

- 1 Operator for plant
- 1 Operator assistant
- 1 Operator for loader
- 1 Oiler
- 1 Weighing personnel

For laying and compacting:

- 1 Operator for finisher
- 1 Operator for pneumatic-tired roller
- 2 Operators for iron drum rollers
- 5 Unskilled workers

For transportation:

- 8 Truck drivers

Laboratory Crew: 2 people

Surveyor Crew: 3 people

Production assumptions and averages:

1. There is a borrow pit 10 km away.
2. Trucks used in transportation, can make 8 trips a day to the disposal area.
3. Each truck can carry 25 $tons$ of load for a trip.

Production calculations:

$$Asphalt\ plant\ production:\ 200\frac{tons}{hour}\times 8\frac{hours}{day}=1600\frac{ton}{day}$$

$$Number\ of\ trips\ for\ a\ day: 1600\frac{tons}{day}\div 25\frac{ton}{trip}=64\frac{trips}{day}$$

$$Required\ number\ of\ trucks: 64\frac{trips}{day}\div 8\frac{trips}{truck}=8\frac{trucks}{day}$$

$$1\ m^3\ Asphalt\ weighs\ \ 2{,}4\ Tons$$

$$8\ cm\ thick\ asphalt\ binder\ layer: 0{,}08\ m\times 2400\frac{tons}{m^3}=0{,}192\frac{tons}{m^2}$$

$$Daily\ binder\ production: 1600\frac{tons}{day}\div 0{,}192\frac{tons}{m^2}=8333{,}33\frac{m^2}{day}$$

$$5\ cm\ thick\ asphalt\ wearing\ layer: 0{,}05\ m\times 2400\frac{ton}{m^3}=0{,}120\frac{ton}{m^2}$$

$$Daily\ wearing\ production: 1600\frac{ton}{day}\div 0{,}120\frac{ton}{m^2}=13333{,}33\frac{m^2}{day}$$

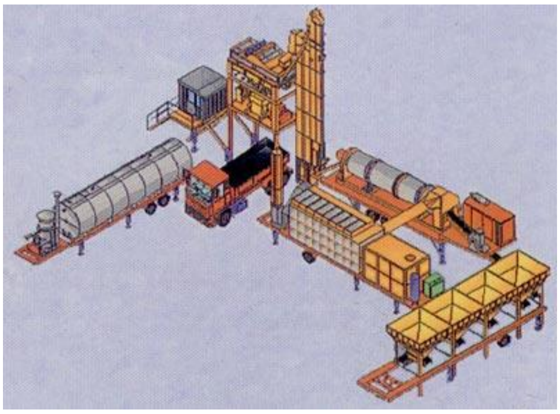


Figure 6.4: Mobile asphalt plant.

Figure 6.5: Asphalt laying and compacting.

6.2.1.3 Drainage

Required Equipment:

- 1 Tractor

Required Crew:

- 1 Driver for tractor
- 5 laborers

Daily drainage production: 100 m/day

6.2.2 Precedence relations

Activities follow the same production order for each location as a little part shown in Table 6.3.

Table 6.3: Activity codes and activities distributed over locations.

	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6
Subbase	S1	S2	S3	S4	S5	S6
Drainage	D1	D2	D3	D4	D5	D6
Plantmix	P1	P2	P3	P4	P5	P6
Binder	B1	B2	B3	B4	B5	B6
Wearing	W1	W2	W3	W4	W5	W6

For instance, in location 1 subbase, drainage, plantmix, binder and wearing productions are performed successively whereas they follow same sequence in location 2, 3 and all.

Besides, the precedence relations between activities can be analyzed in two different aspects, since tasks are linked from two dimensions.

6.2.2.1 Activity orders

Same activity continues through the locations to provide smooth workflow, hence, the activity *i* cannot start in location *j* before it is completed in location *j-1*. The reason for this precedence constraint is that activity *i* is performed with same resources in every location. Each row of Table 6.3 exemplifies activity orders and for instance, Subbase production is carried out as shown in Table 6.4.

Table 6.4: Activity order for subbase activity over locations.

	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6
Subbase	S1	S2	S3	S4	S5	S6

6.2.2.2 Location orders

Activities follow the same production order for each location, however two different and successive tasks cannot be performed in any location in the same time period. Therefore, if activity *i* is the predecessor of activity *k*, activity *k* cannot start in location *j* before activity *i* finishes. The reason for this precedence constraint is that there cannot be enough room for carrying out two or more tasks simultaneously in same location. Each column of Table 6.3 exemplifies activity orders and for instance, tasks are conducted in Location 1 as shown in Table 6.5.

Table 6.5: Location order for activities over Location 1.

	Subbase	Drainage	Plantmix	Binder	Wearing
Location 1	S1	D1	P1	B1	W1

If activity and location orders are evaluated together, in order to comprehend the complete precedence relation picture of activities and locations, laddering activities as shown in Figure 6.6 may be useful to visualize precedence relations better.

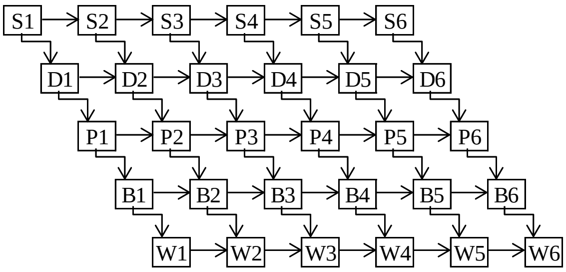


Figure 6.6: Laddering of activities in accordance with activity and location orders.

6.3 Deciding On The Planning System To Be Employed

Since laddering example in Figure 6.6 shows the structure of the activity dependencies for 30 activities, the project investigated with 101 activities is of more complicated structure when planned with CPM in Primavera Project Planner (P6) software. P6 is the commonly used CPM based planning software worldwide and shows every characteristics of CPM planning system. This way of scheduling produces of complex, hard to not only follow but also control schedules.

Besides, resource leveling logic of P6 depends on trimming resource usage peaks and delaying them as much as possible to match the resource constraints of the project (Harris, 2010). Resource leveling options in P6 are as follows:

I. Drag Activities: manually change activity starts to control aggregation and level resources. However, CPM logic has to be broken so as the precedence relations of activities.

II. Constraint Activities: Set a resource limit cannot be exceeded by activities and allocate priorities to activities to use resources.

III. Sequence Activities: Break automated CPM logic and manually create activity orders in accordance with resource utilization rates of activities to level resources.

IV. Leveling Function: Use automatic leveling function of P6, however this tool also breaks CPM logic activity orders in order to guarantee that no activity gets over the resource limits but automatically queues activities without any production logic or precedence relationships. Activities are sequenced only to fulfill limitations (Harris, 2010).

None of the actions above offers a solid leveling option while protecting project logic such as precedence relations and activity orders. As it can be clearly seen that CPM based P6 is not a reliable tool for resource leveling. In addition, complex structure of CPM schedules and controlling difficulties revives the questions of the CPM as a capable resource leveling tool.

Herein, LBP emerges as the answer. LBP uses the calculation logic of CPM, whereas it is far less complicated in visualization of projects, hence provides utmost control of the project. A LBP software VICO Control (VC) is far easier to use and provides total project control both in visual and logical ways.

Therefore, this case study was conducted with Location-Based Planning and VICO Control to produce the initial schedule.

6.4 Preparing the Initial Plan Using LBS and VICO Control

In this section, the preparation of the initial plan using VICO Control will be explained.

6.4.1 LBS

As it is mentioned before, the project was conducted in 21 different locations, so the project was divided into locations by adding locations.

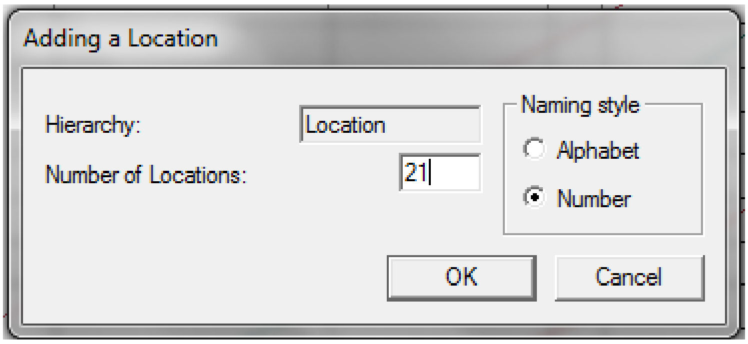


Figure 6.7: Adding locations to the project.

All of these locations were not of same length and should be adjusted accordingly. Quantities of the locations were measured by the distance covered by that specific location. Distances and quantities of the locations can be seen in Table 6.6.

Table 6.6: LBS and location quantities of the project.

Location No.	Location limits (m)	Distance	Quantity
1	0 - 500	500	1
2	500 - 1000	500	1
3	1000 - 1500	500	1
4	1500 - 2000	500	1
5	2000 - 2500	500	1
6	2500 - 3000	500	1
7	3000 - 3500	500	1
8	3500 - 4000	500	1
9	4000 - 4500	500	1
10	4500 - 5000	500	1
11	5000 - 5500	500	1
12	5500 - 6000	500	1
13	6000 - 6500	500	1
14	6500 - 7000	500	1

Table 6.6 (continued): LBS and location quantities of the project.

Location No.	Location limits (m)	Distance	Quantity
15	7000 - 7500	500	1
16	7500 - 8000	500	1
17	8000 - 8380	380	0,76
18	8380 - 8400	20	0,04
19	8400 - 8900	500	1
20	8900 - 9400	500	1

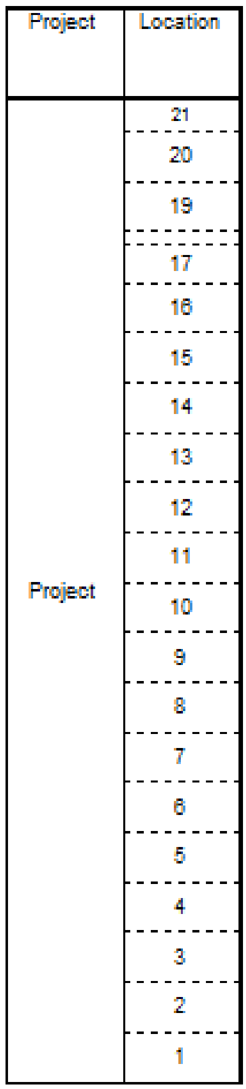


Figure 6.8: Quantity adjusted locations over the project.

6.4.2 Tasks

After completion of the LBS, tasks were drawn roughly in the project flowline view in accordance with activity occurrences throughout the locations. For instance, subbase activity end in location 17 and as it can be seen in Figure 6.9, subbase activity (first line on the left hand side) is not performed between location 18 and 21.

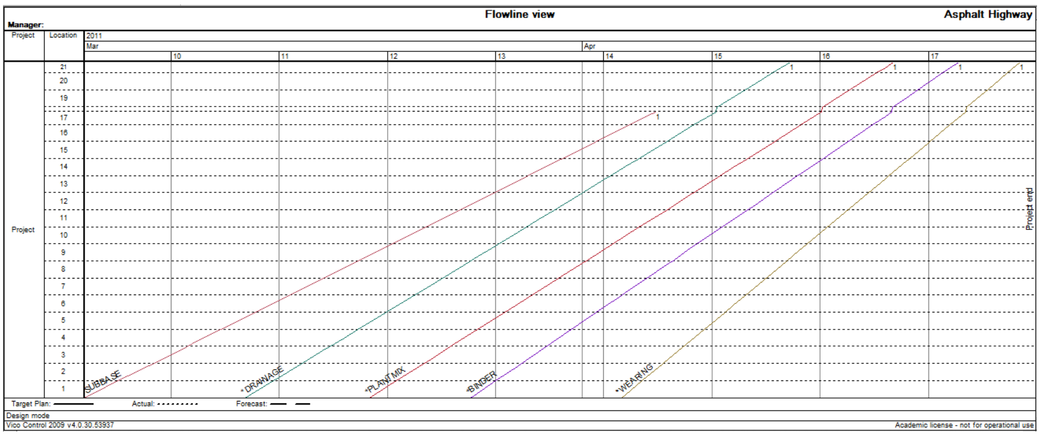


Figure 6.9: Roughly drawn taks in flowline view.

6.4.3 Production rates

VC has a different perception of production rates. In previous chapters production rate calculations were made for each task and the daily production amounts were maintained. However, VC works with hourly consumption per unit as production rate. Hence, further calculations were needed in order to load production info to VC.

For example, one crew was used for binder layer production with daily production rate of 8333,33 m^2/day and the crew was consisted of 8 trucks. Every working day is of 8 hours. So "Consumption hours / units" data for excavation:

$$Consumption\ hours/units\ for\ 1\ truck\ per\ day: \frac{8\ hours}{8333{,}33\ m^3} = 0.00096$$

$$Consumption\ \ hours/units\ \ for\ 8\ trucks: 0.00096 \times 8 = 0.008$$

All of these VC type production rates are calculated and the results are shown in Table 6.7.

Table 6.7: Calculated production rates to be used in VC.

Code	Name	Consumption hours/units
P001	Subbase	0,0720
P002	Drainage	0,0800
P003	Plantmix	0,0768
P004	Binder	0,0080
P005	Wearing	0,0048

6.4.4 Bill of quantities

VICO Control produces different project analysis screens, which are all linked. Any change in one of these screens, is simultaneously implemented to another view. Hence, activities drawn in flowline view were also appeared in Bill of Quantities (BOQ) screen as shown in Figure 6.10.

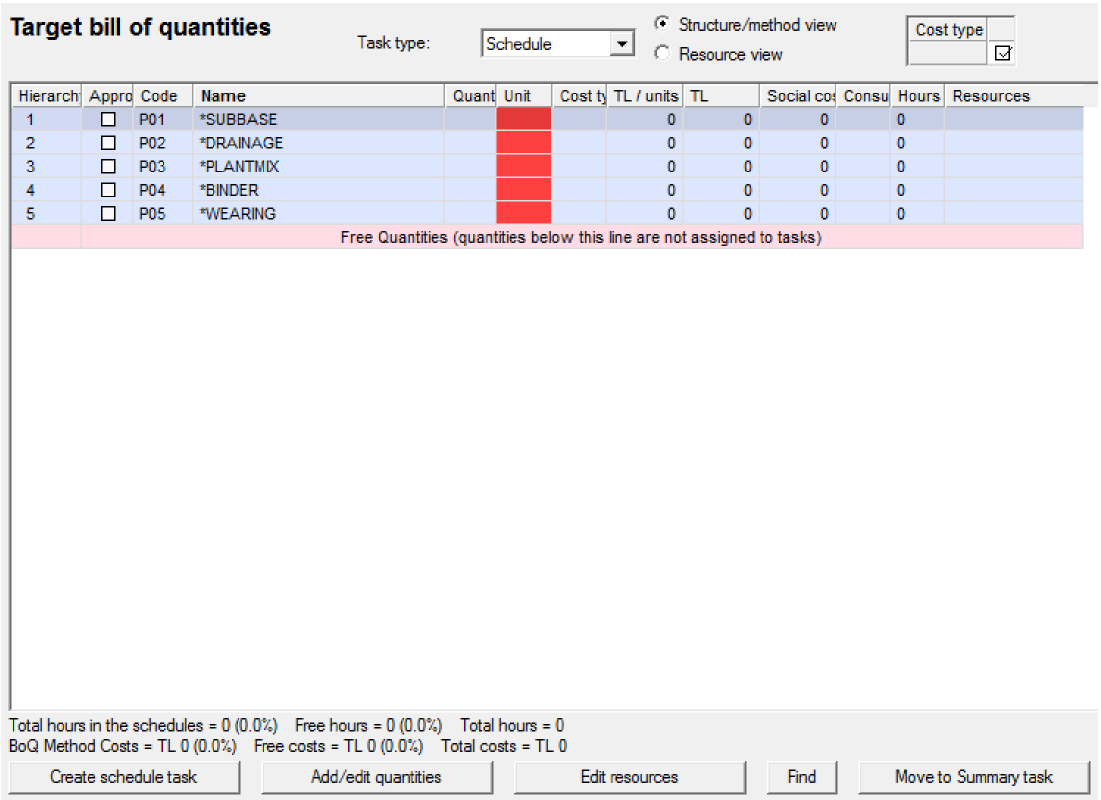


Figure 6.10: Activites in BOQ screen.

Another easiness and practicality of VC is that it is possible to add quantities from MS Excel on condition that sheets were prepared in accordance with VC's specific BOQ format as shown in Table 6.8.

Table 6.8: Total quantities of the activites.

Code	Name	Consumption hours/units	Quantity	Unit
P001	Subbase	0,0768	39000,00	M3
P002	Drainage	0,0800	5415,00	M
P003	Plant mix base	0,0768	30500,00	M3
P004	Binder	0,0080	196150,00	M2
P005	Wearing Course	0,0048	193760,00	M2

After BOQ info was inserted into VC, quantity data became available for the activity distribution as in Figure 6.11.

Hierarch	Appro	Code	Name	Quantity	Unit	Consumption	Hours	↑Resources
1	☐	P001	*SUBBASE				0	
2	☐	P002	*DRAINAGE				0	
3	☐	P003	*PLANTMIX				0	
4	☐	P004	*BINDER				0	
5	☐	P05	*WEARING				0	
-	Free Quantities (quantities below this line are not assigned to tasks)							
1	☐	P001	Subbase	39000	M3	0.0768	2995	
2	☐	P002	Drainage	5415	M	0.08	433	
3	☐	P003	Plant mix base	30500	M3	0.0768	2342	
4	☐	P004	Binder	196150	M2	0.008	1569	
5	☐	P005	Wearing Course	193760	M2	0.0048	930	

Figure 6.11: Activities with undistributed quantities.

Quantities were allocated to the activities by using quantity transfer window as shown in Figure 6.12. All of the quantity information was paired with the appropriate activities in order to match correct quantities with each activity.

Some activites were not performend in some locations. For instance, subbase had not been produced in locations after 17^{th}. Therefore, during mentioned quantity allocation, locations, in which specific activities were not undertaken, were eliminated form the distribution in order to match each quantity requirement in each location and allocate quantity percentages correctly.

Quantity distribution view for activities and the mentioned subbase example of location elimination after 17^{th} from quantitiy distribution can be in Figure 6.13 and 6.14, respectively.

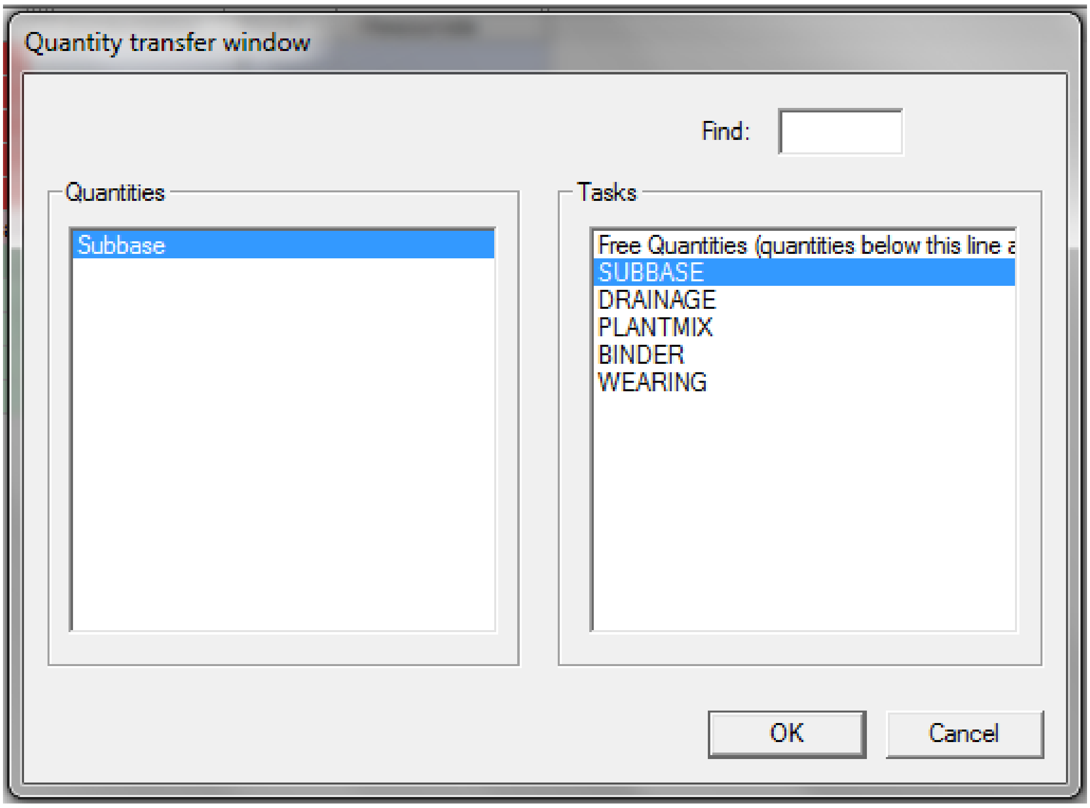


Figure 6.12: Quantity distribution for subbase layer.

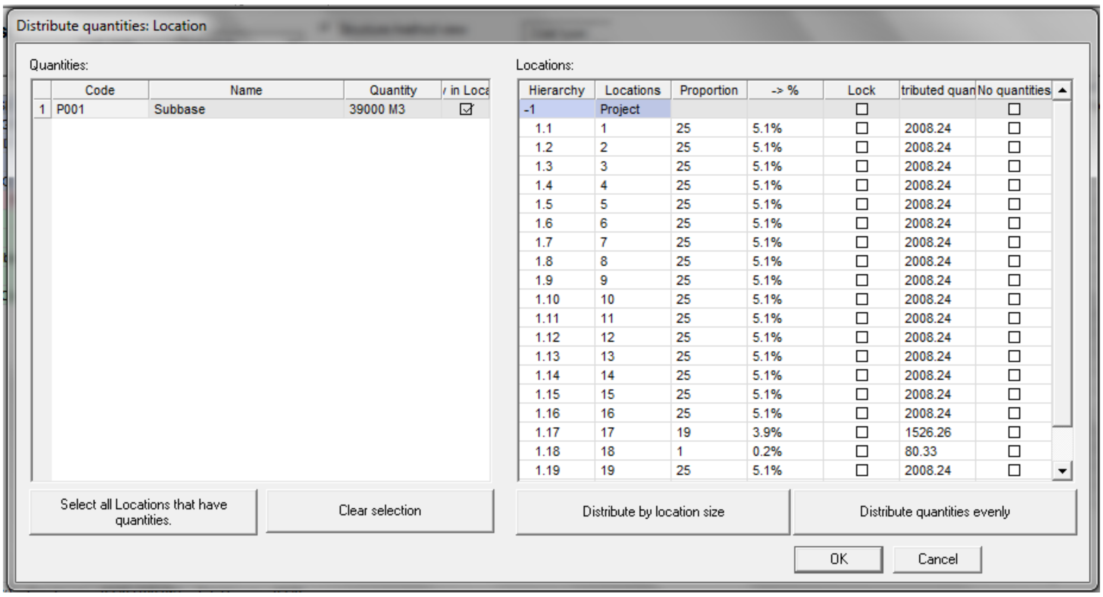
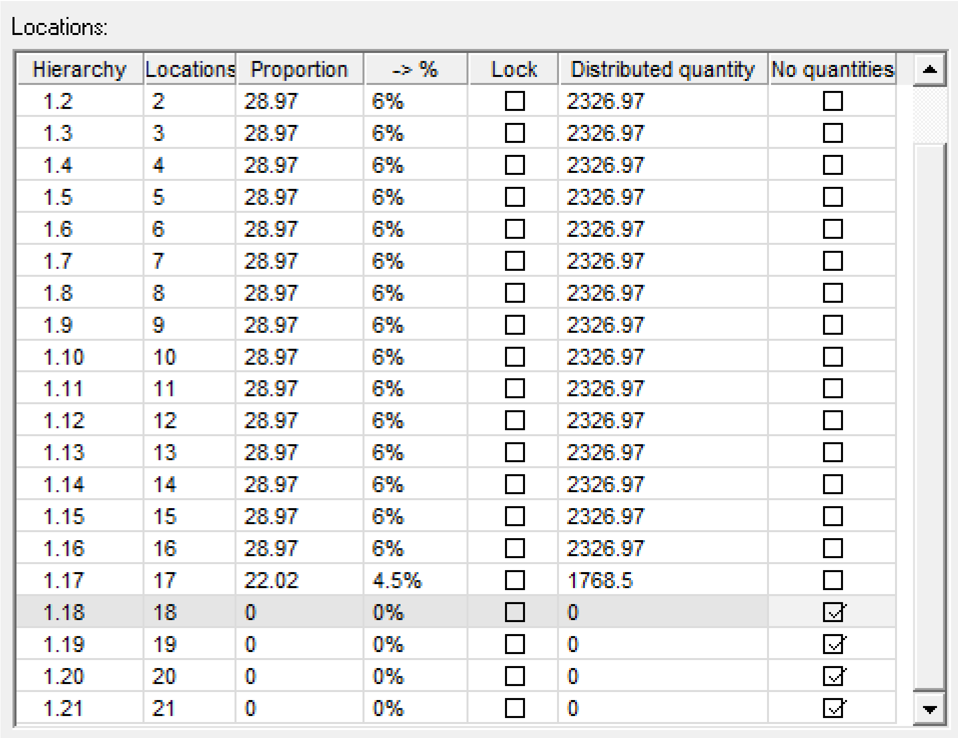


Figure 6.13: Quantity distribution view for activities.


Locations:

Hierarchy	Locations	Proportion	-> %	Lock	Distributed quantity	No quantities
1.2	2	28.97	6%	☐	2326.97	☐
1.3	3	28.97	6%	☐	2326.97	☐
1.4	4	28.97	6%	☐	2326.97	☐
1.5	5	28.97	6%	☐	2326.97	☐
1.6	6	28.97	6%	☐	2326.97	☐
1.7	7	28.97	6%	☐	2326.97	☐
1.8	8	28.97	6%	☐	2326.97	☐
1.9	9	28.97	6%	☐	2326.97	☐
1.10	10	28.97	6%	☐	2326.97	☐
1.11	11	28.97	6%	☐	2326.97	☐
1.12	12	28.97	6%	☐	2326.97	☐
1.13	13	28.97	6%	☐	2326.97	☐
1.14	14	28.97	6%	☐	2326.97	☐
1.15	15	28.97	6%	☐	2326.97	☐
1.16	16	28.97	6%	☐	2326.97	☐
1.17	17	22.02	4.5%	☐	1768.5	☐
1.18	18	0	0%	☐	0	☑
1.19	19	0	0%	☐	0	☑
1.20	20	0	0%	☐	0	☑
1.21	21	0	0%	☐	0	☑

Figure 6.14: Identifying locations without quantities.

6.4.5 Resources

Activities of the project include many different types of resources as it can be seen in production rate calculations. All of the required equipment and crews of activities can be subject to resource leveling process. However, as it is mentioned before, aim of this study is to level truck utilization throughout the project. Therefore, only trucks were registered as resources to the VC and assigned to the activities using trucks in accordance with their production rate calculations. Total of 50 trucks within the limits of companies vehicle park are registered with resource code TRC as in Figure 6.15.

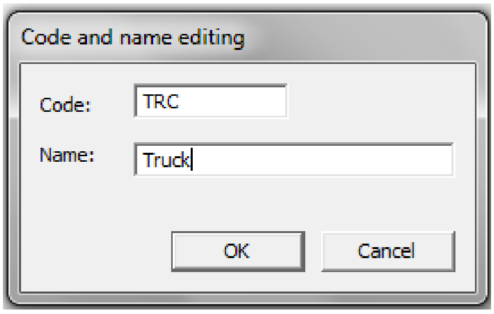


Figure 6.15: Resource registration.

Moreover, registered resources were allocated to the activities as seen in Figure 6.16.

Hierarchy	App	↑Code	Name	Quantity	Unit	Consumption	Hours	Resources
+1	☐	P001	SUBBASE	39000	M3	0.0768	2995	Truck: 16
+2	☐	P002	DRAINAGE	5415	M	0.08	433	
+3	☐	P003	PLANTMIX	30500	M3	0.0768	2342	Truck: 16
+4	☐	P004	BINDER	196150	M2	0.008	1569	Truck: 8
+5	☐	P005	WEARING	193760	M2	0.0048	930	Truck: 8

Figure 6.16: Allocated resources to the activities.

6.4.6 Dependencies

Activity dependencies were generated as in the previously mentioned order and all of the activities in the project were bounded to each other by Finish to Start (FS) dependency links.

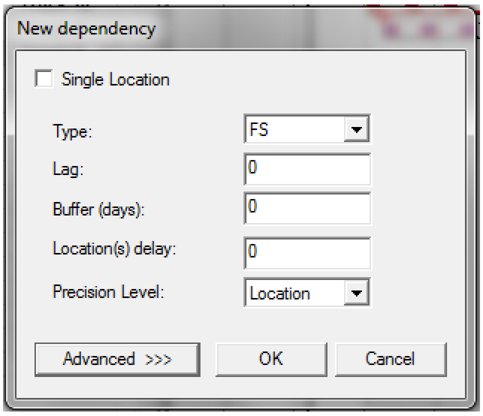


Figure 6.17: Dependency generating between activities.

6.4.7 Durations and schedule

After all available data, such as tasks, production rates, quantities, resources, and dependencies were loaded; VC produced activity durations and creates the schedule as seen in Figure 6.18.

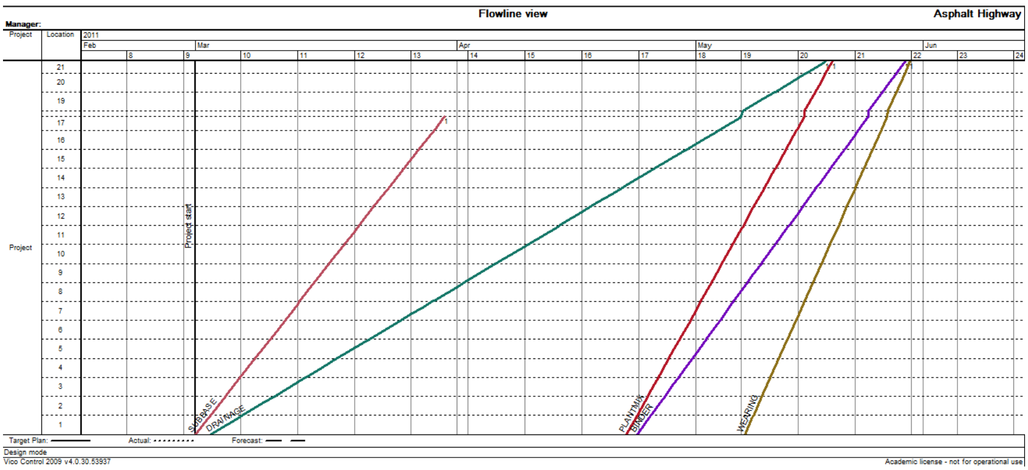


Figure 6.18: Location-based schedule on flowline view.

However, this schedule was based on default priority of VC, continuity. In order to obtain earliest start dates to be used in CPM pass calculations, activities should be forced to start "As early as possible" but also not to be forced continuity, which can be done by making adjustments in task editing box as seen in Figure 6.19.

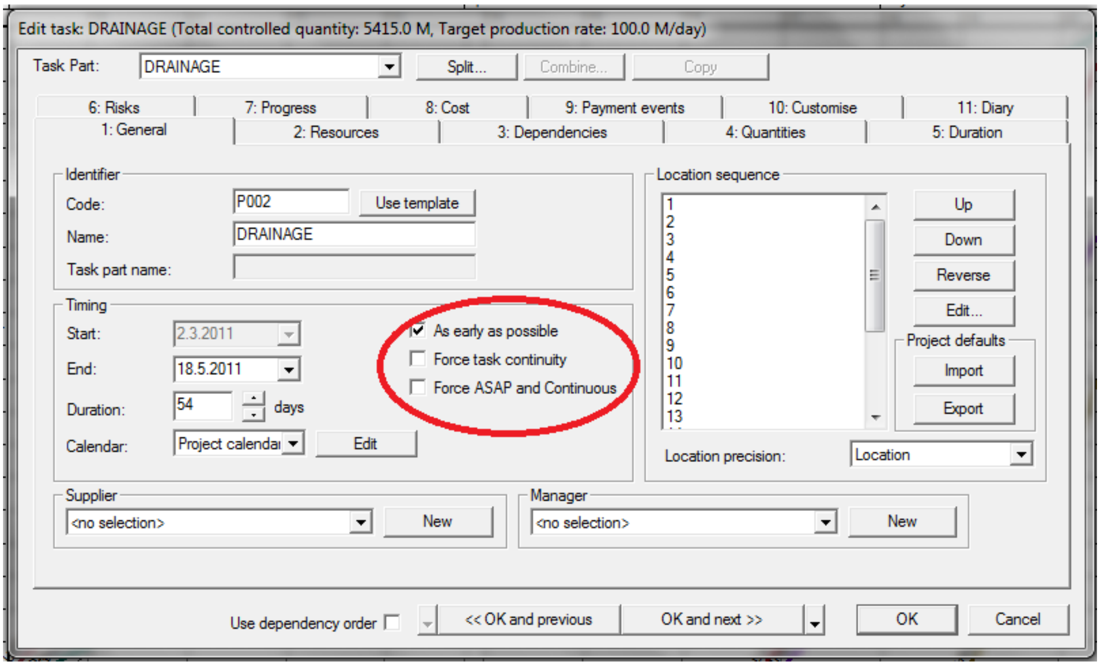


Figure 6.19: Task editing in order to obtain earliest start dates.

After all activities were adjusted to start as early as possible and not to be forced for task continuity, available activities were splitted and the schedule transforms to the state as shown in Figure 6.20.

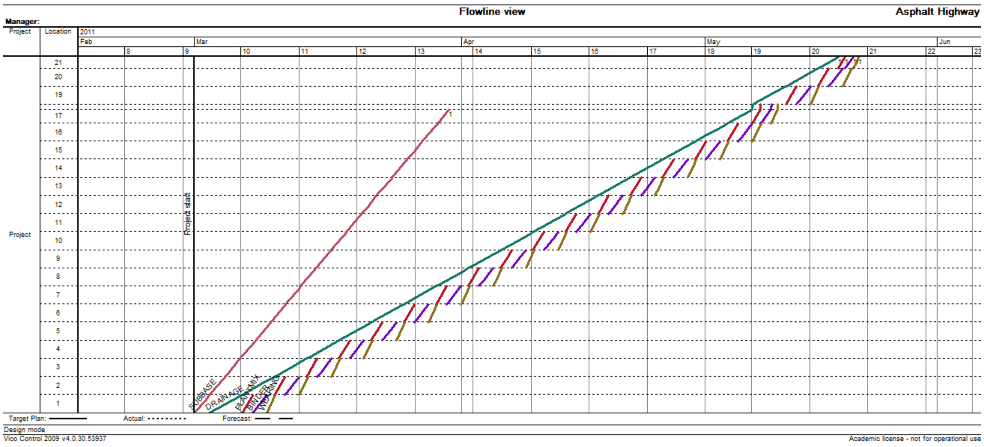


Figure 6.20: Location-based schedule with activities starting as early as possible.

Activity earliest start times were obtained by starting activities as early as possible and it will be analyzed in detail on next section.

6.5 Start date calculations

6.5.1 Earliest start dates

All activities, starting as early as possible, were scheduled in accordance with aforementioned precedence relations, and earliest start dates, calculated automatically by VC, were obtained as they can be seen in Table 6.9.

Table 6.9: Complete schedule with activity earliest time and durations.

No.	Name	Location	Earliest Start	Duration
1	Subbase	1	1,00	1,30
2	Subbase	2	2,30	1,30
3	Subbase	3	3,60	1,30
4	Subbase	4	4,90	1,30
5	Subbase	5	6,20	1,30
6	Subbase	6	7,50	1,30
7	Subbase	7	8,80	1,30
8	Subbase	8	10,10	1,30
9	Subbase	9	11,40	1,30
10	Subbase	10	12,70	1,30
11	Subbase	11	14,00	1,30
12	Subbase	12	15,30	1,30
13	Subbase	13	16,60	1,30
14	Subbase	14	17,90	1,30
15	Subbase	15	19,20	1,30
16	Subbase	16	20,50	1,30
17	Subbase	17	21,80	1,00
18	Drainage	1	2,30	2,80
19	Drainage	2	5,10	2,80
20	Drainage	3	7,90	2,80
21	Drainage	4	10,70	2,80
22	Drainage	5	13,50	2,80
23	Drainage	6	16,30	2,80
24	Drainage	7	19,10	2,80
25	Drainage	8	21,90	2,80
26	Drainage	9	24,70	2,80
27	Drainage	10	27,50	2,80
28	Drainage	11	30,30	2,80
29	Drainage	12	33,10	2,80
30	Drainage	13	35,90	2,80
31	Drainage	14	38,70	2,80
32	Drainage	15	41,50	2,80
33	Drainage	16	44,30	2,80
34	Drainage	17	47,10	2,10
35	Drainage	18	49,20	0,10
36	Drainage	19	49,30	2,80
37	Drainage	20	52,10	2,80

Table 6.9 (continued): Complete schedule with activity earliest time and durations.

No.	Name	Location	Earliest Start	Duration
38	Drainage	21	54,90	1,70
39	Plantmix	1	5,10	0,90
40	Plantmix	2	7,90	0,90
41	Plantmix	3	10,70	0,90
42	Plantmix	4	13,50	0,90
43	Plantmix	5	16,30	0,90
44	Plantmix	6	19,10	0,90
45	Plantmix	7	21,90	0,90
46	Plantmix	8	24,70	0,90
47	Plantmix	9	27,50	0,90
48	Plantmix	10	30,30	0,90
49	Plantmix	11	33,10	0,90
50	Plantmix	12	35,90	0,90
51	Plantmix	13	38,70	0,90
52	Plantmix	14	41,50	0,90
53	Plantmix	15	44,30	0,90
54	Plantmix	16	47,10	0,90
55	Plantmix	17	49,20	0,70
56	Plantmix	18	49,90	0,10
57	Plantmix	19	52,10	0,90
58	Plantmix	20	54,90	0,90
59	Plantmix	21	56,60	0,60
60	Binder	1	6,00	1,20
61	Binder	2	8,80	1,20
62	Binder	3	11,60	1,20
63	Binder	4	14,40	1,20
64	Binder	5	17,20	1,20
65	Binder	6	20,00	1,20
66	Binder	7	22,80	1,20
67	Binder	8	25,60	1,20
68	Binder	9	28,40	1,20
69	Binder	10	31,20	1,20
70	Binder	11	34,00	1,20
71	Binder	12	36,80	1,20
72	Binder	13	39,60	1,20
73	Binder	14	42,40	1,20
74	Binder	15	45,20	1,20
75	Binder	16	48,00	1,20
76	Binder	17	49,90	0,90
77	Binder	18	50,80	0,10
78	Binder	19	53,00	1,20
79	Binder	20	55,80	1,20
80	Binder	21	57,20	0,80
81	Wearing	1	7,20	0,70
82	Wearing	2	10,00	0,70
83	Wearing	3	12,80	0,70

Table 6.9 (continued): Complete schedule with activity earliest time and durations.

No.	Name	Location	Earliest Start	Duration
84	Wearing	4	15,60	0,70
85	Wearing	5	18,40	0,70
86	Wearing	6	21,20	0,70
87	Wearing	7	24,00	0,70
88	Wearing	8	26,80	0,70
89	Wearing	9	29,60	0,70
90	Wearing	10	32,40	0,70
91	Wearing	11	35,20	0,70
92	Wearing	12	38,00	0,70
93	Wearing	13	40,80	0,70
94	Wearing	14	43,60	0,70
95	Wearing	15	46,40	0,70
96	Wearing	16	49,20	0,70
97	Wearing	17	50,80	0,60
98	Wearing	18	51,40	0,10
99	Wearing	19	54,20	0,70
100	Wearing	20	57,00	0,70
101	Wearing	21	58,00	0,50

6.5.2 Backward pass and latest start calculation with total floats

After all of the earliest start time were maintained, latest start time of the last activity was taken equal to its earliest start time and latest start times of all remaining activities were calculated manually by backward pass calculations using total floats as it is in CPM. In order to use total floats in backward pass, latest start times of successor activities were taken into consideration for obtaining latest start of the predecessors. Moreover, as successor of each activity, mostly there were two different activities, which was previously explained in detail in precedence relations, due to activity orders and location orders. Therefore, while making backward pass calculations there was generally two different latest start values calculated from two different successors. In order to eliminate one of those and obtain the correct latest start date of predecessor, that would not change the complete project duration, following formulation was used:

LS_i: Latest start time of the activity *i*

t_i: Duration of the activity i

$LS_{j,L+1}$: Latest start time of the activity *j* within the same task but in the next location (activity order)

$LS_{k,A+1}$: Latest start time of the activity k in the same location but the following task (location order)

$$LS_i = \min(LS_{j,L+1}; LS_{k,A+1}) - t_i \quad \textbf{(6.1)}$$

These calculations were made for all activities and complete earliest, latest start data set was maintained, which is shown in Table 6.10.

Table 6.10: Complete data set calculated with total floats.

No.	Name	Location	Earliest Start	Latest Start	Duration	Total Float
1	Subbase	1	1,00	1,00	1,30	0,00
2	Subbase	2	2,30	3,80	1,30	1,50
3	Subbase	3	3,60	6,60	1,30	3,00
4	Subbase	4	4,90	9,40	1,30	4,50
5	Subbase	5	6,20	12,20	1,30	6,00
6	Subbase	6	7,50	15,00	1,30	7,50
7	Subbase	7	8,80	17,80	1,30	9,00
8	Subbase	8	10,10	20,60	1,30	10,50
9	Subbase	9	11,40	23,40	1,30	12,00
10	Subbase	10	12,70	26,20	1,30	13,50
11	Subbase	11	14,00	29,00	1,30	15,00
12	Subbase	12	15,30	31,80	1,30	16,50
13	Subbase	13	16,60	34,60	1,30	18,00
14	Subbase	14	17,90	37,40	1,30	19,50
15	Subbase	15	19,20	40,20	1,30	21,00
16	Subbase	16	20,50	43,00	1,30	22,50
17	Subbase	17	21,80	46,10	1,00	24,30
18	Drainage	1	2,30	2,30	2,80	0,00
19	Drainage	2	5,10	5,10	2,80	0,00
20	Drainage	3	7,90	7,90	2,80	0,00
21	Drainage	4	10,70	10,70	2,80	0,00
22	Drainage	5	13,50	13,50	2,80	0,00
23	Drainage	6	16,30	16,30	2,80	0,00
24	Drainage	7	19,10	19,10	2,80	0,00
25	Drainage	8	21,90	21,90	2,80	0,00
26	Drainage	9	24,70	24,70	2,80	0,00
27	Drainage	10	27,50	27,50	2,80	0,00
28	Drainage	11	30,30	30,30	2,80	0,00
29	Drainage	12	33,10	33,10	2,80	0,00
30	Drainage	13	35,90	35,90	2,80	0,00
31	Drainage	14	38,70	38,70	2,80	0,00
32	Drainage	15	41,50	41,50	2,80	0,00
33	Drainage	16	44,30	44,30	2,80	0,00
34	Drainage	17	47,10	47,10	2,10	0,00
35	Drainage	18	49,20	49,20	0,10	0,00
36	Drainage	19	49,30	49,30	2,80	0,00
37	Drainage	20	52,10	52,10	2,80	0,00

Table 6.10 (continued): Complete data set calculated with total floats.

No.	Name	Location	Earliest Start	Latest Start	Duration	Total Float
38	Drainage	21	54,90	54,90	1,70	0,00
39	Plantmix	1	5,10	33,70	0,90	28,60
40	Plantmix	2	7,90	34,90	0,90	27,00
41	Plantmix	3	10,70	36,10	0,90	25,40
42	Plantmix	4	13,50	37,30	0,90	23,80
43	Plantmix	5	16,30	38,50	0,90	22,20
44	Plantmix	6	19,10	39,70	0,90	20,60
45	Plantmix	7	21,90	40,90	0,90	19,00
46	Plantmix	8	24,70	42,10	0,90	17,40
47	Plantmix	9	27,50	43,30	0,90	15,80
48	Plantmix	10	30,30	44,50	0,90	14,20
49	Plantmix	11	33,10	45,70	0,90	12,60
50	Plantmix	12	35,90	46,90	0,90	11,00
51	Plantmix	13	38,70	48,10	0,90	9,40
52	Plantmix	14	41,50	49,30	0,90	7,80
53	Plantmix	15	44,30	50,50	0,90	6,20
54	Plantmix	16	47,10	51,70	0,90	4,60
55	Plantmix	17	49,20	53,10	0,70	3,90
56	Plantmix	18	49,90	53,80	0,10	3,90
57	Plantmix	19	52,10	53,90	0,90	1,80
58	Plantmix	20	54,90	55,10	0,90	0,20
59	Plantmix	21	56,60	56,60	0,60	0,00
60	Binder	1	6,00	34,60	1,20	28,60
61	Binder	2	8,80	35,80	1,20	27,00
62	Binder	3	11,60	37,00	1,20	25,40
63	Binder	4	14,40	38,20	1,20	23,80
64	Binder	5	17,20	39,40	1,20	22,20
65	Binder	6	20,00	40,60	1,20	20,60
66	Binder	7	22,80	41,80	1,20	19,00
67	Binder	8	25,60	43,00	1,20	17,40
68	Binder	9	28,40	44,20	1,20	15,80
69	Binder	10	31,20	45,40	1,20	14,20
70	Binder	11	34,00	46,60	1,20	12,60
71	Binder	12	36,80	47,80	1,20	11,00
72	Binder	13	39,60	49,00	1,20	9,40
73	Binder	14	42,40	50,20	1,20	7,80
74	Binder	15	45,20	51,40	1,20	6,20
75	Binder	16	48,00	52,60	1,20	4,60
76	Binder	17	49,90	53,80	0,90	3,90
77	Binder	18	50,80	54,70	0,10	3,90
78	Binder	19	53,00	54,80	1,20	1,80
79	Binder	20	55,80	56,00	1,20	0,20
80	Binder	21	57,20	57,20	0,80	0,00
81	Wearing	1	7,20	44,70	0,70	37,50
82	Wearing	2	10,00	45,40	0,70	35,40
83	Wearing	3	12,80	46,10	0,70	33,30

Table 6.10 (continued): Complete data set calculated with total floats.

No.	Name	Location	Earliest Start	Latest Start	Duration	Total Float
84	Wearing	4	15,60	46,80	0,70	31,20
85	Wearing	5	18,40	47,50	0,70	29,10
86	Wearing	6	21,20	48,20	0,70	27,00
87	Wearing	7	24,00	48,90	0,70	24,90
88	Wearing	8	26,80	49,60	0,70	22,80
89	Wearing	9	29,60	50,30	0,70	20,70
90	Wearing	10	32,40	51,00	0,70	18,60
91	Wearing	11	35,20	51,70	0,70	16,50
92	Wearing	12	38,00	52,40	0,70	14,40
93	Wearing	13	40,80	53,10	0,70	12,30
94	Wearing	14	43,60	53,80	0,70	10,20
95	Wearing	15	46,40	54,50	0,70	8,10
96	Wearing	16	49,20	55,20	0,70	6,00
97	Wearing	17	50,80	55,90	0,60	5,10
98	Wearing	18	51,40	56,50	0,10	5,10
99	Wearing	19	54,20	56,60	0,70	2,40
100	Wearing	20	57,00	57,30	0,70	0,30
101	Wearing	21	58,00	58,00	0,50	0,00

In accordance with the logic of CPM and LBP, activities with same earliest and latest start times, which means without total float (TF=0), are critical activities. As far as the calculations showed, 24 of total 101 activities (23.76%) does not have total float and are critical. Therefore, resource leveling model can work on the remaining 77 activities (76.24%) for achieving model objectives.

6.5.3 Backward pass and latest start date calculation with free floats

After all of the earliest start time were maintained, latest start time of the last activity was taken equal to its earliest start time and latest start times of all remaining activities were calculated manually by backward pass calculations using free floats as it is in CPM. Unlike the calculations with total floats, earliest start times of successor activities were taken into consideration for obtaining latest start of the predecessors, in order to use free floats in backward pass. Moreover, as successor of each activity, mostly there were two different activities, which was previously explained in detail in precedence relations, due to activity orders and location orders. Therefore, while making backward pass calculations there was generally two different earliest start values taken from two different successors. In order to eliminate one of those and obtain the correct latest start date of predecessor, that would not change the complete project duration, following formulation was used:

LS_i: Latest start time of the activity *i*

t_i: Duration of the activity i

$ES_{j,L+1}$: Latest start time of the activity *j* within the same task but in the next location (activity order)

$ES_{k,A+1}$: Latest start time of the activity *k* in the same location but the following task (location order)

$$LS_i = \min(ES_{j,L+1}; ES_{k,A+1}) - t_i \quad \textbf{(6.2)}$$

These calculations were made for all activities and complete earliest, latest start data set was maintained, which is shown in Table 6.11.

Table 6.11: Complete data set calculated with free floats.

No.	Name	Location	Earliest Start	Latest Start	Duration	Free Float
1	Subbase	1	1,00	1,00	1,30	0,00
2	Subbase	2	2,30	3,80	1,30	1,50
3	Subbase	3	3,60	6,60	1,30	3,00
4	Subbase	4	4,90	9,40	1,30	4,50
5	Subbase	5	6,20	12,20	1,30	6,00
6	Subbase	6	7,50	15,00	1,30	7,50
7	Subbase	7	8,80	17,80	1,30	9,00
8	Subbase	8	10,10	20,60	1,30	10,50
9	Subbase	9	11,40	23,40	1,30	12,00
10	Subbase	10	12,70	26,20	1,30	13,50
11	Subbase	11	14,00	29,00	1,30	15,00
12	Subbase	12	15,30	31,80	1,30	16,50
13	Subbase	13	16,60	34,60	1,30	18,00
14	Subbase	14	17,90	37,40	1,30	19,50
15	Subbase	15	19,20	40,20	1,30	21,00
16	Subbase	16	20,50	43,00	1,30	22,50
17	Subbase	17	21,80	46,10	1,00	24,30
18	Drainage	1	2,30	2,30	2,80	0,00
19	Drainage	2	5,10	5,10	2,80	0,00
20	Drainage	3	7,90	7,90	2,80	0,00
21	Drainage	4	10,70	10,70	2,80	0,00
22	Drainage	5	13,50	13,50	2,80	0,00
23	Drainage	6	16,30	16,30	2,80	0,00
24	Drainage	7	19,10	19,10	2,80	0,00
25	Drainage	8	21,90	21,90	2,80	0,00
26	Drainage	9	24,70	24,70	2,80	0,00

Table 6.11 (continued): Complete data set calculated with free floats

No.	Name	Location	Earliest Start	Latest Start	Duration	Free Float
27	Drainage	10	27,50	27,50	2,80	0,00
28	Drainage	11	30,30	30,30	2,80	0,00
29	Drainage	12	33,10	33,10	2,80	0,00
30	Drainage	13	35,90	35,90	2,80	0,00
31	Drainage	14	38,70	38,70	2,80	0,00
32	Drainage	15	41,50	41,50	2,80	0,00
33	Drainage	16	44,30	44,30	2,80	0,00
34	Drainage	17	47,10	47,10	2,10	0,00
35	Drainage	18	49,20	49,20	0,10	0,00
36	Drainage	19	49,30	49,30	2,80	0,00
37	Drainage	20	52,10	52,10	2,80	0,00
38	Drainage	21	54,90	54,90	1,70	0,00
39	Plantmix	1	5,10	33,70	0,90	28,60
40	Plantmix	2	7,90	34,90	0,90	27,00
41	Plantmix	3	10,70	36,10	0,90	25,40
42	Plantmix	4	13,50	37,30	0,90	23,80
43	Plantmix	5	16,30	38,50	0,90	22,20
44	Plantmix	6	19,10	39,70	0,90	20,60
45	Plantmix	7	21,90	40,90	0,90	19,00
46	Plantmix	8	24,70	42,10	0,90	17,40
47	Plantmix	9	27,50	43,30	0,90	15,80
48	Plantmix	10	30,30	44,50	0,90	14,20
49	Plantmix	11	33,10	45,70	0,90	12,60
50	Plantmix	12	35,90	46,90	0,90	11,00
51	Plantmix	13	38,70	48,10	0,90	9,40
52	Plantmix	14	41,50	49,30	0,90	7,80
53	Plantmix	15	44,30	50,50	0,90	6,20
54	Plantmix	16	47,10	51,70	0,90	4,60
55	Plantmix	17	49,20	53,10	0,70	3,90
56	Plantmix	18	49,90	53,80	0,10	3,90
57	Plantmix	19	52,10	53,90	0,90	1,80
58	Plantmix	20	54,90	55,10	0,90	0,20
59	Plantmix	21	56,60	56,60	0,60	0,00
60	Binder	1	6,00	34,60	1,20	28,60
61	Binder	2	8,80	35,80	1,20	27,00
62	Binder	3	11,60	37,00	1,20	25,40
63	Binder	4	14,40	38,20	1,20	23,80
64	Binder	5	17,20	39,40	1,20	22,20
65	Binder	6	20,00	40,60	1,20	20,60
66	Binder	7	22,80	41,80	1,20	19,00
67	Binder	8	25,60	43,00	1,20	17,40
68	Binder	9	28,40	44,20	1,20	15,80
69	Binder	10	31,20	45,40	1,20	14,20
70	Binder	11	34,00	46,60	1,20	12,60
71	Binder	12	36,80	47,80	1,20	11,00
72	Binder	13	39,60	49,00	1,20	9,40

Table 6.11 (continued): Complete data set calculated with free floats

No.	Name	Location	Earliest Start	Latest Start	Duration	Free Float
73	Binder	14	42,40	50,20	1,20	7,80
74	Binder	15	45,20	51,40	1,20	6,20
75	Binder	16	48,00	52,60	1,20	4,60
76	Binder	17	49,90	53,80	0,90	3,90
77	Binder	18	50,80	54,70	0,10	3,90
78	Binder	19	53,00	54,80	1,20	1,80
79	Binder	20	55,80	56,00	1,20	0,20
80	Binder	21	57,20	57,20	0,80	0,00
81	Wearing	1	7,20	44,70	0,70	37,50
82	Wearing	2	10,00	45,40	0,70	35,40
83	Wearing	3	12,80	46,10	0,70	33,30
84	Wearing	4	15,60	46,80	0,70	31,20
85	Wearing	5	18,40	47,50	0,70	29,10
86	Wearing	6	21,20	48,20	0,70	27,00
87	Wearing	7	24,00	48,90	0,70	24,90
88	Wearing	8	26,80	49,60	0,70	22,80
89	Wearing	9	29,60	50,30	0,70	20,70
90	Wearing	10	32,40	51,00	0,70	18,60
91	Wearing	11	35,20	51,70	0,70	16,50
92	Wearing	12	38,00	52,40	0,70	14,40
93	Wearing	13	40,80	53,10	0,70	12,30
94	Wearing	14	43,60	53,80	0,70	10,20
95	Wearing	15	46,40	54,50	0,70	8,10
96	Wearing	16	49,20	55,20	0,70	6,00
97	Wearing	17	50,80	55,90	0,60	5,10
98	Wearing	18	51,40	56,50	0,10	5,10
99	Wearing	19	54,20	56,60	0,70	2,40
100	Wearing	20	57,00	57,30	0,70	0,30
101	Wearing	21	58,00	58,00	0,50	0,00

As far as the calculations showed, 79 of total 101 activities (78.22%) does not have free float. Therefore, resource leveling model can only work on the remaining 22 activities (21.78%) for achieving model objectives.

6.5.4 Completing initial location-based plan and data set

All start date, duration and resource utilization data belonging to activities were obtained and initial plan and data set were completed. Next, the resource leveling process, using recently maintained data set, will be explained.

6.6 Resource Leveling Process

6.6.1 Objective Functions

Since, resource leveling may have different objectives, as mentioned earlier, base point of the process is to determine on the leveling objective and the objective function. The mathematical formulation of the chosen objective functions, which the mathematical models were based on, will be explained under this topic.

As it was explained in Chapter 4.2.3.4. Leveling, first six of these objective functions are linear and suitable for linear programming and mixed integer programming techniques, of which Branch and Bound Algorithm is a type. The remaining three are only suitable for non-linear programming techniques and cannot be solved with B&B. To wit, only linear objectives (Objectives No. 1-6) could be used with B&B in this study.

Table 6.12: Resource leveling criteria and objective function formulations

Objective No.	Leveling Criteria	Formulation
1	Minimization of the sum of the absolute deviations in daily resource usage	$Z = min \sum_{i=1}^{T} \lvert Rdev_i \rvert$
2	Minimization of the sum of only the increases in daily resource usage from one day to the next	$Z = min \sum_{i=1}^{T} \lvert Rinc_i \rvert$
3	Minimization of the sum of the absolute deviations between daily resource usage and the average resource usage	$Z = min \sum_{i=1}^{T} \lvert R_i - R_{avg} \rvert$
4	Minimization of the maximum daily resource usage	$Z = min[max(R_i)]$
5	Minimization of the maximum deviation in daily resource usage	$Z = min[\max \lvert Rdev_i \rvert]$
6	Minimization of the maximum absolute deviation between daily resource usage and the average resource usage	$Z = min[\max \lvert R_i - R_{avg} \rvert]$

Table 6.12 (continued): Resource leveling criteria and objective function formulations

Objective No.	Leveling Criteria	Formulation
7	Minimization of the sum of the square of daily resource usage	$Z = min\sum_{i=1}^{T}(R_i)^2$
8	Minimization of the sum of the square of the deviations in daily resource usage	$Z = min\sum_{i=1}^{T}(R_{dev})^2$
9	Minimization of the sum of the square of the deviations between daily resource usage and the average resource usage	$Z = min\sum_{i=1}^{T}\left(R_i - R_{avg}\right)^2$

6.6.1.1 Linear objectives

Objective functions no.1, 2, 3, 4, 5 and 6 are all linear functions and each of them consists of linear equations between decision variables. These equations represent linear programming problems, which can be solved with integer programming techniques as it is mentioned in previous chapters. Therefore, identification of linear objectives is of great importance for this proposed study,where integer programming metholodgy was utilized.

6.6.1.2 Non-linear objectives

Objective functions no. 7, 8 and 9 are all nonlinear functions in the sense that each of them contains a multiplication of at least two decision variables. Such problems are called nonlinear programming (NLP) problems and they are much harder to solve than regular linear programming (LP) problems. The feasible region of a linear programming problem is a convex set and if a specific LP has an optimal solution, it is guaranteed to have an extreme point of the feasible region that is optimal. On the other hand, for the NLP problems, there is no such a property. Even if the feasible region of an NLP is a convex set, the optimal solution is not necessarily an extreme point of the feasible region. The feasible region of an NLP may look like as in Figure 6.21.

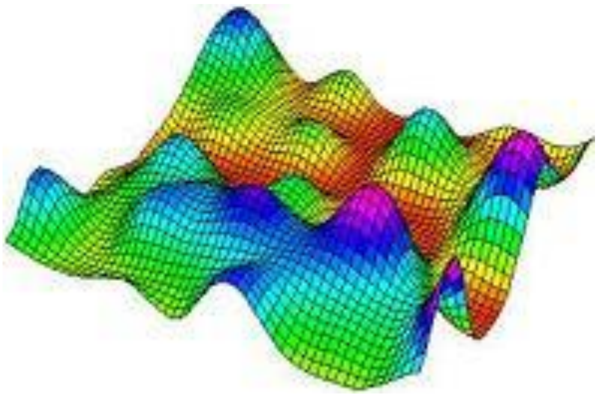


Figure 6.21: An exemplary figure for representing the feasible region of a nonlinear program

Because of this property, while solving an NLP, it is very easy to get stuck on a local extremum and never find the global extremum. As an example, for a minimization problem, a point is a local minimum if f(x)≤f(x') for all feasible x' that are close to x when f(x) is defined as the objective function value at point x. However, the global optimum may be satisfied at another point x'' where f(x'') ≤ f(x). Because of this solving an NLP is much harder than solving an LP.

When these nonlinear objective functions are considered on an integer program, it becomes even more difficult since integer programs are already much more difficult to solve than linear programs. Because of this reason, no results could be obtained with the above objective functions in this context.

6.6.2 Working with OPL

In addition, in order to use scheduling data in B&B algorithm for resource leveling, another software, OPL (Optimization Programming Language), was used and model was established for optimization.

OPL (Optimization Programming Language) is a modeling tool used for solving different linear programming, integer programming and combinatorial optimization problems. It was originally developed by Pascal Van Hentenryck. It is a product of IBM and it provides a very easy user interface and efficient features (Hentenryck, 1999).

OPL consists of expressive data structures, allows users to use specialized optimization algorithms. In addition, it is a combination of constraint logic programming and mathematical modelling languages, however it is not a universal programming language (Url – 3).

6.6.3 Transforming data set for integer programming

Calculated start dates are of decimal digits as it can be seen in a small sample of data set in Table 6.13.

Table 6.13: Sample data set with decimal digits.

No.	Name	Location	Earliest Start	Latest Start	Duration
1	Subbase	1	1,00	1,00	1,30
2	Subbase	2	2,30	3,80	1,30
3	Subbase	3	3,60	6,60	1,30

However, as it is explained before decision variables represent continuous, real numbers cannot be used in integer programming models, decision variables should take integer values. In order to be able to use data in IP models, all start dates and durations with decimal digits should be multiplied with 10 or its multiples. In this study, multiplying mentioned data with 10 was more than enough, since there was maximum of one decimal digit among all data set.

Table 6.14: Sample data set multiplied with 10.

No.	Name	Location	Earliest Start	Latest Start	Duration
1	Subbase	1	10,0	10,0	13,0
2	Subbase	2	23,0	38,0	13,0
3	Subbase	3	36,0	66,0	13,0

After the multiplation, data set was used as an input to OPL and mathematical optimization model. Later, output start dates, obtained from the model, were divided by 10, in order to transform output data to real time results.

6.6.4 First mathematical optimization model

To begin with, before generating the programming model, an objective is chosen to be used in the model. For the resource leveling problem, several objective functions may be chosen to work with. In the initial model, *"minimization of the sum of the absolute deviations between daily resource usage and the average resource usage"* is preferred as the optimization criteria.

6.6.4.1 Model analysis

Next, the proposed problem of resource leveling will be formulated as a Binary Integer Programming Model. Before explaining this model, the explanations of the decision variables, which are the variables that give the solution to the problem, will be given. The following definitions are made:

$$x_{i,t} = \begin{cases} 1 \ if \ activity \ i \ starts \ at \ time \ t \\ 0 \ otherwise \end{cases} \quad \textbf{(6.3)}$$

$$y_{i,t} = \begin{cases} 1 \ if \ activity \ i \ is \ processed \ at \ time \ t \\ 0 \ otherwise \end{cases} \quad \textbf{(6.4)}$$

Both of these variables are binary variables, hence, making the model a Binary Integer Programming Model.

Furthermore, the following parameters are defined; these values are the obtained values from the project and are input to the model.

R_i = The resource used by activity i per time period in units

R_{avg} = The average resource used over the entire project in units

$$R_{avg} = \frac{\sum_{i=1}^{T} R_i}{T} \quad \textbf{(6.5)}$$

D_i = The duration of activity i in time units

$$Prec_{i,k} = \begin{cases} 1 \ if \ activity \ k \ is \ the \ predecessor \ of \ activity \ i \\ 0 \ otherwise \end{cases}$$

ES_i = the earliest start date of activity i obtained from LBP

LS_i = the latest start date of activity i calculated manually

T = Total project duration

Therefore, the objective function is formulated as:

$$Z = \min \sum_{i=1}^{T} |R_i - R_{avg}| \quad \textbf{(6.6)}$$

Using the decision variables, the following model is proposed:

$$min \sum_t Dev_t \quad \textbf{(6.7)}$$

$$Dev_t = \left|\sum_i (R_i y_{i,t}) - R_{avg}\right| \quad \forall t \quad \textbf{(6.8)}$$

$$x_{i,t} \leq y_{i,j} \quad \forall i, t, j = t, \dots t + D_i - 1 \quad \textbf{(6.9)}$$

$$\sum_j y_{i,j} = D_i \quad \forall i \qquad \textbf{(6.10)}$$

$$\sum_{t=ES_i}^{LS_i} x_{i,t} = 1 \quad \forall i \qquad \textbf{(6.11)}$$

$$M(1 - x_{i,t}) - Prec_{i,k}\left(D_k - \sum_{j=1}^{t-1} y_{k,j}\right) \geq 0 \quad \forall i, t, k \qquad \textbf{(6.12)}$$

By using Constraint 6.8, the definition of the deviation function is made. In this project, for the resource leveling criterion, the absolute difference between the total resources used at time t and the average resource level used over the entire project is used. This deviation function is defined for each time period t. Hence, the objective function becomes minimizing the total deviation over the whole planning horizon.

Constraint ii states that once any activity starts to be processed, it should continue to be processed until it is finished. It is known that both x and y variables are binary. Hence, if, at time t, x equals one; meaning that the activity's start day is time t; then constraint 6.8 forces y to also be equal to one until the activity is finished. Notice that if the activity i started at time t and is processed until it is finished, it will finish at time $t+D_i-1$. On the other hand, if, at time t and for activity i, x equals zero, then, this constraint only says that y should be greater than or equal to zero for the following D_i periods. Hence, in this case, this constraint becomes not binding and can be ignored.

Constraint 6.10 states that each activity should be started and finished during the planning horizon. Since binary variable y takes the value of one only at the time periods that activity is being processed, summation of y variables over the planning horizon should be equal to the duration of that activity.

As explained above, the variable x for activity i at time t takes the value of one if and only if time t is the start date of activity i. Hence, on Constraint 6.11, it is stated that the each activity should start between its corresponding earliest and latest start dates, which are input to the model.

Constraint 6.12 is the activity precedence constraint. The activities in this study are defined to have finish to start precedence relations and are demonstrated by the parameter $Prec_{i,k}$ for activities i and k. As stated before, if this value is equal to one for activities i and k, then this means that for activity i to start, activity k should be finished. Now, Constraint 6.12 will be explained considering different cases for activities i and k. Without loss of generality, assume that these activities are not the same activity. The value M, used in this constraint, is just an arbitrary, large number.

Case 1: $Prec_{i,k} = 0$

In this case, Constraint 6.12 becomes:

$$M(1 - x_{i,t}) \geq 0 \quad \textbf{(6.13)}$$

Notice that this equation is always satisfied (whether $x_{i,k}$ is zero or one), indicating that there is no constraining precedence relation between i and k.

Case 2: $Prec_{i,k} = 1$

In this case, it is known that activity k should be completed for activity i to start. Constraint 6.12 becomes:

$$M(1 - x_{i,t}) \geq D_k - \sum_{j=1}^{t-1} y_{k,j} \quad \forall i, t, k \quad \textbf{(6.14)}$$

Now, consider the activity k. At time t, activity k can have only one of the following properties:

- *Activity k has not started processing.*

In this case, the following equation directly follows:

$$\sum_{j=1}^{t-1} y_{k,j} = 0 \quad \textbf{(6.15)}$$

So, Constraint 6.12 becomes:

$$M(1 - x_{i,t}) \geq D_k \quad \forall i, t, k \quad \textbf{(6.16)}$$

In this version of Constraint 6.12, the variable xi,t can never take the value 1 since this would make the constraint infeasible. Hence, if activity k has not started processing, activity i cannot start processing either.

- *Activity k has started processing but has not finished yet.*

In this case, the following equations directly follow:

$$0 < \sum_{j=1}^{t-1} y_{k,j} < D_k \quad \textbf{(6.17)}$$

$$0 < D_k - \sum_{j=1}^{t-1} y_{k,j} < D_k \quad \textbf{(6.18)}$$

Considering Constraint 6.12 for this case, the following conclusions can be made:

The variable $x_{i,t}$ can never take the value one since this would make new equation given above and Constraint 6.12 to contradict each other. Hence, if activity k has started processing but is not finished yet, activity i cannot start processing.

- *Activity k has started processing and finished.*

In this case, the following equation directly follows:

$$\sum_{j=1}^{t-1} y_{k,j} = D_k \quad \textbf{(6.19)}$$

So, Constraint 6.12 becomes:

$$M(1 - x_{i,t}) \geq 0 \quad \forall i, t \quad \textbf{(6.20)}$$

In this version of Constraint 6.12, the variable $x_{i,t}$ is free to take values either zero or one. Hence, if activity k has started processing and finished, activity i can, but is not forced to, start processing.

6.6.4.2 Data input

After the model was complete, scheduling data was loaded to OPL by making it read the information from MS Excel spreadsheets. Earlieast start, latest start, duration and resource usage data were obtained values from the scheduling proces. For precedence variable Prec, a precedence matrix was prepared showing precedence relations between activites in binary system, shown in Table 6.15. The location order and activity order precendence relations between activities were considered and if there was a dependency between two activities and activity *j* is the successor of the activity *i*, the cell on intersection of the column *i* and the row *j* was marked with “1” value, and “0” otherwise.

6.6.4.3 Problems

After the model was completed, entire input data set, calculated with total floats, was inserted to OPL. However, even without starting iterations, the model ran out of memory and could not give any solutions. This problem was occurred mainly due to following two reasons:

- *the way that precedence relations were defined,*

The model was trying to understand precedence relations from a 101x101 matrix as shown in Table 6.15, by going through every column of every row and extracting task orders for each day. Besides, since the start dates were multiplied with 10 to get rid of decimal digits, the model was perceiving the project calendar as virtual 584 days instead of 58.4 days in real time. Considering all these facts, the model was generating;

$$(58{,}4 \times 10) \times 101 \times 101 = 5.957.384$$

constraints and possibly even before completing all, it ran out of memory.

It was obvious and even unevitable that in order to let the model start computing, the number of almost 6 million constraints should be decreased and memory should be reserved for further computations.

- *necessity of the absolute value for the seleceted objective function and complexity of absolute value definitions in the model*

The absolute value definition used in the aforementioned model analysis was way too complex for the way of "thinking" of the model and OPL. Absolute value definition should be eliminated to not only simplify the model but also let the OPL analyze and compute over inserted the objective functions. Therefore, it was obliged to describe objective functions in a different way but in the same meaning.

6.6.5 Second mathematical optimization model

It was clear that, in order to overcome mentioned problems, some changes should be made in the model, so it was redefined. Redefinition of both precedence relations among activities and absolute value characteristics in objective functions were aimed in the second mathematical model. As it was the case for the faced problems in the first model, alterations in the second will also be examined under two topics.

6.6.5.1 New precedence definitions

The issue with the recent precedence definitions was previously explained. Previous precedence relations between activities were creating almost 6 million constraints for the model, which eventually led into memory shortage in OPL. Precedence relations were of utmost significance in the model and it was vital to insert them correctly into the model. Redefinition of the relations was obligatory. During the redefinition process of precedence realtions, the main purpose was to make relations so compact and simple that the excessive amount of memory usage could be prevented. First, a new decision variable denoting activity start times is defined:

$$S_i = \sum_{t=ES_i}^{LS_i} (t.\, x_{i,t}) \qquad \forall\, i \tag{6.21}$$

Table 6.15: Precedence matrix

No.	Name	Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101
1	Subbase	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Subbase	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Subbase	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Subbase	4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Subbase	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Subbase	6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Subbase	7	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Subbase	8	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Subbase	9	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Subbase	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Subbase	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Subbase	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Subbase	13	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	Subbase	14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Subbase	15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	Subbase	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Subbase	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Drainage	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	Drainage	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Drainage	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	Drainage	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	Drainage	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Drainage	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Drainage	7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Drainage	8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Drainage	9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Drainage	10	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Drainage	11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	Drainage	12	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	Drainage	13	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	Drainage	14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	Drainage	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	Drainage	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	Drainage	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	Drainage	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	Drainage	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Drainage	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	Drainage	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	Plantmix	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	Plantmix	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	Plantmix	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	Plantmix	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	Plantmix	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	Plantmix	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	Plantmix	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Plantmix	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	Plantmix	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	Plantmix	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Plantmix	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Plantmix	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	Plantmix	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	Plantmix	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	Plantmix	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	Plantmix	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	Plantmix	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	Plantmix	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	Plantmix	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	Plantmix	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	Plantmix	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	Binder	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	Binder	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	Binder	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	Binder	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	Binder	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	Binder	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	Binder	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	Binder	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	Binder	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Binder	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	Binder	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
71	Binder	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	Binder	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
73	Binder	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	Binder	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	Binder	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	Binder	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	Binder	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	Binder	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79	Binder	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	Binder	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	Wearing	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	Wearing	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	Wearing	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	Wearing	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	Wearing	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	Wearing	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	Wearing	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	Wearing	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	Wearing	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
90	Wearing	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
91	Wearing	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
92	Wearing	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
93	Wearing	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
94	Wearing	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
95	Wearing	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
96	Wearing	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
97	Wearing	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
98	Wearing	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
99	Wearing	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
100	Wearing	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
101	Wearing	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Where,

$$x_{i,t} = \begin{cases} 1 \text{ if activity i starts at time t} \\ 0 \text{ otherwise} \end{cases} \quad \textbf{(6.22)}$$

ESi = the earliest start date of activity i obtained from LBP

LSi = the latest start date of activity I calculated manually

$$S_i = \text{Start time of activity I} \quad \textbf{(6.23)}$$

This new decision variable generates values for each activity, in each t time. For instance, if 2nd activity with earliest start time in 23rd day and latest start in 38th day, starts in 25th day:

$$S_2 = \sum_{t=23}^{38} t.x_{2,t} \quad \textbf{(6.24)}$$

$$S_2 = 23.x_{2,23} + 24.x_{2,24} + 25.x_{2,25} + \cdots + 38.x_{2,38} \quad \textbf{(6.25)}$$

$$S_2 = 23.0 + 24.0 + 25.1 + \cdots + 38.0 = 25 \quad \textbf{(6.26)}$$

Instead of the previously used precedence matrix, a new precedence list was formed, so that, the model could take precedence relations into consideration while calculating start dates (S_i) of each activity. This new precedence list was formed in accordance with aforementioned task precedence orders: Activity orders and Location orders. All in all, new precedence list was formed as shown in table 6.16.

Table 6.16: Precedence list

Predecessor	Successor	Task Order
1	2	Activity Orders
2	3	
3	4	
4	5	
5	6	
6	7	
7	8	
8	9	
9	10	
10	11	
11	12	
12	13	
…	…	
100	101	

Table 6.16 (continued): Precedence list

Predecessor	Successor	Task Order
1	18	
2	19	
3	20	
4	21	
5	22	
6	23	Location Orders
7	24	
8	25	
9	26	
…	…	
80	101	

With the help of this new list, a new constraint was defined for start date calculations of each activity in accordance with precedence relations.

If activity i is the predecessor of activity k (i → k);

Di = The duration of activity i in time units

$$S_k \geq S_i + D_i \quad \forall\ (i, k) \text{ pairs from the list} \qquad \textbf{(6.27)}$$

Since, this constraint goes through the list for every i – k activity couples (predecessor – successor), it considers both precedence orders at the same time.

The second model, generates 101 (from equation 6.21) + 176 (from equation 6.27) = 277 constraints which is completely smaller and more compact than approximately 6 million constraints in the first model.

6.6.5.2 New absolute value definitions

Instead of defining absolute value calculations directly in the model, a new z_i value was defined, such that:

for any x_i;

z_i is the minimum integer value satisfying

$$z_i \geq x_i \ and \ z_i \geq -x_i \qquad \textbf{(6.28)}$$

For instance;

$$\text{if } x_i = -5 \qquad \textbf{(6.29)}$$

Minimum integer value of z_i satisfying,

$$z_i \geq -5 \text{ and } z_i \geq -(-5) \tag{6.30}$$

is +5, which is also the absolute value of $x_i = (-5)$.

To sum up, the previous absolute value definition was:

$$\min \sum_t Dev_t \tag{6.31}$$

$$Dev_t = \left|\sum_i \left(R_i y_{i,t}\right) - R_{avg}\right| \quad \forall t \tag{6.32}$$

However, the new definition is:

$$\min \sum_t z_t \tag{6.33}$$

$$z_t \geq \sum_i \left(R_i y_{i,t}\right) - R_{avg} \quad \forall t \tag{6.34}$$

$$z_t \geq R_{avg} - \sum_i \left(R_i y_{i,t}\right) \quad \forall t \tag{6.35}$$

Despite all of the alterations above, the second model could not give any solutions for objective function with the leveling criteria of “minimization of the sum of the absolute deviations between Daily resource usage and the average resource usage”. However, the new model started iterations and after approx. 20 hours and 22 millions of iterations, it ran out of memory. But, this has shown that, all these alterations worked and at least let the model start calculations.

6.6.6 Solutions

After the mathematical model was revised, data sets formed using both total and free floats were tried in all six objective functions. However, data of total float did not produce any solutions with objective functions except for the Objective No.4. On the other hand, data set calculated with free floats worked in all six objectives.

6.6.6.1 Solutions with total float

Since the number of activities with total floats is 76.24% of the total project, there are too many possibilities for resource leveling process using latest start dates calculated with total floats. Due to the mentioned possibilities, proposed model had to generate vast number of iterations, which made it impossible for the model to reach a solution. These results mostly occurred owing to exceeding the memory available for the model.

Solutions for objectives no. 2, 3 and 5 ran out of memory in approximately 20 hours of solving process whereas the gap between LP relaxation and the best possible integer solution for objectives no. 1 and 6 was 93% and 97% respectively at same amount of time. Proposed model could give results only for objective function no.4, which is seemably the easiest objective to solve for the model (and the only one without absolute value in its formula) not only in its mathematical formulation but also with the number of iterations.

Objective Function No.4 with Total Float Data Set

Solution statistics of the solution of the objective function no.4 for data set of the start dates calculated with total float were as shown in Figure 6.22

Cplex	solution (optimal) with objective 24
Constraints	755615
Variables	128646
Binary	127967
Non-zero coefficients	1648542
MIP	
Objective	24
Incumbent	24
Nodes	591
Remaining nodes	0
Iterations	978795
Solution pool	
Count	3
Mean objective	34.666667

Figure 6.22: Solution statistics – Objective 4 / Total Float

In addition, start dates of the same data set after leveling can be seen in Table 6.17.

Table 6.17: Start dates – Objective 4 / Total Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
1	Subbase	1	1	1	1	TF=0
2	Subbase	2	2,3	2,3	3,8	ES
3	Subbase	3	3,6	4,1	6,6	
4	Subbase	4	4,9	6,7	9,4	
5	Subbase	5	6,2	9,5	12,2	
6	Subbase	6	7,5	12,1	15	
7	Subbase	7	8,8	13,7	17,8	
8	Subbase	8	10,1	15,1	20,6	

Table 6.17 (continued): Start dates – Objective 4 / Total Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
9	Subbase	9	11,4	18,2	23,4	
10	Subbase	10	12,7	20,7	26,2	
11	Subbase	11	14	22	29	
12	Subbase	12	15,3	24,7	31,8	
13	Subbase	13	16,6	31,2	34,6	
14	Subbase	14	17,9	37,4	37,4	LS
15	Subbase	15	19,2	39,7	40,2	
16	Subbase	16	20,5	42,7	43	
17	Subbase	17	21,8	45,2	46,1	
18	Drainage	1	2,3	2,3	2,3	TF=0
19	Drainage	2	5,1	5,1	5,1	TF=0
20	Drainage	3	7,9	7,9	7,9	TF=0
21	Drainage	4	10,7	10,7	10,7	TF=0
22	Drainage	5	13,5	13,5	13,5	TF=0
23	Drainage	6	16,3	16,3	16,3	TF=0
24	Drainage	7	19,1	19,1	19,1	TF=0
25	Drainage	8	21,9	21,9	21,9	TF=0
26	Drainage	9	24,7	24,7	24,7	TF=0
27	Drainage	10	27,5	27,5	27,5	TF=0
28	Drainage	11	30,3	30,3	30,3	TF=0
29	Drainage	12	33,1	33,1	33,1	TF=0
30	Drainage	13	35,9	35,9	35,9	TF=0
31	Drainage	14	38,7	38,7	38,7	TF=0
32	Drainage	15	41,5	41,5	41,5	TF=0
33	Drainage	16	44,3	44,3	44,3	TF=0
34	Drainage	17	47,1	47,1	47,1	TF=0
35	Drainage	18	49,2	49,2	49,2	TF=0
36	Drainage	19	49,3	49,3	49,3	TF=0
37	Drainage	20	52,1	52,1	52,1	TF=0
38	Drainage	21	54,9	54,9	54,9	TF=0
39	Plantmix	1	5,1	5,4	33,7	
40	Plantmix	2	7,9	8	34,9	
41	Plantmix	3	10,7	10,9	36,1	
42	Plantmix	4	13,5	17,2	37,3	
43	Plantmix	5	16,3	19,8	38,5	
44	Plantmix	6	19,1	23,7	39,7	
45	Plantmix	7	21,9	27,5	40,9	
46	Plantmix	8	24,7	28,4	42,1	
47	Plantmix	9	27,5	29,4	43,3	
48	Plantmix	10	30,3	30,3	44,5	ES
49	Plantmix	11	33,1	33,7	45,7	
50	Plantmix	12	35,9	36,5	46,9	

Table 6.17 (continued): Start dates – Objective 4 / Total Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
51	Plantmix	13	38,7	38,7	48,1	ES
52	Plantmix	14	41,5	41,7	49,3	
53	Plantmix	15	44,3	44,3	50,5	ES
54	Plantmix	16	47,1	47,3	51,7	
55	Plantmix	17	49,2	50,3	53,1	
56	Plantmix	18	49,9	53,6	53,8	
57	Plantmix	19	52,1	53,7	53,9	
58	Plantmix	20	54,9	54,9	55,1	ES
59	Plantmix	21	56,6	56,6	56,6	TF=0
60	Binder	1	6	19,5	34,6	
61	Binder	2	8,8	20,7	35,8	
62	Binder	3	11,6	22,1	37	
63	Binder	4	14,4	23,4	38,2	
64	Binder	5	17,2	26,2	39,4	
65	Binder	6	20	27,8	40,6	
66	Binder	7	22,8	29,1	41,8	
67	Binder	8	25,6	30,5	43	
68	Binder	9	28,4	32,1	44,2	
69	Binder	10	31,2	33,3	45,4	
70	Binder	11	34	34,7	46,6	
71	Binder	12	36,8	39,5	47,8	
72	Binder	13	39,6	41,6	49	
73	Binder	14	42,4	42,8	50,2	
74	Binder	15	45,2	46,3	51,4	
75	Binder	16	48	48,2	52,6	
76	Binder	17	49,9	53,2	53,8	
77	Binder	18	50,8	54,2	54,7	
78	Binder	19	53	54,6	54,8	
79	Binder	20	55,8	55,8	56	ES
80	Binder	21	57,2	57,2	57,2	TF=0
81	Wearing	1	7,2	24,8	44,7	
82	Wearing	2	10	25,5	45,4	
83	Wearing	3	12,8	26,8	46,1	
84	Wearing	4	15,6	33	46,8	
85	Wearing	5	18,4	35,2	47,5	
86	Wearing	6	21,2	35,9	48,2	
87	Wearing	7	24	36,6	48,9	
88	Wearing	8	26,8	37,4	49,6	
89	Wearing	9	29,6	38,2	50,3	
90	Wearing	10	32,4	41	51	
91	Wearing	11	35,2	44,3	51,7	
92	Wearing	12	38	45,7	52,4	

Table 6.17 (continued): Start dates – Objective 4 / Total Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
93	Wearing	13	40,8	46,5	53,1	
94	Wearing	14	43,6	47,6	53,8	
95	Wearing	15	46,4	51,3	54,5	
96	Wearing	16	49,2	52,2	55,2	
97	Wearing	17	50,8	54,3	55,9	
98	Wearing	18	51,4	55,8	56,5	
99	Wearing	19	54,2	55,9	56,6	
100	Wearing	20	57	57	57,3	ES
101	Wearing	21	58	58	58	TF=0

Both number and percentage of the activities starting on either earliest or latest start dates are as shown in Table 6.18.

Table 6.18: Activity start date statistics – Objective 4 / Total Float

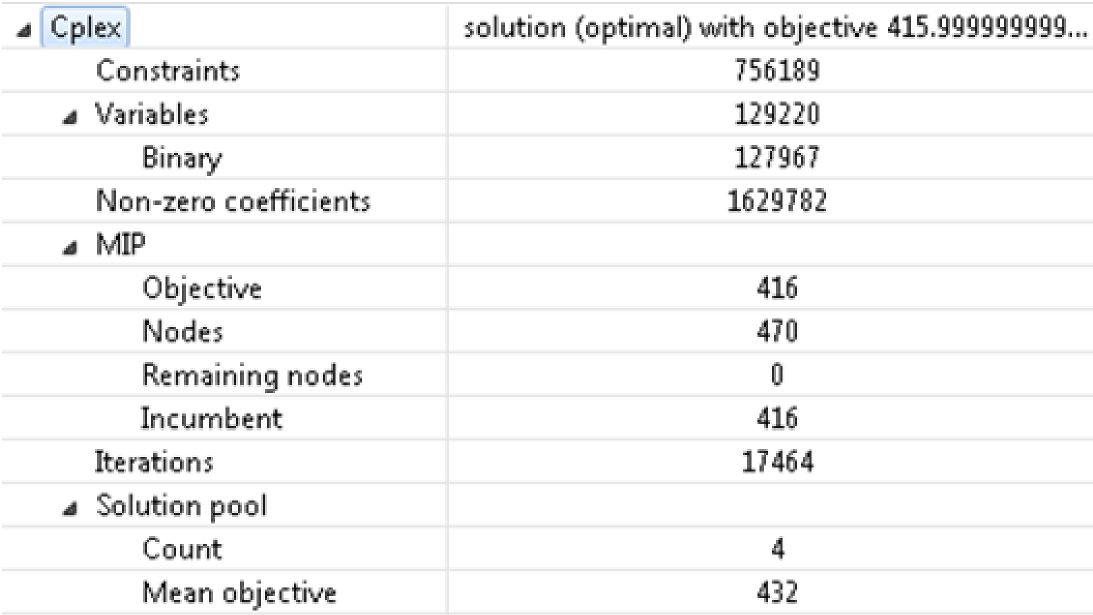
	Activities with float	
	Starting on ES	Starting on LS
Number of activities	7	1
Percentage of activities	9,09	1,30

6.6.6.2 Solutions with free float

Latest start date calculated with free float had shown that, most of the activities (79 of 101 exactly) did not have free floats, which means that earliest and start dates for these activities are the same. Due to that fact, the proposed model could only work on the remaining activities (22 of 101). Since the number of the activities available for the leveling process is low, model could solve this data set for all objective function despite all complexities. Because, the data set prepared with free floats did not require much iteration, as it was the case with data set prepared with total floats.

Objective Function No.1 with Free Float Data Set

Solution statistics of the solution of the objective function no.1 for data set of the start dates calculated with free float were as shown in Figure 6.23.



Cplex	solution (optimal) with objective 415.999999999...
Constraints	756189
Variables	129220
Binary	127967
Non-zero coefficients	1629782
MIP	
Objective	416
Nodes	470
Remaining nodes	0
Incumbent	416
Iterations	17464
Solution pool	
Count	4
Mean objective	432

Figure 6.23: Solution statistics – Objective 1 / Free Float

In addition, start dates of the same data set after leveling can be seen in Table 6.19.

Table 6.19: Start dates – Objective 1 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
1	Subbase	1	1	1	1	FF=0
2	Subbase	2	2,3	2,3	2,3	FF=0
3	Subbase	3	3,6	3,6	3,6	FF=0
4	Subbase	4	4,9	4,9	4,9	FF=0
5	Subbase	5	6,2	6,2	6,2	FF=0
6	Subbase	6	7,5	7,5	7,5	FF=0
7	Subbase	7	8,8	8,8	8,8	FF=0
8	Subbase	8	10,1	10,1	10,1	FF=0
9	Subbase	9	11,4	11,4	11,4	FF=0
10	Subbase	10	12,7	12,7	12,7	FF=0
11	Subbase	11	14	14	14	FF=0
12	Subbase	12	15,3	15,3	15,3	FF=0
13	Subbase	13	16,6	16,6	16,6	FF=0
14	Subbase	14	17,9	17,9	17,9	FF=0
15	Subbase	15	19,2	19,2	19,2	FF=0
16	Subbase	16	20,5	20,5	20,5	FF=0
17	Subbase	17	21,8	21,8	46,1	ES
18	Drainage	1	2,3	2,3	2,3	FF=0
19	Drainage	2	5,1	5,1	5,1	FF=0
20	Drainage	3	7,9	7,9	7,9	FF=0
21	Drainage	4	10,7	10,7	10,7	FF=0
22	Drainage	5	13,5	13,5	13,5	FF=0
23	Drainage	6	16,3	16,3	16,3	FF=0

Table 6.19 (continued): Start dates – Objective 1 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
24	Drainage	7	19,1	19,1	19,1	FF=0
25	Drainage	8	21,9	21,9	21,9	FF=0
26	Drainage	9	24,7	24,7	24,7	FF=0
27	Drainage	10	27,5	27,5	27,5	FF=0
28	Drainage	11	30,3	30,3	30,3	FF=0
29	Drainage	12	33,1	33,1	33,1	FF=0
30	Drainage	13	35,9	35,9	35,9	FF=0
31	Drainage	14	38,7	38,7	38,7	FF=0
32	Drainage	15	41,5	41,5	41,5	FF=0
33	Drainage	16	44,3	44,3	44,3	FF=0
34	Drainage	17	47,1	47,1	47,1	FF=0
35	Drainage	18	49,2	49,2	49,2	FF=0
36	Drainage	19	49,3	49,3	49,3	FF=0
37	Drainage	20	52,1	52,1	52,1	FF=0
38	Drainage	21	54,9	54,9	54,9	FF=0
39	Plantmix	1	5,1	5,1	5,1	FF=0
40	Plantmix	2	7,9	7,9	7,9	FF=0
41	Plantmix	3	10,7	10,7	10,7	FF=0
42	Plantmix	4	13,5	13,5	13,5	FF=0
43	Plantmix	5	16,3	16,3	16,3	FF=0
44	Plantmix	6	19,1	19,1	19,1	FF=0
45	Plantmix	7	21,9	21,9	21,9	FF=0
46	Plantmix	8	24,7	24,7	24,7	FF=0
47	Plantmix	9	27,5	27,5	27,5	FF=0
48	Plantmix	10	30,3	30,3	30,3	FF=0
49	Plantmix	11	33,1	33,1	33,1	FF=0
50	Plantmix	12	35,9	35,9	35,9	FF=0
51	Plantmix	13	38,7	38,7	38,7	FF=0
52	Plantmix	14	41,5	41,5	41,5	FF=0
53	Plantmix	15	44,3	44,3	44,3	FF=0
54	Plantmix	16	47,1	47,1	47,1	FF=0
55	Plantmix	17	49,2	49,2	49,2	FF=0
56	Plantmix	18	49,9	50,7	50,7	LS
57	Plantmix	19	52,1	52,1	52,1	FF=0
58	Plantmix	20	54,9	54,9	54,9	FF=0
59	Plantmix	21	56,6	56,6	56,6	FF=0
60	Binder	1	6	6	6	FF=0
61	Binder	2	8,8	8,8	8,8	FF=0
62	Binder	3	11,6	11,6	11,6	FF=0
63	Binder	4	14,4	14,4	14,4	FF=0
64	Binder	5	17,2	17,2	17,2	FF=0
65	Binder	6	20	20	20	FF=0

Table 6.19 (continued): Start dates – Objective 1 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
66	Binder	7	22,8	22,8	22,8	FF=0
67	Binder	8	25,6	25,6	25,6	FF=0
68	Binder	9	28,4	28,4	28,4	FF=0
69	Binder	10	31,2	31,2	31,2	FF=0
70	Binder	11	34	34	34	FF=0
71	Binder	12	36,8	36,8	36,8	FF=0
72	Binder	13	39,6	39,6	39,6	FF=0
73	Binder	14	42,4	42,4	42,4	FF=0
74	Binder	15	45,2	45,2	45,2	FF=0
75	Binder	16	48	48	48	FF=0
76	Binder	17	49,9	49,9	49,9	FF=0
77	Binder	18	50,8	50,8	51,3	ES
78	Binder	19	53	53	53	FF=0
79	Binder	20	55,8	55,8	55,8	FF=0
80	Binder	21	57,2	57,2	57,2	FF=0
81	Wearing	1	7,2	7,2	9,3	ES
82	Wearing	2	10	10	12,1	ES
83	Wearing	3	12,8	12,8	14,9	ES
84	Wearing	4	15,6	15,6	17,7	ES
85	Wearing	5	18,4	18,4	20,5	ES
86	Wearing	6	21,2	21,2	23,3	ES
87	Wearing	7	24	24	26,1	ES
88	Wearing	8	26,8	26,8	28,9	ES
89	Wearing	9	29,6	29,6	31,7	ES
90	Wearing	10	32,4	32,4	34,5	ES
91	Wearing	11	35,2	35,2	37,3	ES
92	Wearing	12	38	38	40,1	ES
93	Wearing	13	40,8	40,8	42,9	ES
94	Wearing	14	43,6	43,6	45,7	ES
95	Wearing	15	46,4	46,4	48,5	ES
96	Wearing	16	49,2	49,9	50,1	
97	Wearing	17	50,8	50,8	50,8	FF=0
98	Wearing	18	51,4	52	54,1	
99	Wearing	19	54,2	54,2	56,3	ES
100	Wearing	20	57	57,2	57,3	
101	Wearing	21	58	58	58	FF=0

Both number and percentage of the activities starting on either earliest or latest start dates are as shown in Table 6.20.

Table 6.20: Activity start date statistics – Objective 1 / Free Float

	Activities with float	
	Starting on ES	Starting on LS
Number of activities	18	1
Percentage of activities	81,81	4,54

Objective Function No.2 with Free Float Data Set

Solution statistics of the solution of the objective function no.2 for data set of the start dates calculated with free float were as shown in Figure 6.24.

Cplex	solution (optimal) with objective 200
Constraints	756189
Variables	129220
Binary	127967
Non-zero coefficients	1628632
MIP	
Objective	200
Nodes	245
Remaining nodes	0
Incumbent	200
Iterations	7244
Solution pool	
Count	3
Mean objective	210.666667

Figure 6.24: Solution statistics – Objective 2 / Free Float

In addition, start dates of the same data set after leveling can be seen in Table 6.21.

Table 6.21: Start dates – Objective 2 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
1	Subbase	1	1	1	1	FF=0
2	Subbase	2	2,3	2,3	2,3	FF=0
3	Subbase	3	3,6	3,6	3,6	FF=0
4	Subbase	4	4,9	4,9	4,9	FF=0
5	Subbase	5	6,2	6,2	6,2	FF=0
6	Subbase	6	7,5	7,5	7,5	FF=0
7	Subbase	7	8,8	8,8	8,8	FF=0
8	Subbase	8	10,1	10,1	10,1	FF=0
9	Subbase	9	11,4	11,4	11,4	FF=0

Table 6.21 (continued): Start dates – Objective 2 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
10	Subbase	10	12,7	12,7	12,7	FF=0
11	Subbase	11	14	14	14	FF=0
12	Subbase	12	15,3	15,3	15,3	FF=0
13	Subbase	13	16,6	16,6	16,6	FF=0
14	Subbase	14	17,9	17,9	17,9	FF=0
15	Subbase	15	19,2	19,2	19,2	FF=0
16	Subbase	16	20,5	20,5	20,5	FF=0
17	Subbase	17	21,8	21,8	46,1	ES
18	Drainage	1	2,3	2,3	2,3	FF=0
19	Drainage	2	5,1	5,1	5,1	FF=0
20	Drainage	3	7,9	7,9	7,9	FF=0
21	Drainage	4	10,7	10,7	10,7	FF=0
22	Drainage	5	13,5	13,5	13,5	FF=0
23	Drainage	6	16,3	16,3	16,3	FF=0
24	Drainage	7	19,1	19,1	19,1	FF=0
25	Drainage	8	21,9	21,9	21,9	FF=0
26	Drainage	9	24,7	24,7	24,7	FF=0
27	Drainage	10	27,5	27,5	27,5	FF=0
28	Drainage	11	30,3	30,3	30,3	FF=0
29	Drainage	12	33,1	33,1	33,1	FF=0
30	Drainage	13	35,9	35,9	35,9	FF=0
31	Drainage	14	38,7	38,7	38,7	FF=0
32	Drainage	15	41,5	41,5	41,5	FF=0
33	Drainage	16	44,3	44,3	44,3	FF=0
34	Drainage	17	47,1	47,1	47,1	FF=0
35	Drainage	18	49,2	49,2	49,2	FF=0
36	Drainage	19	49,3	49,3	49,3	FF=0
37	Drainage	20	52,1	52,1	52,1	FF=0
38	Drainage	21	54,9	54,9	54,9	FF=0
39	Plantmix	1	5,1	5,1	5,1	FF=0
40	Plantmix	2	7,9	7,9	7,9	FF=0
41	Plantmix	3	10,7	10,7	10,7	FF=0
42	Plantmix	4	13,5	13,5	13,5	FF=0
43	Plantmix	5	16,3	16,3	16,3	FF=0
44	Plantmix	6	19,1	19,1	19,1	FF=0
45	Plantmix	7	21,9	21,9	21,9	FF=0
46	Plantmix	8	24,7	24,7	24,7	FF=0
47	Plantmix	9	27,5	27,5	27,5	FF=0
48	Plantmix	10	30,3	30,3	30,3	FF=0
49	Plantmix	11	33,1	33,1	33,1	FF=0
50	Plantmix	12	35,9	35,9	35,9	FF=0
51	Plantmix	13	38,7	38,7	38,7	FF=0

Table 6.21 (continued): Start dates – Objective 2 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
52	Plantmix	14	41,5	41,5	41,5	FF=0
53	Plantmix	15	44,3	44,3	44,3	FF=0
54	Plantmix	16	47,1	47,1	47,1	FF=0
55	Plantmix	17	49,2	49,2	49,2	FF=0
56	Plantmix	18	49,9	49,9	50,7	ES
57	Plantmix	19	52,1	52,1	52,1	FF=0
58	Plantmix	20	54,9	54,9	54,9	FF=0
59	Plantmix	21	56,6	56,6	56,6	FF=0
60	Binder	1	6	6	6	FF=0
61	Binder	2	8,8	8,8	8,8	FF=0
62	Binder	3	11,6	11,6	11,6	FF=0
63	Binder	4	14,4	14,4	14,4	FF=0
64	Binder	5	17,2	17,2	17,2	FF=0
65	Binder	6	20	20	20	FF=0
66	Binder	7	22,8	22,8	22,8	FF=0
67	Binder	8	25,6	25,6	25,6	FF=0
68	Binder	9	28,4	28,4	28,4	FF=0
69	Binder	10	31,2	31,2	31,2	FF=0
70	Binder	11	34	34	34	FF=0
71	Binder	12	36,8	36,8	36,8	FF=0
72	Binder	13	39,6	39,6	39,6	FF=0
73	Binder	14	42,4	42,4	42,4	FF=0
74	Binder	15	45,2	45,2	45,2	FF=0
75	Binder	16	48	48	48	FF=0
76	Binder	17	49,9	49,9	49,9	FF=0
77	Binder	18	50,8	50,8	51,3	ES
78	Binder	19	53	53	53	FF=0
79	Binder	20	55,8	55,8	55,8	FF=0
80	Binder	21	57,2	57,2	57,2	FF=0
81	Wearing	1	7,2	7,2	9,3	ES
82	Wearing	2	10	10	12,1	ES
83	Wearing	3	12,8	12,8	14,9	ES
84	Wearing	4	15,6	15,6	17,7	ES
85	Wearing	5	18,4	18,4	20,5	ES
86	Wearing	6	21,2	21,2	23,3	ES
87	Wearing	7	24	24	26,1	ES
88	Wearing	8	26,8	26,8	28,9	ES
89	Wearing	9	29,6	29,6	31,7	ES
90	Wearing	10	32,4	32,4	34,5	ES
91	Wearing	11	35,2	35,2	37,3	ES
92	Wearing	12	38	38	40,1	ES
93	Wearing	13	40,8	40,8	42,9	ES

No.	Name	Location	ES	Leveled Start	LS	Start Info
94	Wearing	14	43,6	43,6	45,7	ES
95	Wearing	15	46,4	46,4	48,5	ES
96	Wearing	16	49,2	50	50,1	
97	Wearing	17	50,8	50,8	50,8	FF=0
98	Wearing	18	51,4	51,4	54,1	ES
99	Wearing	19	54,2	54,2	56,3	ES
100	Wearing	20	57	57	57,3	ES
101	Wearing	21	58	58	58	FF=0

Both number and percentage of the activities starting on either earliest or latest start dates are as shown in Table 6.22.

Table 6.22: Activity start date statistics – Objective 2 / Free Float

	Activities with float	
	Starting on ES	Starting on LS
Number of activities	21	0
Percentage of activities	95,45	0,00

Objective Function No.3 with Free Float Data Set

Solution statistics of the solution of the objective function no.3 for data set of the start dates calculated with free float were as shown in Figure 6.25.

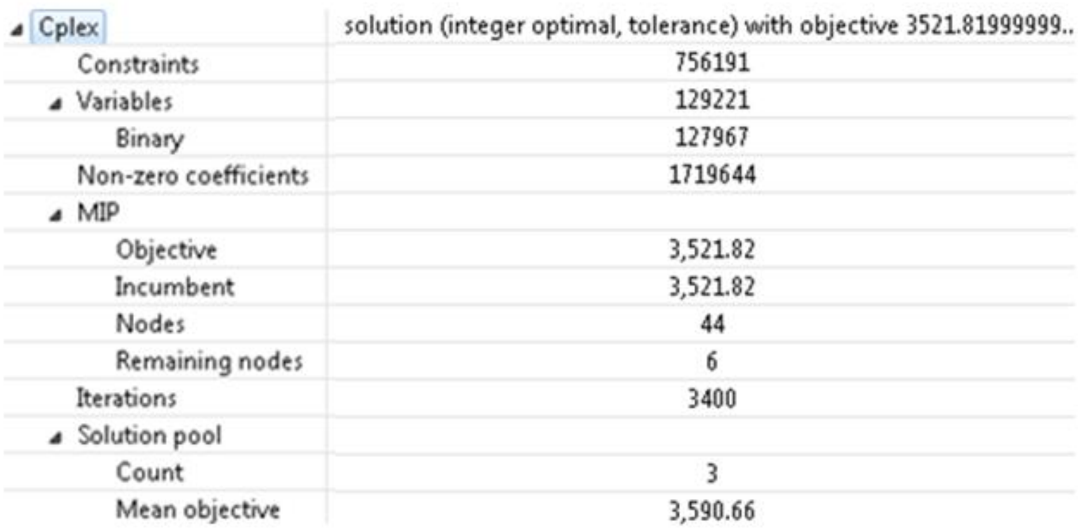


Figure 6.25: Solution statistics – Objective 3 / Free Float

In addition, start dates of the same data set after leveling can be seen in Table 6.23.

Table 6.23: Start dates – Objective 3 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
1	Subbase	1	1	1	1	FF=0
2	Subbase	2	2,3	2,3	2,3	FF=0
3	Subbase	3	3,6	3,6	3,6	FF=0
4	Subbase	4	4,9	4,9	4,9	FF=0
5	Subbase	5	6,2	6,2	6,2	FF=0
6	Subbase	6	7,5	7,5	7,5	FF=0
7	Subbase	7	8,8	8,8	8,8	FF=0
8	Subbase	8	10,1	10,1	10,1	FF=0
9	Subbase	9	11,4	11,4	11,4	FF=0
10	Subbase	10	12,7	12,7	12,7	FF=0
11	Subbase	11	14	14	14	FF=0
12	Subbase	12	15,3	15,3	15,3	FF=0
13	Subbase	13	16,6	16,6	16,6	FF=0
14	Subbase	14	17,9	17,9	17,9	FF=0
15	Subbase	15	19,2	19,2	19,2	FF=0
16	Subbase	16	20,5	20,5	20,5	FF=0
17	Subbase	17	21,8	34,9	46,1	
18	Drainage	1	2,3	2,3	2,3	FF=0
19	Drainage	2	5,1	5,1	5,1	FF=0
20	Drainage	3	7,9	7,9	7,9	FF=0
21	Drainage	4	10,7	10,7	10,7	FF=0
22	Drainage	5	13,5	13,5	13,5	FF=0
23	Drainage	6	16,3	16,3	16,3	FF=0
24	Drainage	7	19,1	19,1	19,1	FF=0
25	Drainage	8	21,9	21,9	21,9	FF=0
26	Drainage	9	24,7	24,7	24,7	FF=0
27	Drainage	10	27,5	27,5	27,5	FF=0
28	Drainage	11	30,3	30,3	30,3	FF=0
29	Drainage	12	33,1	33,1	33,1	FF=0
30	Drainage	13	35,9	35,9	35,9	FF=0
31	Drainage	14	38,7	38,7	38,7	FF=0
32	Drainage	15	41,5	41,5	41,5	FF=0
33	Drainage	16	44,3	44,3	44,3	FF=0
34	Drainage	17	47,1	47,1	47,1	FF=0
35	Drainage	18	49,2	49,2	49,2	FF=0
36	Drainage	19	49,3	49,3	49,3	FF=0
37	Drainage	20	52,1	52,1	52,1	FF=0
38	Drainage	21	54,9	54,9	54,9	FF=0
39	Plantmix	1	5,1	5,1	5,1	FF=0
40	Plantmix	2	7,9	7,9	7,9	FF=0
41	Plantmix	3	10,7	10,7	10,7	FF=0
42	Plantmix	4	13,5	13,5	13,5	FF=0
43	Plantmix	5	16,3	16,3	16,3	FF=0

Table 6.23 (continued): Start dates – Objective 3 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
44	Plantmix	6	19,1	19,1	19,1	FF=0
45	Plantmix	7	21,9	21,9	21,9	FF=0
46	Plantmix	8	24,7	24,7	24,7	FF=0
47	Plantmix	9	27,5	27,5	27,5	FF=0
48	Plantmix	10	30,3	30,3	30,3	FF=0
49	Plantmix	11	33,1	33,1	33,1	FF=0
50	Plantmix	12	35,9	35,9	35,9	FF=0
51	Plantmix	13	38,7	38,7	38,7	FF=0
52	Plantmix	14	41,5	41,5	41,5	FF=0
53	Plantmix	15	44,3	44,3	44,3	FF=0
54	Plantmix	16	47,1	47,1	47,1	FF=0
55	Plantmix	17	49,2	49,2	49,2	FF=0
56	Plantmix	18	49,9	50,6	50,7	
57	Plantmix	19	52,1	52,1	52,1	FF=0
58	Plantmix	20	54,9	54,9	54,9	FF=0
59	Plantmix	21	56,6	56,6	56,6	FF=0
60	Binder	1	6	6	6	FF=0
61	Binder	2	8,8	8,8	8,8	FF=0
62	Binder	3	11,6	11,6	11,6	FF=0
63	Binder	4	14,4	14,4	14,4	FF=0
64	Binder	5	17,2	17,2	17,2	FF=0
65	Binder	6	20	20	20	FF=0
66	Binder	7	22,8	22,8	22,8	FF=0
67	Binder	8	25,6	25,6	25,6	FF=0
68	Binder	9	28,4	28,4	28,4	FF=0
69	Binder	10	31,2	31,2	31,2	FF=0
70	Binder	11	34	34	34	FF=0
71	Binder	12	36,8	36,8	36,8	FF=0
72	Binder	13	39,6	39,6	39,6	FF=0
73	Binder	14	42,4	42,4	42,4	FF=0
74	Binder	15	45,2	45,2	45,2	FF=0
75	Binder	16	48	48	48	FF=0
76	Binder	17	49,9	49,9	49,9	FF=0
77	Binder	18	50,8	51	51,3	
78	Binder	19	53	53	53	FF=0
79	Binder	20	55,8	55,8	55,8	FF=0
80	Binder	21	57,2	57,2	57,2	FF=0
81	Wearing	1	7,2	9,1	9,3	
82	Wearing	2	10	10	12,1	ES
83	Wearing	3	12,8	12,8	14,9	ES
84	Wearing	4	15,6	15,6	17,7	ES
85	Wearing	5	18,4	19,2	20,5	

Table 6.23 (continued): Start dates – Objective 3 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
86	Wearing	6	21,2	22,8	23,3	
87	Wearing	7	24	24	26,1	ES
88	Wearing	8	26,8	26,8	28,9	ES
89	Wearing	9	29,6	29,6	31,7	ES
90	Wearing	10	32,4	32,4	34,5	ES
91	Wearing	11	35,2	37,3	37,3	LS
92	Wearing	12	38	38	40,1	ES
93	Wearing	13	40,8	40,8	42,9	ES
94	Wearing	14	43,6	43,6	45,7	ES
95	Wearing	15	46,4	46,4	48,5	ES
96	Wearing	16	49,2	49,9	50,1	
97	Wearing	17	50,8	50,8	50,8	FF=0
98	Wearing	18	51,4	51,8	54,1	
99	Wearing	19	54,2	54,2	56,3	ES
100	Wearing	20	57	57,3	57,3	LS
101	Wearing	21	58	58	58	FF=0

Both number and percentage of the activities starting on either earliest or latest start dates are as shown in Table 6.24.

Table 6.24: Activity start date statistics – Objective 3 / Free Float

	Activities with float	
	Starting on ES	Starting on LS
Number of activities	12	2
Percentage of activities	54,54	9,09

Objective Function No.4 with Free Float Data Set

Solution statistics of the solution of the objective function no.4 for data set of the start dates calculated with free float were as shown in Figure 6.26

Cplex	solution (optimal) with objective 32
Constraints	755615
Variables	128646
Binary	127967
Non-zero coefficients	1627484
MIP	
Objective	32
Incumbent	32
Nodes	0
Remaining nodes	0
Iterations	2
Solution pool	
Count	1
Mean objective	32

Figure 6.26: Solution statistics – Objective 4 / Free Float

In addition, start dates of the same data set after leveling can be seen in Table 6.25.

Table 6.25: Start dates – Objective 4 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
1	Subbase	1	1	1	1	FF=0
2	Subbase	2	2,3	2,3	2,3	FF=0
3	Subbase	3	3,6	3,6	3,6	FF=0
4	Subbase	4	4,9	4,9	4,9	FF=0
5	Subbase	5	6,2	6,2	6,2	FF=0
6	Subbase	6	7,5	7,5	7,5	FF=0
7	Subbase	7	8,8	8,8	8,8	FF=0
8	Subbase	8	10,1	10,1	10,1	FF=0
9	Subbase	9	11,4	11,4	11,4	FF=0
10	Subbase	10	12,7	12,7	12,7	FF=0
11	Subbase	11	14	14	14	FF=0
12	Subbase	12	15,3	15,3	15,3	FF=0
13	Subbase	13	16,6	16,6	16,6	FF=0
14	Subbase	14	17,9	17,9	17,9	FF=0
15	Subbase	15	19,2	19,2	19,2	FF=0
16	Subbase	16	20,5	20,5	20,5	FF=0
17	Subbase	17	21,8	46,1	46,1	LS
18	Drainage	1	2,3	2,3	2,3	FF=0
19	Drainage	2	5,1	5,1	5,1	FF=0
20	Drainage	3	7,9	7,9	7,9	FF=0
21	Drainage	4	10,7	10,7	10,7	FF=0
22	Drainage	5	13,5	13,5	13,5	FF=0

Table 6.25 (continued): Start dates – Objective 4 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
23	Drainage	6	16,3	16,3	16,3	FF=0
24	Drainage	7	19,1	19,1	19,1	FF=0
25	Drainage	8	21,9	21,9	21,9	FF=0
26	Drainage	9	24,7	24,7	24,7	FF=0
27	Drainage	10	27,5	27,5	27,5	FF=0
28	Drainage	11	30,3	30,3	30,3	FF=0
29	Drainage	12	33,1	33,1	33,1	FF=0
30	Drainage	13	35,9	35,9	35,9	FF=0
31	Drainage	14	38,7	38,7	38,7	FF=0
32	Drainage	15	41,5	41,5	41,5	FF=0
33	Drainage	16	44,3	44,3	44,3	FF=0
34	Drainage	17	47,1	47,1	47,1	FF=0
35	Drainage	18	49,2	49,2	49,2	FF=0
36	Drainage	19	49,3	49,3	49,3	FF=0
37	Drainage	20	52,1	52,1	52,1	FF=0
38	Drainage	21	54,9	54,9	54,9	FF=0
39	Plantmix	1	5,1	5,1	5,1	FF=0
40	Plantmix	2	7,9	7,9	7,9	FF=0
41	Plantmix	3	10,7	10,7	10,7	FF=0
42	Plantmix	4	13,5	13,5	13,5	FF=0
43	Plantmix	5	16,3	16,3	16,3	FF=0
44	Plantmix	6	19,1	19,1	19,1	FF=0
45	Plantmix	7	21,9	21,9	21,9	FF=0
46	Plantmix	8	24,7	24,7	24,7	FF=0
47	Plantmix	9	27,5	27,5	27,5	FF=0
48	Plantmix	10	30,3	30,3	30,3	FF=0
49	Plantmix	11	33,1	33,1	33,1	FF=0
50	Plantmix	12	35,9	35,9	35,9	FF=0
51	Plantmix	13	38,7	38,7	38,7	FF=0
52	Plantmix	14	41,5	41,5	41,5	FF=0
53	Plantmix	15	44,3	44,3	44,3	FF=0
54	Plantmix	16	47,1	47,1	47,1	FF=0
55	Plantmix	17	49,2	49,2	49,2	FF=0
56	Plantmix	18	49,9	50,7	50,7	LS
57	Plantmix	19	52,1	52,1	52,1	FF=0
58	Plantmix	20	54,9	54,9	54,9	FF=0
59	Plantmix	21	56,6	56,6	56,6	FF=0
60	Binder	1	6	6	6	FF=0
61	Binder	2	8,8	8,8	8,8	FF=0
62	Binder	3	11,6	11,6	11,6	FF=0
63	Binder	4	14,4	14,4	14,4	FF=0
64	Binder	5	17,2	17,2	17,2	FF=0

Table 6.25 (continued): Start dates – Objective 4 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
65	Binder	6	20	20	20	FF=0
66	Binder	7	22,8	22,8	22,8	FF=0
67	Binder	8	25,6	25,6	25,6	FF=0
68	Binder	9	28,4	28,4	28,4	FF=0
69	Binder	10	31,2	31,2	31,2	FF=0
70	Binder	11	34	34	34	FF=0
71	Binder	12	36,8	36,8	36,8	FF=0
72	Binder	13	39,6	39,6	39,6	FF=0
73	Binder	14	42,4	42,4	42,4	FF=0
74	Binder	15	45,2	45,2	45,2	FF=0
75	Binder	16	48	48	48	FF=0
76	Binder	17	49,9	49,9	49,9	FF=0
77	Binder	18	50,8	51,3	51,3	LS
78	Binder	19	53	53	53	FF=0
79	Binder	20	55,8	55,8	55,8	FF=0
80	Binder	21	57,2	57,2	57,2	FF=0
81	Wearing	1	7,2	9,3	9,3	LS
82	Wearing	2	10	12,1	12,1	LS
83	Wearing	3	12,8	14,9	14,9	LS
84	Wearing	4	15,6	17,7	17,7	LS
85	Wearing	5	18,4	20,5	20,5	LS
86	Wearing	6	21,2	23,3	23,3	LS
87	Wearing	7	24	26,1	26,1	LS
88	Wearing	8	26,8	28,9	28,9	LS
89	Wearing	9	29,6	31,7	31,7	LS
90	Wearing	10	32,4	34,5	34,5	LS
91	Wearing	11	35,2	37,3	37,3	LS
92	Wearing	12	38	40,1	40,1	LS
93	Wearing	13	40,8	42,9	42,9	LS
94	Wearing	14	43,6	45,7	45,7	LS
95	Wearing	15	46,4	48,5	48,5	LS
96	Wearing	16	49,2	50,1	50,1	LS
97	Wearing	17	50,8	50,8	50,8	FF=0
98	Wearing	18	51,4	54,1	54,1	LS
99	Wearing	19	54,2	56,3	56,3	LS
100	Wearing	20	57	57,3	57,3	LS
101	Wearing	21	58	58	58	FF=0

Both number and percentage of the activities starting on either earliest or latest start dates are as shown in Table 6.26.

Table 6.26: Activity start date statistics – Objective 4 / Free Float

	Activities with float	
	Starting on ES	Starting on LS
Number of activities	0	22
Percentage of activities	0,00	100

Objective Function No.5 with Free Float Data Set

Solution statistics of the solution of the objective function no.5 for data set of the start dates calculated with free float were as shown in Figure 6.27.

Cplex	solution (optimal) with objective 16
Constraints	756764
Variables	129221
Binary	127967
Non-zero coefficients	1630932
MIP	
Objective	16
Nodes	0
Remaining nodes	0
Incumbent	16
Iterations	26
Solution pool	
Count	1
Mean objective	16

Figure 6.27: Solution statistics – Objective 5 / Free Float

In addition, start dates of the same data set after leveling can be seen in Table 6.27.

Table 6.27: Start dates – Objective 5 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
1	Subbase	1	1	1	1	FF=0
2	Subbase	2	2,3	2,3	2,3	FF=0
3	Subbase	3	3,6	3,6	3,6	FF=0
4	Subbase	4	4,9	4,9	4,9	FF=0
5	Subbase	5	6,2	6,2	6,2	FF=0
6	Subbase	6	7,5	7,5	7,5	FF=0
7	Subbase	7	8,8	8,8	8,8	FF=0
8	Subbase	8	10,1	10,1	10,1	FF=0
9	Subbase	9	11,4	11,4	11,4	FF=0

Table 6.27 (continued): Start dates – Objective 5 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
10	Subbase	10	12,7	12,7	12,7	FF=0
11	Subbase	11	14	14	14	FF=0
12	Subbase	12	15,3	15,3	15,3	FF=0
13	Subbase	13	16,6	16,6	16,6	FF=0
14	Subbase	14	17,9	17,9	17,9	FF=0
15	Subbase	15	19,2	19,2	19,2	FF=0
16	Subbase	16	20,5	20,5	20,5	FF=0
17	Subbase	17	21,8	45,6	46,1	
18	Drainage	1	2,3	2,3	2,3	FF=0
19	Drainage	2	5,1	5,1	5,1	FF=0
20	Drainage	3	7,9	7,9	7,9	FF=0
21	Drainage	4	10,7	10,7	10,7	FF=0
22	Drainage	5	13,5	13,5	13,5	FF=0
23	Drainage	6	16,3	16,3	16,3	FF=0
24	Drainage	7	19,1	19,1	19,1	FF=0
25	Drainage	8	21,9	21,9	21,9	FF=0
26	Drainage	9	24,7	24,7	24,7	FF=0
27	Drainage	10	27,5	27,5	27,5	FF=0
28	Drainage	11	30,3	30,3	30,3	FF=0
29	Drainage	12	33,1	33,1	33,1	FF=0
30	Drainage	13	35,9	35,9	35,9	FF=0
31	Drainage	14	38,7	38,7	38,7	FF=0
32	Drainage	15	41,5	41,5	41,5	FF=0
33	Drainage	16	44,3	44,3	44,3	FF=0
34	Drainage	17	47,1	47,1	47,1	FF=0
35	Drainage	18	49,2	49,2	49,2	FF=0
36	Drainage	19	49,3	49,3	49,3	FF=0
37	Drainage	20	52,1	52,1	52,1	FF=0
38	Drainage	21	54,9	54,9	54,9	FF=0
39	Plantmix	1	5,1	5,1	5,1	FF=0
40	Plantmix	2	7,9	7,9	7,9	FF=0
41	Plantmix	3	10,7	10,7	10,7	FF=0
42	Plantmix	4	13,5	13,5	13,5	FF=0
43	Plantmix	5	16,3	16,3	16,3	FF=0
44	Plantmix	6	19,1	19,1	19,1	FF=0
45	Plantmix	7	21,9	21,9	21,9	FF=0
46	Plantmix	8	24,7	24,7	24,7	FF=0
47	Plantmix	9	27,5	27,5	27,5	FF=0
48	Plantmix	10	30,3	30,3	30,3	FF=0
49	Plantmix	11	33,1	33,1	33,1	FF=0
50	Plantmix	12	35,9	35,9	35,9	FF=0
51	Plantmix	13	38,7	38,7	38,7	FF=0

Table 6.27 (continued): Start dates – Objective 5 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
52	Plantmix	14	41,5	41,5	41,5	FF=0
53	Plantmix	15	44,3	44,3	44,3	FF=0
54	Plantmix	16	47,1	47,1	47,1	FF=0
55	Plantmix	17	49,2	49,2	49,2	FF=0
56	Plantmix	18	49,9	49,9	50,7	ES
57	Plantmix	19	52,1	52,1	52,1	FF=0
58	Plantmix	20	54,9	54,9	54,9	FF=0
59	Plantmix	21	56,6	56,6	56,6	FF=0
60	Binder	1	6	6	6	FF=0
61	Binder	2	8,8	8,8	8,8	FF=0
62	Binder	3	11,6	11,6	11,6	FF=0
63	Binder	4	14,4	14,4	14,4	FF=0
64	Binder	5	17,2	17,2	17,2	FF=0
65	Binder	6	20	20	20	FF=0
66	Binder	7	22,8	22,8	22,8	FF=0
67	Binder	8	25,6	25,6	25,6	FF=0
68	Binder	9	28,4	28,4	28,4	FF=0
69	Binder	10	31,2	31,2	31,2	FF=0
70	Binder	11	34	34	34	FF=0
71	Binder	12	36,8	36,8	36,8	FF=0
72	Binder	13	39,6	39,6	39,6	FF=0
73	Binder	14	42,4	42,4	42,4	FF=0
74	Binder	15	45,2	45,2	45,2	FF=0
75	Binder	16	48	48	48	FF=0
76	Binder	17	49,9	49,9	49,9	FF=0
77	Binder	18	50,8	51,3	51,3	LS
78	Binder	19	53	53	53	FF=0
79	Binder	20	55,8	55,8	55,8	FF=0
80	Binder	21	57,2	57,2	57,2	FF=0
81	Wearing	1	7,2	8,6	9,3	
82	Wearing	2	10	10	12,1	ES
83	Wearing	3	12,8	12,8	14,9	ES
84	Wearing	4	15,6	15,6	17,7	ES
85	Wearing	5	18,4	18,4	20,5	ES
86	Wearing	6	21,2	21,2	23,3	ES
87	Wearing	7	24	24	26,1	ES
88	Wearing	8	26,8	26,8	28,9	ES
89	Wearing	9	29,6	29,6	31,7	ES
90	Wearing	10	32,4	32,4	34,5	ES
91	Wearing	11	35,2	35,2	37,3	ES
92	Wearing	12	38	38	40,1	ES
93	Wearing	13	40,8	40,8	42,9	ES

Table 6.27 (continued): Start dates – Objective 5 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
94	Wearing	14	43,6	43,6	45,7	ES
95	Wearing	15	46,4	46,4	48,5	ES
96	Wearing	16	49,2	49,7	50,1	
97	Wearing	17	50,8	50,8	50,8	FF=0
98	Wearing	18	51,4	52	54,1	
99	Wearing	19	54,2	56,3	56,3	LS
100	Wearing	20	57	57	57,3	ES
101	Wearing	21	58	58	58	FF=0

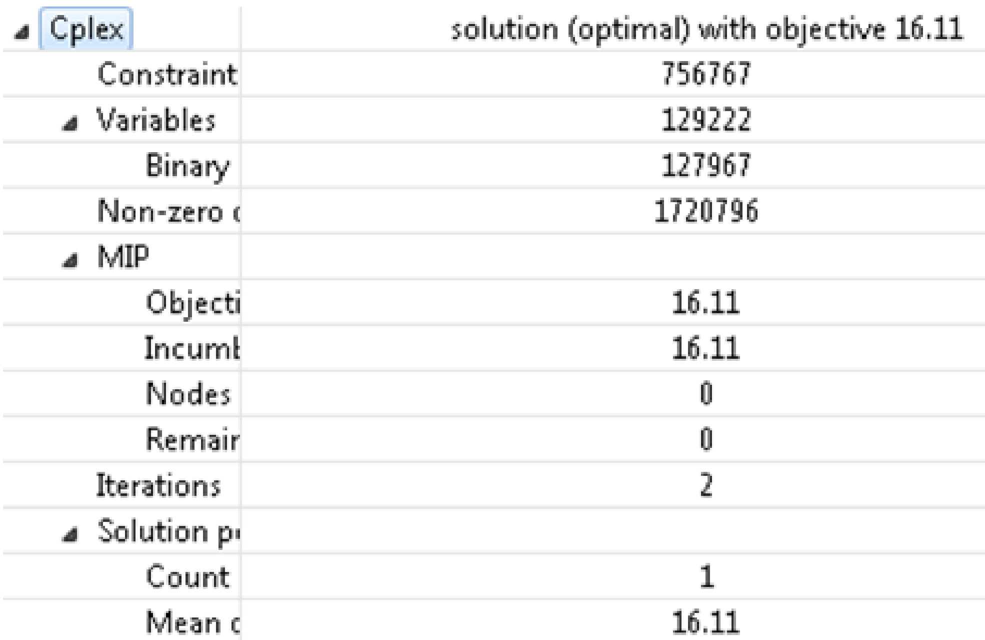
Both number and percentage of the activities starting on either earliest or latest start dates are as shown in Table 6.28.

Table 6.28: Activity start date statistics – Objective 5 / Free Float

	Activities with float	
	Starting on ES	Starting on LS
Number of activities	16	2
Percentage of activities	72,72	9,09

Objective Function No.6 with Free Float Data Set

Solution statistics of the solution of the objective function no.3 for data set of the start dates calculated with free float were as shown in Figure 6.28.



Cplex	solution (optimal) with objective 16.11
Constraint	756767
Variables	129222
Binary	127967
Non-zero c	1720796
MIP	
Objecti	16.11
Incumb	16.11
Nodes	0
Remair	0
Iterations	2
Solution p	
Count	1
Mean c	16.11

Figure 6.28: Solution statistics – Objective 6 / Free Float

In addition, start dates of the same data set after leveling can be seen in Table 6.29.

Table 6.29: Start dates – Objective 6 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
1	Subbase	1	1	1	1	FF=0
2	Subbase	2	2,3	2,3	2,3	FF=0
3	Subbase	3	3,6	3,6	3,6	FF=0
4	Subbase	4	4,9	4,9	4,9	FF=0
5	Subbase	5	6,2	6,2	6,2	FF=0
6	Subbase	6	7,5	7,5	7,5	FF=0
7	Subbase	7	8,8	8,8	8,8	FF=0
8	Subbase	8	10,1	10,1	10,1	FF=0
9	Subbase	9	11,4	11,4	11,4	FF=0
10	Subbase	10	12,7	12,7	12,7	FF=0
11	Subbase	11	14	14	14	FF=0
12	Subbase	12	15,3	15,3	15,3	FF=0
13	Subbase	13	16,6	16,6	16,6	FF=0
14	Subbase	14	17,9	17,9	17,9	FF=0
15	Subbase	15	19,2	19,2	19,2	FF=0
16	Subbase	16	20,5	20,5	20,5	FF=0
17	Subbase	17	21,8	46,1	46,1	LS
18	Drainage	1	2,3	2,3	2,3	FF=0
19	Drainage	2	5,1	5,1	5,1	FF=0
20	Drainage	3	7,9	7,9	7,9	FF=0
21	Drainage	4	10,7	10,7	10,7	FF=0
22	Drainage	5	13,5	13,5	13,5	FF=0
23	Drainage	6	16,3	16,3	16,3	FF=0
24	Drainage	7	19,1	19,1	19,1	FF=0
25	Drainage	8	21,9	21,9	21,9	FF=0
26	Drainage	9	24,7	24,7	24,7	FF=0
27	Drainage	10	27,5	27,5	27,5	FF=0
28	Drainage	11	30,3	30,3	30,3	FF=0
29	Drainage	12	33,1	33,1	33,1	FF=0
30	Drainage	13	35,9	35,9	35,9	FF=0
31	Drainage	14	38,7	38,7	38,7	FF=0
32	Drainage	15	41,5	41,5	41,5	FF=0
33	Drainage	16	44,3	44,3	44,3	FF=0
34	Drainage	17	47,1	47,1	47,1	FF=0
35	Drainage	18	49,2	49,2	49,2	FF=0
36	Drainage	19	49,3	49,3	49,3	FF=0
37	Drainage	20	52,1	52,1	52,1	FF=0
38	Drainage	21	54,9	54,9	54,9	FF=0
39	Plantmix	1	5,1	5,1	5,1	FF=0
40	Plantmix	2	7,9	7,9	7,9	FF=0
41	Plantmix	3	10,7	10,7	10,7	FF=0

Table 6.29 (continued): Start dates – Objective 6 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
42	Plantmix	4	13,5	13,5	13,5	FF=0
43	Plantmix	5	16,3	16,3	16,3	FF=0
44	Plantmix	6	19,1	19,1	19,1	FF=0
45	Plantmix	7	21,9	21,9	21,9	FF=0
46	Plantmix	8	24,7	24,7	24,7	FF=0
47	Plantmix	9	27,5	27,5	27,5	FF=0
48	Plantmix	10	30,3	30,3	30,3	FF=0
49	Plantmix	11	33,1	33,1	33,1	FF=0
50	Plantmix	12	35,9	35,9	35,9	FF=0
51	Plantmix	13	38,7	38,7	38,7	FF=0
52	Plantmix	14	41,5	41,5	41,5	FF=0
53	Plantmix	15	44,3	44,3	44,3	FF=0
54	Plantmix	16	47,1	47,1	47,1	FF=0
55	Plantmix	17	49,2	49,2	49,2	FF=0
56	Plantmix	18	49,9	50,7	50,7	LS
57	Plantmix	19	52,1	52,1	52,1	FF=0
58	Plantmix	20	54,9	54,9	54,9	FF=0
59	Plantmix	21	56,6	56,6	56,6	FF=0
60	Binder	1	6	6	6	FF=0
61	Binder	2	8,8	8,8	8,8	FF=0
62	Binder	3	11,6	11,6	11,6	FF=0
63	Binder	4	14,4	14,4	14,4	FF=0
64	Binder	5	17,2	17,2	17,2	FF=0
65	Binder	6	20	20	20	FF=0
66	Binder	7	22,8	22,8	22,8	FF=0
67	Binder	8	25,6	25,6	25,6	FF=0
68	Binder	9	28,4	28,4	28,4	FF=0
69	Binder	10	31,2	31,2	31,2	FF=0
70	Binder	11	34	34	34	FF=0
71	Binder	12	36,8	36,8	36,8	FF=0
72	Binder	13	39,6	39,6	39,6	FF=0
73	Binder	14	42,4	42,4	42,4	FF=0
74	Binder	15	45,2	45,2	45,2	FF=0
75	Binder	16	48	48	48	FF=0
76	Binder	17	49,9	49,9	49,9	FF=0
77	Binder	18	50,8	51,3	51,3	LS
78	Binder	19	53	53	53	FF=0
79	Binder	20	55,8	55,8	55,8	FF=0
80	Binder	21	57,2	57,2	57,2	FF=0
81	Wearing	1	7,2	9,3	9,3	LS
82	Wearing	2	10	12,1	12,1	LS
83	Wearing	3	12,8	14,9	14,9	LS

Table 6.29 (continued): Start dates – Objective 6 / Free Float

No.	Name	Location	ES	Leveled Start	LS	Start Info
84	Wearing	4	15,6	17,7	17,7	LS
85	Wearing	5	18,4	20,5	20,5	LS
86	Wearing	6	21,2	23,3	23,3	LS
87	Wearing	7	24	26,1	26,1	LS
88	Wearing	8	26,8	28,9	28,9	LS
89	Wearing	9	29,6	31,7	31,7	LS
90	Wearing	10	32,4	34,5	34,5	LS
91	Wearing	11	35,2	37,3	37,3	LS
92	Wearing	12	38	40,1	40,1	LS
93	Wearing	13	40,8	42,9	42,9	LS
94	Wearing	14	43,6	45,7	45,7	LS
95	Wearing	15	46,4	48,5	48,5	LS
96	Wearing	16	49,2	50,1	50,1	LS
97	Wearing	17	50,8	50,8	50,8	FF=0
98	Wearing	18	51,4	54,1	54,1	LS
99	Wearing	19	54,2	56,3	56,3	LS
100	Wearing	20	57	57,3	57,3	LS
101	Wearing	21	58	58	58	FF=0

Both number and percentage of the activities starting on either earliest or latest start dates are as shown in Table 6.30.

Table 6.30: Activity start date statistics – Objective 6 / Free Float

	Activities with float	
	Starting on ES	Starting on LS
Number of activities	0	22
Percentage of activities	0,00	100

7. RESULTS & DISCUSSIONS

Resource histogram for the activities starting on earliest start dates is as shown in Figure 7.1.

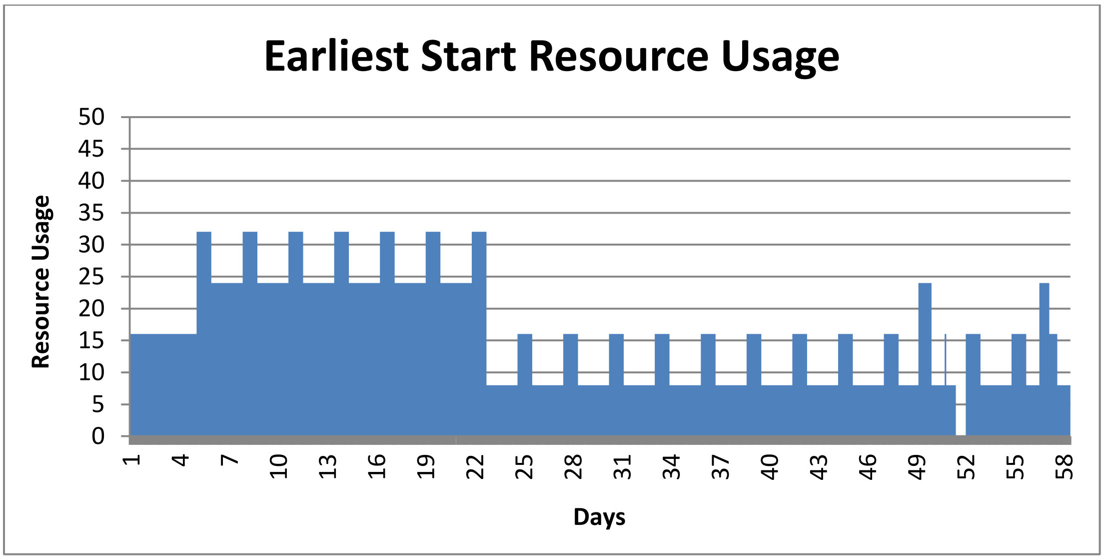


Figure 7.1: Resource histogram for earliest start dates

Resource histogram for the activities starting on latest start dates calculated with total floats is as shown in Figure 7.2.

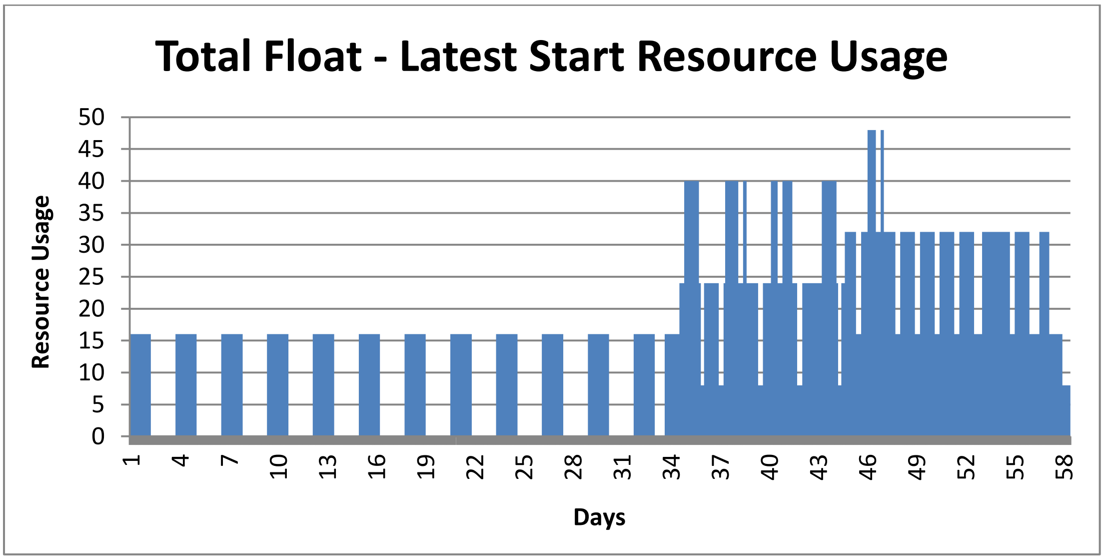


Figure 7.2: Resource histogram for latest start dates (total float)

Resource histogram for the activities starting on latest start dates calculated with free floats is as shown in Figure 7.3.

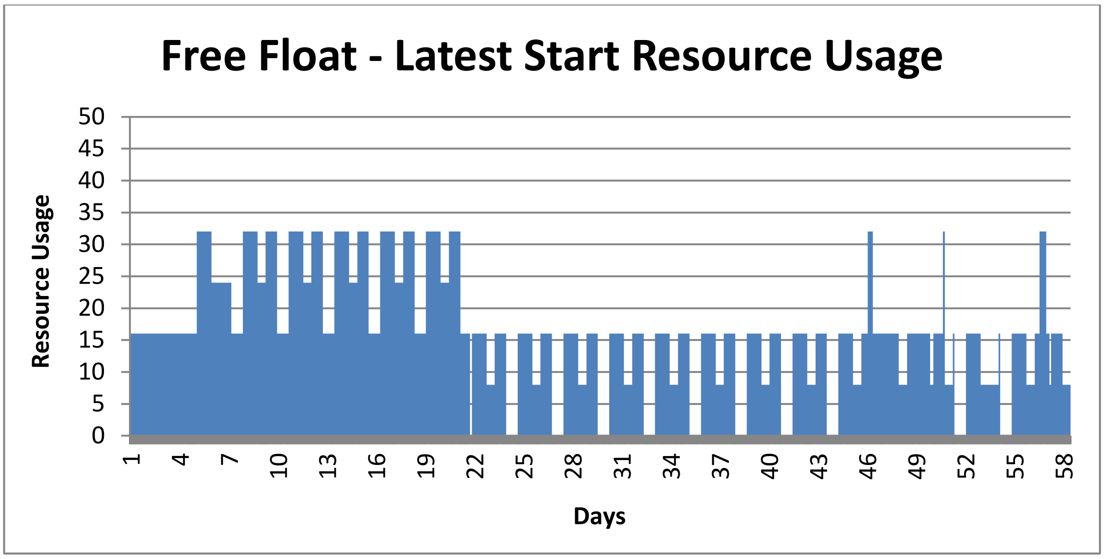


Figure 7.3: Resource histogram for latest start dates (free float)

Resource histogram of the data set prepared with total floats and leveled with objective function no.4 is as shown in Figure 7.4, which was prepared with 0,1 day precision.

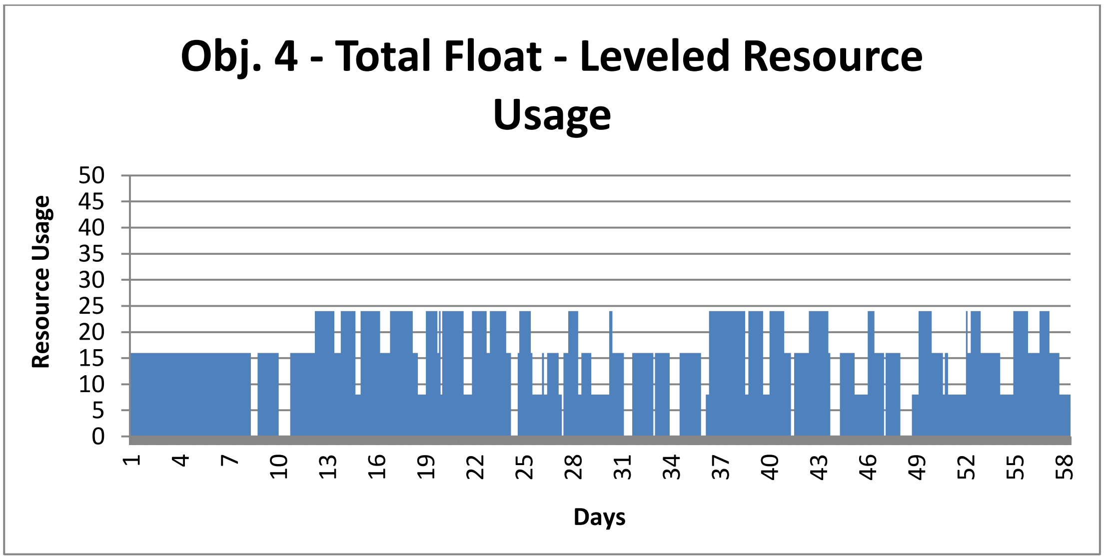


Figure 7.4: Resource histogram – Objective 4 / Total Float

Resource requirement graph of the data set prepared with total floats and leveled with objective function no.4 is as shown in Figure 7.5, which shows the maximum resource requirement of each day.

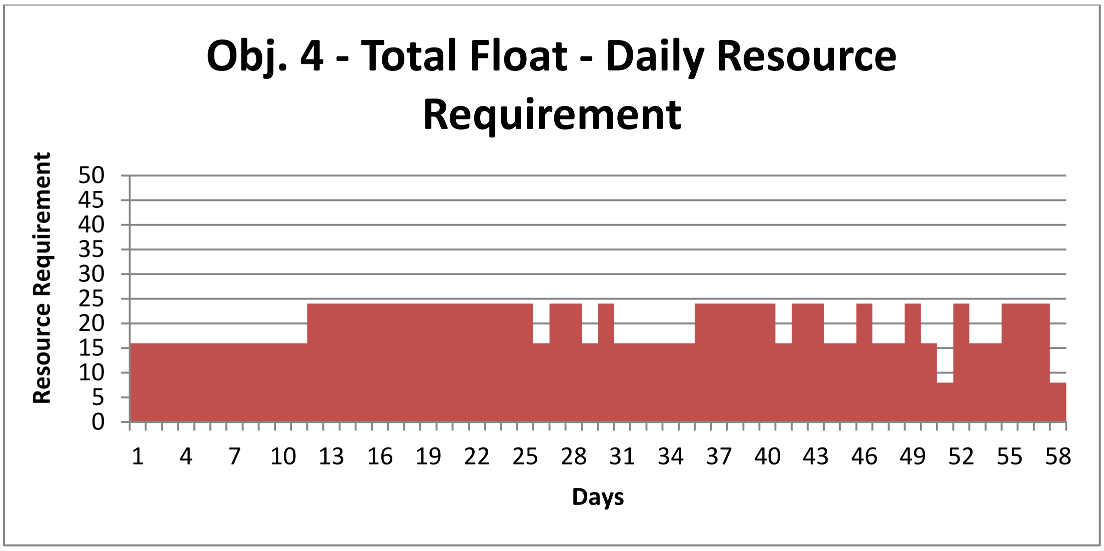


Figure 7.5: Resource requirement – Objective 4 / Total Float

Resource histogram of the data set prepared with free floats and leveled with objective function no.1 is as shown in Figure 7.6, which was prepared with 0,1 day precision.

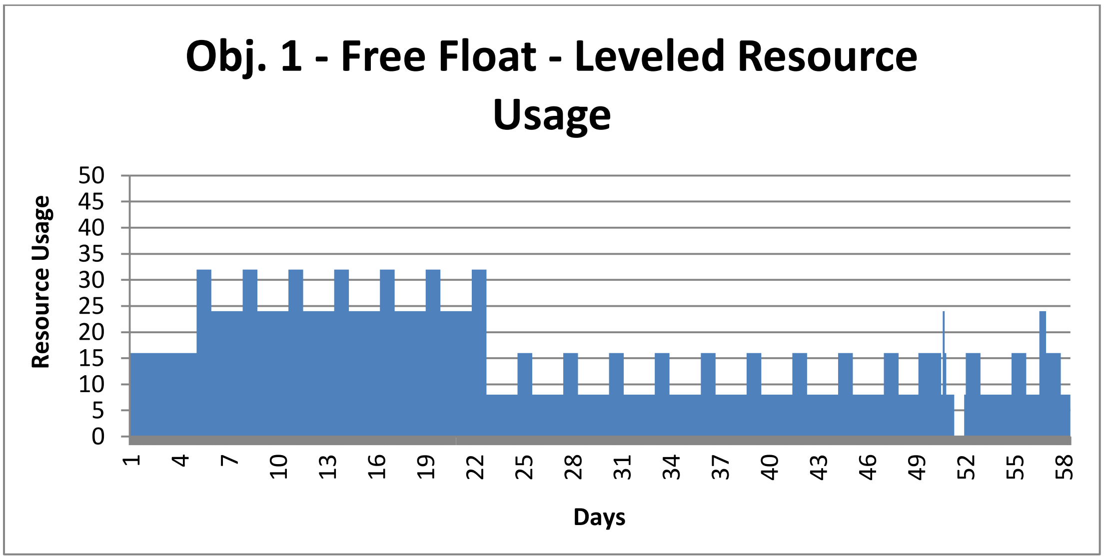


Figure 7.6: Resource histogram – Objective 1 / Free Float

Resource requirement graph of the data set prepared with free floats and leveled with objective function no.1 is as shown in Figure 7.7, which shows the maximum resource requirement of each day.

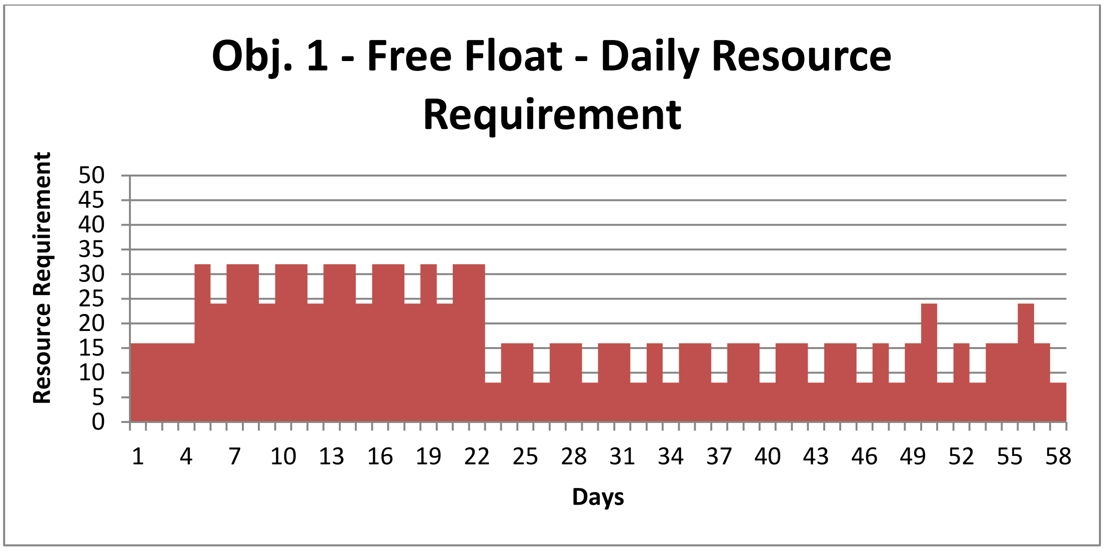


Figure 7.7: Resource requirement – Objective 1 / Free Float

Resource histogram of the data set prepared with free floats and leveled with objective function no.2 is as shown in Figure 7.8, which was prepared with 0,1 day precision.

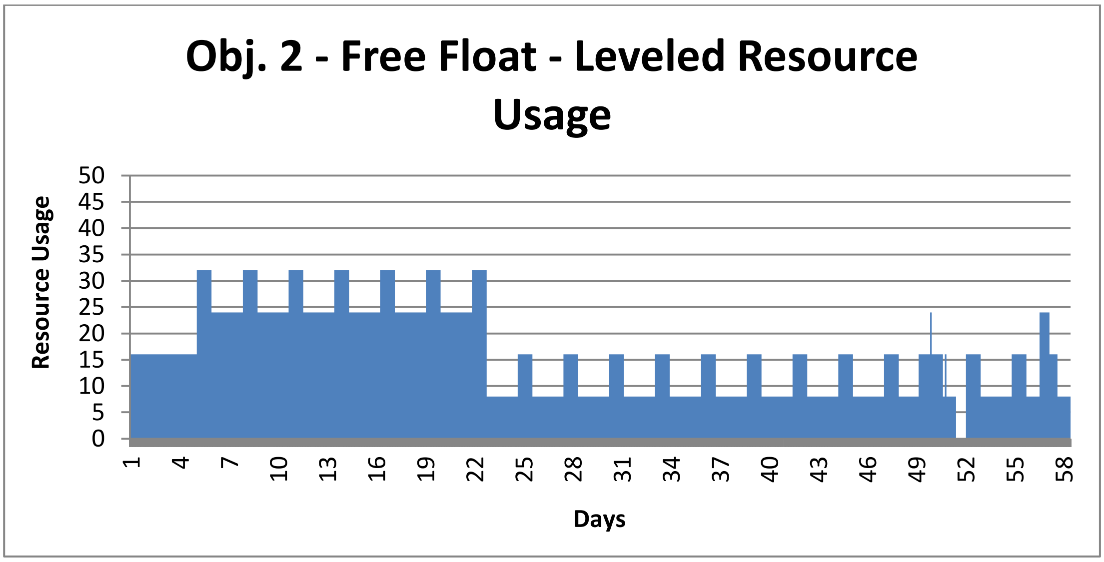


Figure 7.8: Resource histogram – Objective 2 / Free Float

Resource requirement graph of the data set prepared with free floats and leveled with objective function no.2 is as shown in Figure 7.9, which shows the maximum resource requirement of each day.

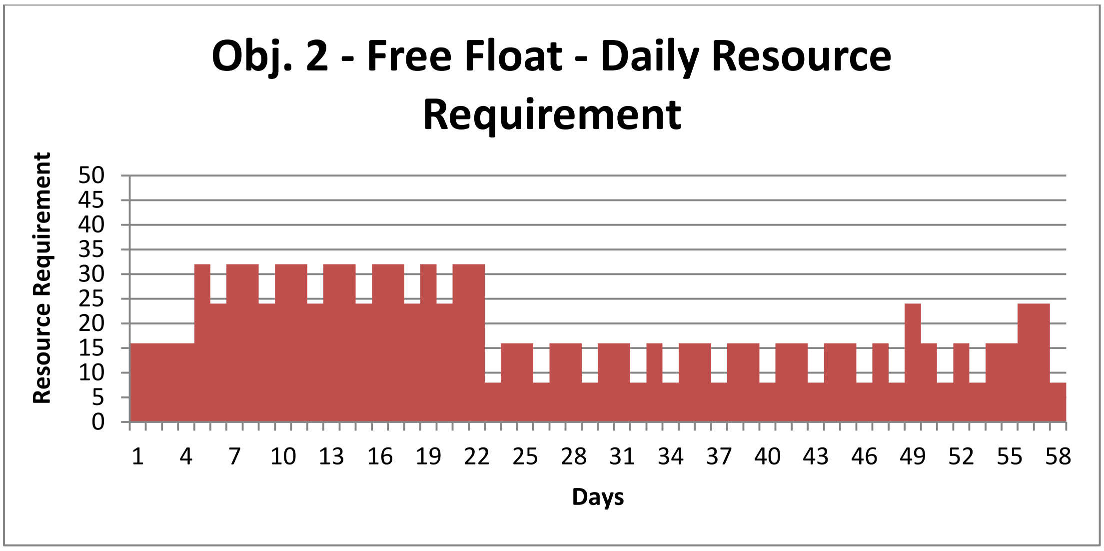


Figure 7.9: Resource requirement – Objective 2 / Free Float

Resource histogram of the data set prepared with free floats and leveled with objective function no.3 is as shown in Figure 7.10, which was prepared with 0,1 day precision.

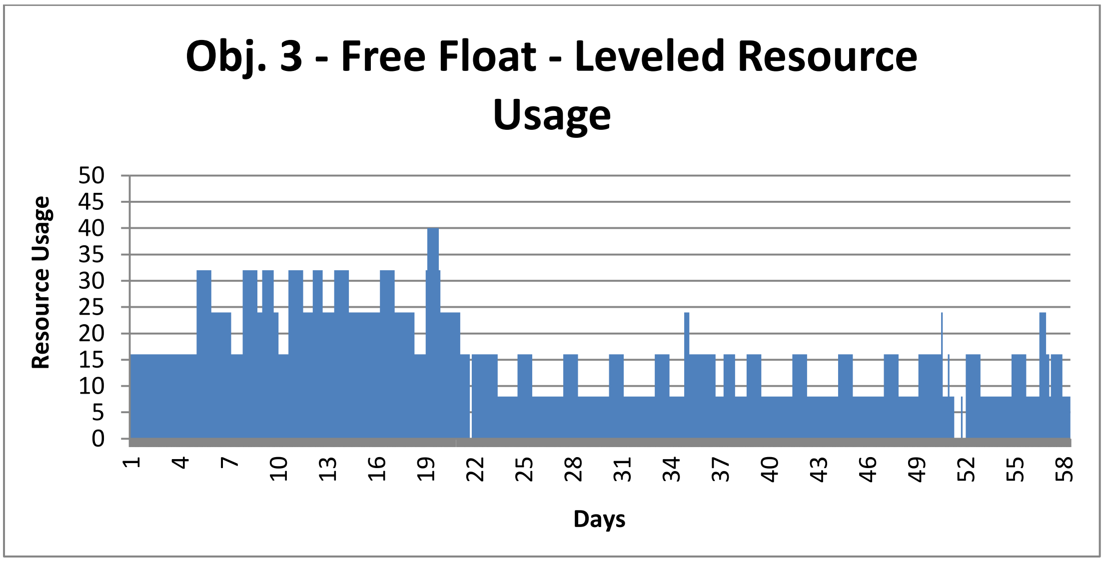


Figure 7.10: Resource histogram – Objective 3 / Free Float

Resource requirement graph of the data set prepared with free floats and leveled with objective function no.3 is as shown in Figure 7.11, which shows the maximum resource requirement of each day.

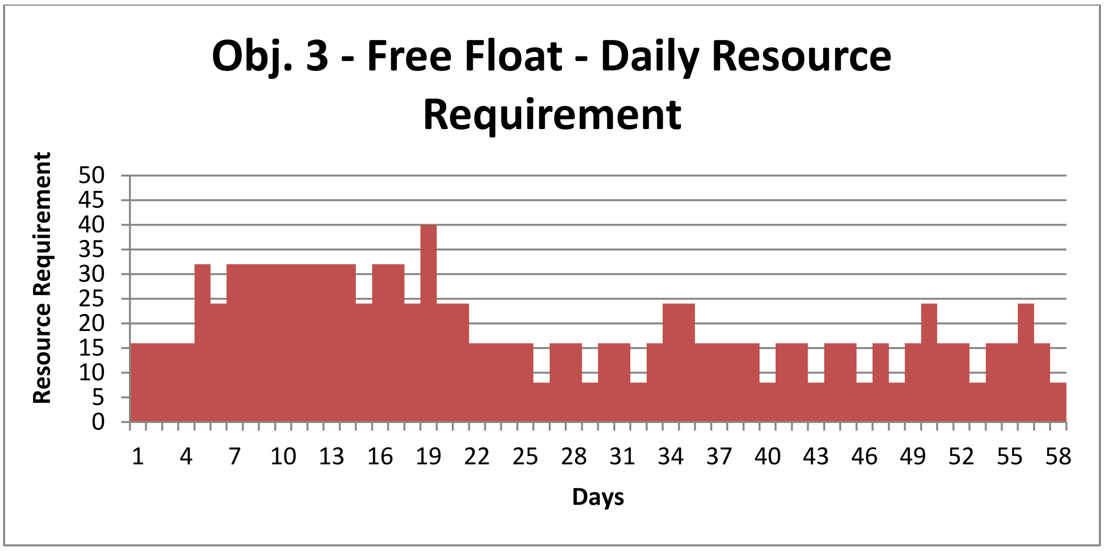


Figure 7.11: Resource requirement – Objective 3 / Free Float

Resource histogram of the data set prepared with free floats and leveled with objective function no.4 is as shown in Figure 7.12, which was prepared with 0,1 day precision.

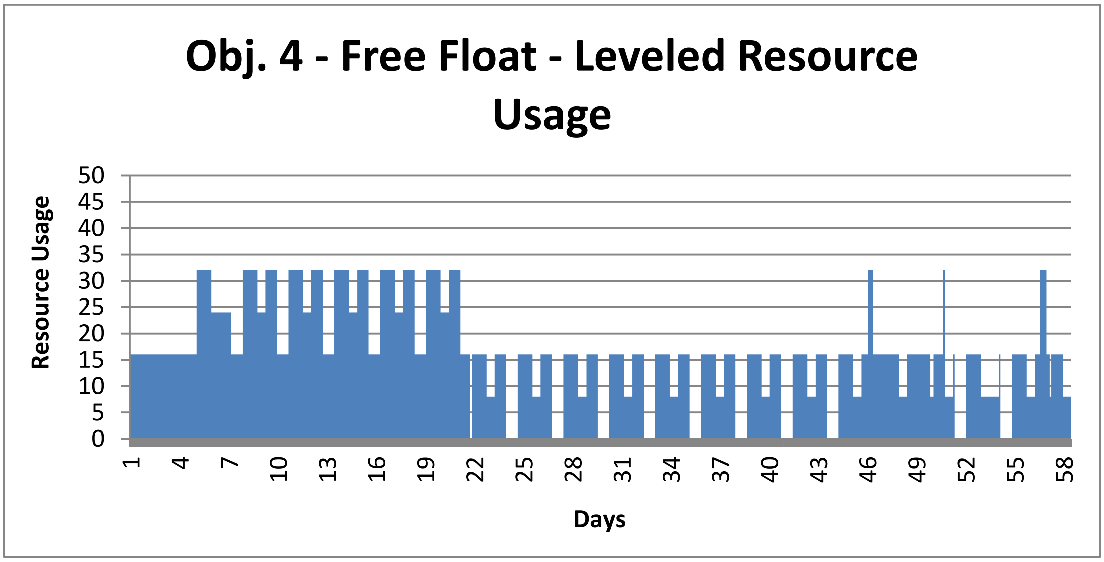


Figure 7.12: Resource histogram – Objective 4 / Free Float

Resource requirement graph of the data set prepared with free floats and leveled with objective function no.4 is as shown in Figure 7.13, which shows the maximum resource requirement of each day.

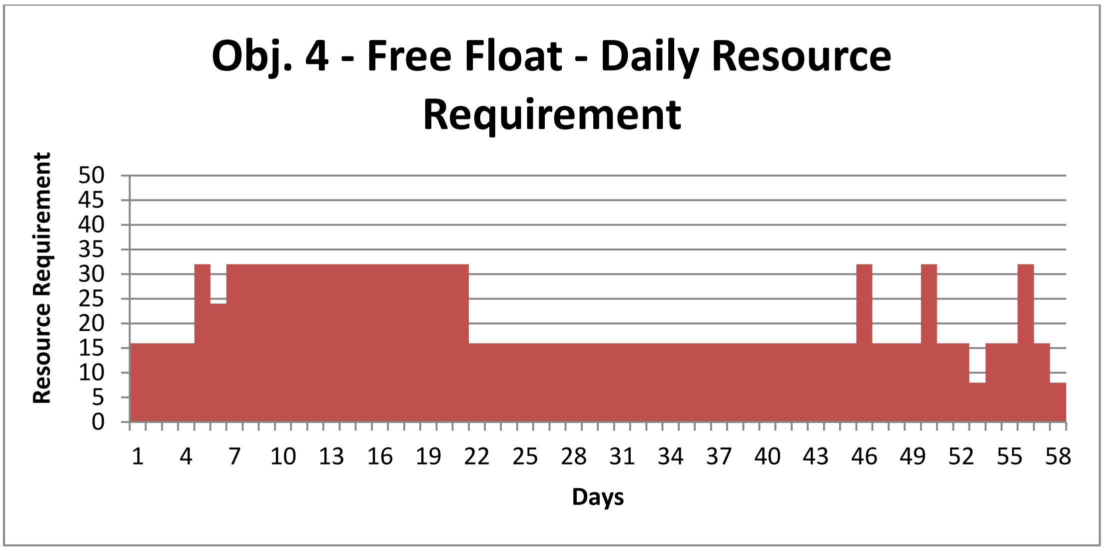


Figure 7.13: Resource requirement – Objective 4 / Free Float

Resource histogram of the data set prepared with free floats and leveled with objective function no.5 is as shown in Figure 7.14, which was prepared with 0,1 day precision.

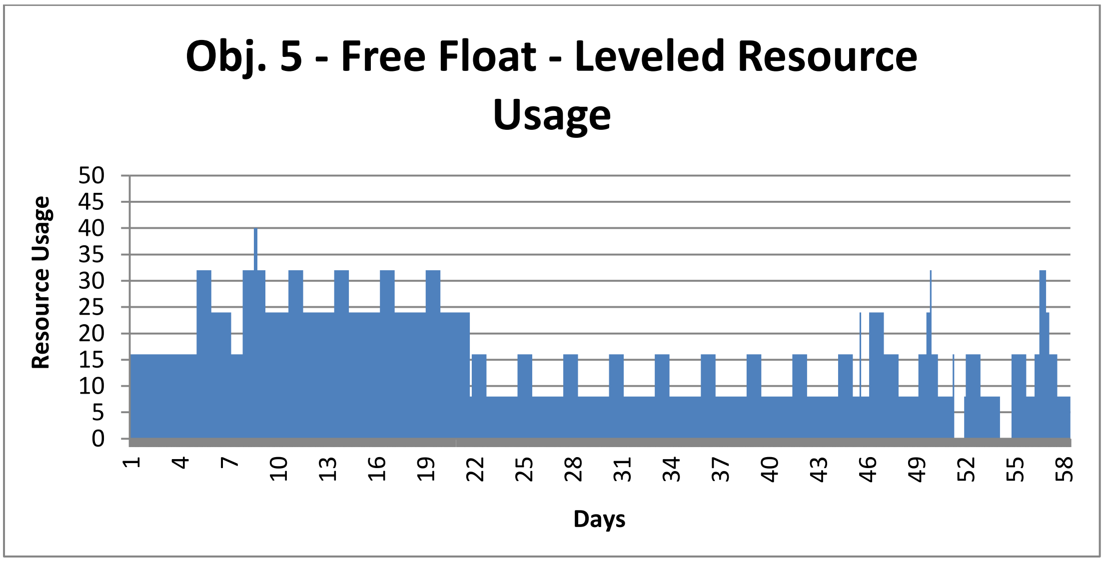


Figure 7.14: Resource histogram – Objective 5 / Free Float

Resource requirement graph of the data set prepared with free floats and leveled with objective function no.5 is as shown in Figure 7.15, which shows the maximum resource requirement of each day.

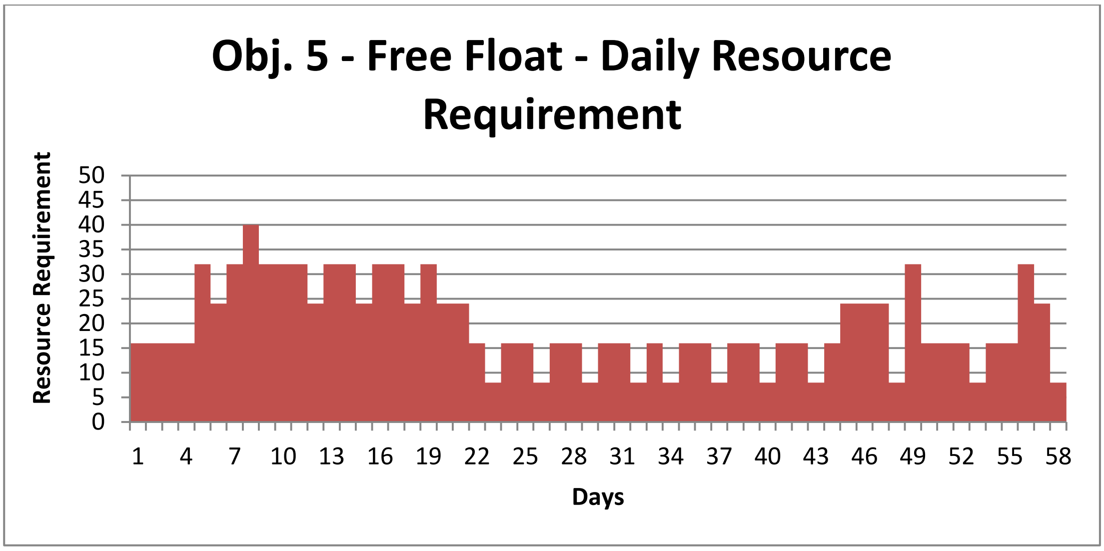


Figure 7.15: Resource requirement – Objective 5 / Free Float

Resource histogram of the data set prepared with free floats and leveled with objective function no.6 is as shown in Figure 7.16, which was prepared with 0,1 day precision.

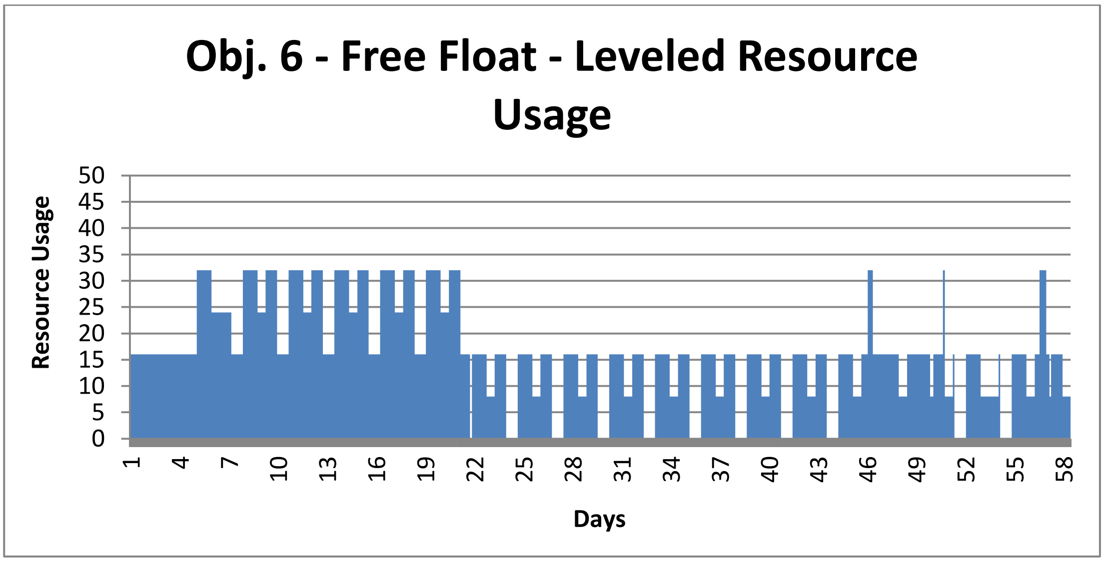


Figure 7.16: Resource histogram – Objective 6 / Free Float

Resource requirement graph of the data set prepared with free floats and leveled with objective function no.6 is as shown in Figure 7.17, which shows the maximum resource requirement of each day.

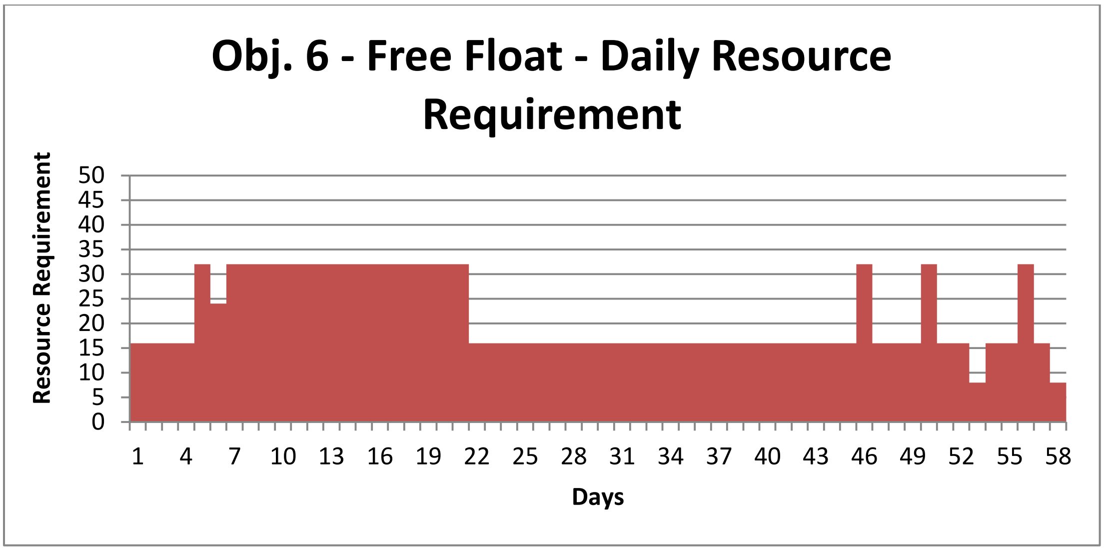


Figure 7.17: Resource requirement – Objective 6 / Free Float

To be able to analyze above-mentioned results in order to decide and propose best possible optimization criteria and objective function for resource leveling, two different tables were prepared. In first, Table 7.1, each solution was evaluated in terms of the metrics of aforementioned optimization criteria. Values of the each metric for each solution and before leveling results were calculated and minimum values for each evaluation criteria are shown in yellow for each row of the Table 7.1 as best values, since all of the optimization criteria were minimization-oriented. However, solution for objective function no.4 with data set prepared with total floats was not compared with the free float data, since these two data set were not of same characteristics and meaningless in terms of comparison. Solution of objective function no.1 with free float data set had the highest count of best values.

Besides, to sharpen the image of the best optimization criteria, a score was also calculated. Main purpose to calculate this score is to give the meaning to counting the best values, since some objective share best values in some evaluation criteria. Score of the each solution was calculated by adding up the ratio of count of the best values of each column to total number of best values on each row. To explain better, take solution values of objective no.1:

(Row 1: 1/1) + (Row 2: 1/2) + (Row 3: 0) +

(Row 4: 1/4) + (Row 5: 0) + (Rom 6: 1/6) = 1,92

In terms of these scores, objective function no.1 also gave the best result.

Table 7.1: Evaluation of the solutions in terms of objective metrics

Solution Evaluation Criteria	Solution Evaluation Formula	Before Leveling			B&B Leveled Solutions						
		Earliest Start	Latest Start		Total Float	Free Float					
			Total Float	Free Float	Objective 4	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5	Objective 6
Sum of the absolute deviations in daily resource usage	$\sum_{i=1}^{T}\lvert Rdev_i\rvert$	416	1104	976	976	16	416	592	976	544	976
Sum of only the increases in daily resource usage from one day to the next	$\sum_{i=1}^{T}\lvert Rinc_i\rvert$	200	544	480	480	200	200	288	480	264	480
Sum of the absolute deviations between daily resouce usage and the average resource usage	$\sum_{i=1}^{T}\lvert R_i - R_{avg}\rvert$	3994,89	5861,67	3646,25	2962,43	3852,87	3884,43	3505,93	3646,25	3854,41	3646,25
Maximum daily resource usage	$[\max(R_i)]$	32	48	32	24	32	32	40	32	40	32
Maximum deviation in daily resource usage	$[max\lvert Rdev_i\rvert]$	24	16	24	16	24	24	16	24	16	24
Maximum absolute deviation between daily resource usage and the average resource usage	$[max\lvert R_i - R_{avg}\rvert]$	16,11	32,11	16,11	15,89	15,89	15,89	15,89	15,89	15,89	15,89
Best Solution			Count			4	3	3	2	2	2
			Score			1,92	1,42	1,67	0,42	0,67	0,42

Additionally, to analyze results in more detail, improvements provided by each solution compared to before-leveling values were calculated and can be found in Table 7.2. If any of the objective function was failed to provide an improvement in terms of the evaluation criteria, it was taken as zero. In order to obtain the total improvement of each objective function, all improvements provided by objective, were summed up and divided by total number of evaluation criteria, six. Again, total float solution did not compared with free float solutions and objective function no.1 worked with free float data set gave the best improvement rate among the free float solutions.

To sum up, objective function no.1 worked with free float data set gave the best resource leveling results among the free float data sets. However, even it is neither possible nor meaningful to compare total float result with free float results, it can be seen in the Tables 7.1 and 7.2 that, total float data set worked in objective function no.4 was provided better numerical results than any other solutions. This can be explained by the total float data set offer more possibilities for optimization since, 76,24 % of activities were of total floats and available for optimization iterations.

Table 7.2: Improvements provided by leveled solutions

Criteria	Formula	B&B Leveled Solutions						
		Total Float	Free Float					
		Objective 4	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5	Objective 6
Sum of the absolute deviations in daily resource usage	$\sum_{i=1}^{T} \lvert Rdev_i \rvert$	0	0,9615	0	0	0	0	0
Sum of only the increases in daily resource usage from one day to the next	$\sum_{i=1}^{T} \lvert Rinc_i \rvert$	0	0	0	0	0	0	0
Sum of the absolute deviations between daily resouce usage and the average resource usage	$\sum_{i=1}^{T} \lvert R_i - R_{avg} \rvert$	0,2584	0,0356	0,0277	0,1224	0,0873	0,0352	0,0873
Maximum daily resource usage	$[\max(R_i)]$	0,2500	0	0	0	0	0	0
Maximum deviation in daily resource usage	$[max \lvert Rdev_i \rvert]$	0,3333	0	0	0,3333	0	0,3333	0
Maximum absolute deviation between daily resource usage and the average resource usage	$[max \lvert R_i - R_{avg} \rvert]$	0,0137	0,0137	0,0137	0,0137	0,0137	0,0137	0,0137
Average Improvement		0,1426	0,1685	0,0069	0,0782	0,0168	0,0637	0,0168
	%	14,26	16,85	0,69	7,82	1,68	6,37	1,68

8. CONCLUSIONS

This research proposed a mathematical model for leveling resources of a linear construction project scheduled with location-based planning technique. The mathematical programming method used to provide leveling solutions was mixed-integer programming with branch and bound algorithm.

Objectives of the study provided in the earlier stages were all achieved by;

I. *Developing a resource leveling model using branch and bound algorithm for a highway construction project scheduled according to location-based scheduling method.* In the case study, proposed model was examined in detail and all steps to accomplish the development of a new model was represented.

II. *Determining and analyzing the effects of using different objective functions in modeling.* Different resource histograms derived from the solutions of various objective functions, are compared and examined.

III. *Determining and analyzing the impact of considering different type of project floats on resources and leveling process.* Two data set obtained from different project floats was used in proposed model with different objective functions. Since, all of the objective functions with total floats could not give solution due to excessive memory usage, it is hard to deliver a comparison and/or analysis regarding the effect of total floats. However, a detailed examination was available for data set with free floats in different objective functions hence, best solution for free float data set was shown from various evaluation aspects.

Besides, it is shown that, LBP offers better layout for resource leveling than CPM due to easier project control and less complexity. In addition, proposed model emerges as a reliable resource leveling tool, since it takess many aspects of project into consideration such as production rates, exact durations and complete precedence relations without breaking project order logic.

As for the future study,

- a dynamic programming model, that can consider and level different types of resources with various weighing simultaneously,
- a mathematical modeling tool, that can work with non-linear formulation while providing deterministic solutions,

can be worked on developed if possible.

In conclusion, this study is contributed to the field by proposing a mathematical model with branch and bound algorithm for resource leveling of linear construction projects. This contribution can be expanded by considering provided future work areas and more.

REFERENCES

Adeli, H., Karim, A. (2001). *Construction Scheduling, Cost Optimization and Management.* Spon Press, New York, USA.

Arditi D., Tokdemir, O.B. & Suh, K. (2001). "Scheduling System for Repetitive Unit Construction Using Line-of-Balance technology*", Engineering, Construction and Architectural Management*, Vol.8(2), 90-103.

Arditi D., Tokdemir, O.B. & Suh, K. (2002a). "Challenges in Line-of-Balance Scheduling", *Journal of Construction Engineering and Management*, Vol. 128, No. 6, 545-556.

Arditi D., Sikangwan, P. & Tokdemir, O.B. (2002b). "Scheduling System for High Rise Building Construction", *Construction Management and Economics*, Vol.20, No.4, 353-364.

Callahan, M.T., Quackenbush, D.G & Rowings, J.E. (1992). *Construction Project Scheduling*, McGraw-Hill, New York, USA.

CMAA <http://cmaanet.org/construction-management>, date retrieved 12.09.2011.

Doyle, A.C. (1930). "A Study in Scarlet" *The Complete Sherlock Holmes.* Doubleday & Co., New York, USA.

Firat, C.E., Arditi, D. & Kiiras J. (2009). "Advanced Line of Balance (ALoB) in Model-Based Scheduling in Residential Building Projects". 5th International Conference on Construction on the 21st Century Collaboration & Integration in Engineering, Management and Technology CITC-V, Istanbul, Turkey.

Forman, E.H., Selly, M.A. (2002) *Decision by Objectives: How to Convince Others That You Are Right*, World Scientific Publishing, Singapore.

Goldratt, E. (1997). *Critical Chain*, North Rivers Press, Great Barrington, MA.

Gordon, J., Tulip, A. (1997). "Resource Scheduling". *International Journal of Project Management*, 15(6): 359-370.

Griffis, F.H. , Farr, J.V. (2000). *Construction Planning for Engineers.* McGraw-Hill, New York, USA.

Harris, P.E. (2010). *Project Planning and Control UsingPrimavera P6*. Eastwood Harris Pty. Ltd., Victoria, Australia.

Harris, R.B. & Ioannou, G. (1998). "Scheduling Projects with Repeating Activities", *Journal of Construction Engineering and Management*, Vol. 124, No. 4, 269-278.

Hendrickson, C., **Au, T.** (1989). *Project Management for Construction; Fundemental Concepts for Owners, Engineers, Architects and Builders.* Prentice Hall, New Jersey, USA.

Hentenryck, P.V. (1999). *The OPL Optimization Programming Language*. The MIT Press, Cambridge, Massachusets, USA.

Hinze, J. (1993). *Construction Contracts.* McGraw-Hill, New York, USA.

Hinze, J. (2008). *Construction Planning and Scheduling.* Pearson, New Jersey, USA.

Kankainen, J. & Sandvik, T. (1993). Rakennushankkeen Ohjaus. (Controlling a Construction Project), Confederation of Finnish Construction Industries, Rakennustieto Oy, Helsinki, Finland.

Kankainen, J. & Seppänen, O. (2003). "A Line-of-Balance Based Schedule Planning and Control System", 11th Annual Conference on Lean Construction, International Group of Lean Construction, Virginia Tech, Blacksburg, Virginia, USA.

Kelley, J.E. (1961). Critical-Path planning and scheduling: Mathematical basis. *Operations Research* 9(3): 296-320.

Kenley, R. (2004). "Project Micromanagement: Practical Site Planning and Management of Work Flow", IGLC-12, 12th Con. of the Int. Group for Lean Construction, Helsingor, Denmark, 194-205.

Kenley, R. & Seppänen, O. (2009). "Location-Based Management of Construction Projects: Part of a New Typology for Project Scheduling Methodologies", Winter Simulation Conference, Austin, TX, USA, 2563-2570.

Kenley, R., Seppanen, O. (2010). *Location-Based Management for Construction*. Spon Press, New York, USA.

Kiiras, J. (1989). OPAS ja TURVA, Erityiskohteiden Työnaikaista Ohjausta Palveleva Aikataulu- Ja Resurssisuunnittelu. (A Schedule and Resource Planning System for the Implementation Phase Control of Special Projects), HUT/CEM Publications. Espoo, Finland.

Kog Y.C., Chua D.K.H., Loh P.K., Jaselskis E.J. 1999. Key determinants for construction schedule performance. *International Journal of Project Management*, Vol. 17, No. 6, 1999, pp. 351-359.

Kuruoğlu, M., Özvek, A. Proje Planlama Çalışmaları Gerekli Mi?, <http://www.ins.itu.edu.tr/murkur/MURKUR/documan/pdf/PROJE%20PLANLAMA%20ÇALIŞMALARI%20GEREKLİ%20Mİ.pdf>, date retrieved 5.12.2009

Lumsden, P. (1968). *The Line of Balance Method*, Pergamon Press, London, UK.

Malcolm, D.G., Roseboom, J.H., Clark, C.E. & Fazar, W. (1959). "Application of a technique for research and development program evaluation", *Operations Research* 7(5): 646-669.

Mattila, K.G. (1997). *Resource Leveling of Linear Schedules: A Mathematical Approach Using Integer Linear Programming* (Ph.D. dissertation), Purdue University, Indiana, USA.

Newitt, J. S. (2009). *Construction Scheduling; Principles and Practices.* Pearson, New Jersey, USA.

Polat, G., Ergen, E. & Gürcanlı, E. (2008). *Construction Management Course Notes - 1* İstanbul: Istanbul Technical University, Civil Engineering Faculty Construction Managment Department.

Popescu, C.M. (1976). *How to Use C.P.M. in Practice*, Dept. of Civil Engineering, University of Texas at Austin, 1st edition, Texas, USA.

RTGDH (Republic of Turkey General Diretorate of Highways) Technical Specification**.** (2006).

Url – 1 Pennsylvania State University World Campus - Project Management Program, MANGT 520: Planning and Resource Management lecture notes, <https://courses.worldcampus.psu.edu/welcome/pmangt/samplecontent/toc.html#less8>, date retrieved: 10.11.2011.

Url – 2 <http://office.microsoft.com/en-us/project-help/about-resource-leveling-HP001041939.aspx >, date retrieved: 15.11.2011

Url – 3 <http://ww2.cs.mu.oz.au/433/clpopl-notes.pdf >, date retrieved: 15.12.2011

Url – 4 WOLFRAM, <http://www.wolfram.com/products/applications/mathoptpro/>, date retrieved: 20.01.2012

Wagner, H.M., Giglio, R.J. & Glaser R.G. (1964). "Preventive Maintenance Scheduling by Mathematical Programming", *Management Science*, 10(2), 316-334.

Winston, W.L. (2004) *Operations Research Applications and Algorithms,* Crooks/Cole Cengage Learning, 4th edition, California, USA.

Wolsey, L.A. (1998). *Integer Programming*, John Wiley & Sons, Inc., New York, USA.

CURRICULUM VITAE

Name Surname: Resulali Emre ÖRGÜT

Place and Date of Birth: Adapazarı / SAKARYA – 09/05/1987

Address: Nispetiye Aytar Caddesi, Bilgin Sokak, Ocak Apt., No:8/5
Levent/ISTANBUL

E-Mail: res.orgut@gmail.com

B.Sc.: ITU Civil Engineering

Professional Experience:

Mak-In Engineering & Construction, Istanbul, Turkey *(04/2010-09/2011)*

Site Engineer in Zorlu Real Estate A.Ş., Zorlu Center Project Rough Construction