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DISASSEMBLY AND DISTRIBUTION PLANNING CONSIDERING 3D PRINTING TECHNOLOGY

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DISASSEMBLY AND DISTRIBUTION PLANNING CONSIDERING 3D PRINTING TECHNOLOGY

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in

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Supervisor
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by

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Zülal DİRİ KENGER

ABSTRACT

DISASSEMBLY AND DISTRIBUTION PLANNING CONSIDERING 3D PRINTING TECHNOLOGY

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Increasing world population and consumption leads to the increase in total amount of waste. Recycling of valuable materials in waste is quite important for both environmental awareness and cost. All these processes increase the importance of disassembly, which has been popular in recent years. An effective routing plan to distribute the recycled components, generated by the disassembly process, to the remanufacturing centres (RC), is also important for recycling operations. Thus, the vehicle routing problem (VRP) plays an important role in the distribution of recycled components. Additionally, some parts may be damaged during the disassembly process, due to the operation complexity or workers. In the present case, additive manufacturing (AM) can be used to produce new parts instead of damaged parts. Using only the required amount of material, the 3D printing (3DP) technology will be able to prohibit the waste material problem in production and by this means, pollution will be prevented. This thesis introduces the integrated disassembly line balancing and routing problem (I-DLB-RP), the I-DLB-RP with 3D printers (I-DLB-RP-3DP), the integrated collection-disassembly-distribution problem (I-CDDP), the I-DLB-RP with mobile AM (I-DLB-RP-MAM), respectively. Several mathematical formulations are presented for solving the aforementioned problems and a number of scenario analysis are considered to indicate the benefits.

Keywords: Disassembly Line Balancing, Vehicle Routing, Additive Manufacturing, 3D Printing, Recycling.

ÖZET

3B YAZICI TEKNOLOJİSİNİN ENTEGRASYONU İLE DEMONTAJ VE DAĞITIM PLANLAMASI

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121 sayfa

Artan dünya nüfusu ve tüketimi, toplam atık miktarının artmasına neden olmaktadır. Atık içindeki değerli malzemelerin geri dönüşümü hem çevre bilinci hem de maliyet açısından oldukça önemlidir. Tüm bu işlemler son yıllarda popüler olan demontajın önemini artırmaktadır. Demontaj işlemi ile ortaya çıkan geri dönüştürülmüş bileşenleri (yeniden) üretim merkezlerine dağıtmak için etkin bir dağıtım planı da geri dönüşüm işlemleri için önemlidir. Bu nedenle, araç rotalama problemi (ARP), geri dönüştürülmüş bileşenlerin dağıtımında önemli bir rol oynar. Ek olarak, demontaj işlemi sırasında işlemin karmaşıklığı veya işçiler nedeniyle bazı parçalar hasar görebilir. Mevcut durumda, eklemeli imalat, hasarlı parçalar yerine yeni parçalar üretmek için kullanılabilir. 3B baskı teknolojisi, sadece gerekli miktarda malzeme kullanarak üretimde atık madde sorununun önüne geçilecek ve bu sayede çevre kirliliği önlenecektir. Bu tez, sırasıyla entegre demontaj hattı dengeleme ve rotalama problemini (E-DHD-RP), 3B yazıcıların dahil olduğu E-DHD-RP (E-DHD-RP-3B), entegre toplama-demontaj-dağıtım problemini (E-TDDP), mobil eklemeli üretimin dahil olduğu E-DHD-RP (I-DHD-RP-MEÜ) problemini tanımlamıştır. Tanımlanan problemleri çözmek için çeşitli matematiksel formülasyonlar geliştirilmiş ve senaryo analizleri üzerinde kapsamlı deneysel çalışmalar gerçekleştirilmiştir.

Anahtar Kelimeler: Demontaj Hattı Dengeleme, Araç Rotalama, Eklemeli Üretim, 3B Baskı, Geri Dönüşüm.

''Dedicated to my family and husband''

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LIST OF ABBREVIATIONS

3DP	3D Printing
AM	Additive Manufacturing
CLSC	Closed Loop Supply Chain
DC	Disassembly Centre
DL	Disassembly Line
DLB	Disassembly Line Balancing
DT	Disassembly Tree
EOL	End of Life
I-CDDP	Integrated Collection-Disassembly-Distribution Problem
I-DLB-RP	Integrated Disassembly Line Balancing and Routing Problem
I-DLB-RP-3DP	Integrated Disassembly Line Balancing and Routing Problem with 3D printers
I-DLB-RP-MAM	Integrated Disassembly Line Balancing and Routing Problem with Mobile Additive Manufacturing
MINLP	Mixed-Integer Non-Linear Programming
MIP	Mixed Integer Programming
NLP	Non-linear Programming
RC	Remanufacturing Centre
RL	Reverse Logistics
RSC	Reverse Supply Chain
SC	Supply Chain
SCM	Supply Chain Management
TAOG	Transformed AND/OR Graph
VRP	Vehicle Routing Problem

CHAPTER I

INTRODUCTION

1.1. Motivation of Study

Rapid developments in technology cause a continuous increase in the amount of consumption and consequently increase the amount of waste. Product recovery aims at minimizing the amount of waste sent to landfill area by recovering materials and parts from end of life (EOL) products through recycling and remanufacturing (Güngör and Gupta, 1999a). Material and product recovery are realized mainly due to three reasons: (1) hidden economic value of solid waste, (2) governmental regulations, (3) market requirements (Güngör and Gupta, 1999a). Another reason of product recovery is requirement for a clean environment. Because, when a product completes its life, the biggest damage is given to the environment (Güngör and Gupta, 1999a). The most important step is the disassembly to tackle these problems. Disassembly is an important process associated with every step of product recovery including remanufacturing, recycling, disposal and reuse (Kalayci and Gupta, 2013a). The disassembly line (DL) is the best option for automated disassembly due to having highest productivity (Güngör and Gupta, 2001; Kalayci and Gupta, 2013b). One of the main focus of this thesis is disassembly line balancing (DLB) problem and DLB problem can be defined as assigning disassembly tasks of an EOL product to workstations such that the precedence relationships are satisfied and some measure of effectiveness is optimized (Güngör and Gupta, 1999b; Altekin et al., 2008).

Today, logistics becomes one of the most important, largest and most dynamic sector in the world. Rapidly growing international trade and economic activities have made logistics management activities a strategic decision. Logistics companies have to perform their services in the most effective and efficient way and in the shortest time in order to make a profit in a competitive environment and to sustain their existence. The vehicle routing problem (VRP) has become an important issue in terms of quick response to demands and providing economic advantages. The classical VRP aims to construct routes to serve a set of customers with a fleet of homogeneous vehicles. Each customer is travelled once by one vehicle, each route starts and ends at the depot, and some constraints are satisfied (Koç and Laporte, 2018). The basic assumptions of VRP are as follows (Toth and Vigo, 2002):

i) Customer demands are certain, known and indivisible,

ii) The transportation times (distances) between the depot and the customer and between customers are fixed and known,

iii) The vehicles have equal capacity; the capacity is known, and they are ready to serve the customers in the central depot.

In the light of these assumptions, the purpose of VRP is to determine the smallest cost routes that meet the needs of all customers. VRP has different types according to their constraints and is a NP-hard problem (Toth and Vigo, 2002).

One of the recent revolutions in the field of manufacturing is 3D printing (3DP) technology which is also considered as Additive Manufacturing (AM). Both DLB and VRP have an important effect on supply chain management (SCM) in terms of product recovery, environment and cost. The 3DP technology is among the current research area trends also affects SCM (Khajavi et al., 2014). Potential advantages of 3DP technology can be sorted as less labour and inventory cost, high efficiency and flexibility, and process simplifications (Li et al., 2016; Chan et al., 2018). Also, 3DP technology is fast to set up without custom tooling and infinitely customizable. Thus, it obtains highly flexible production. 3DP technology has been considerably used in industrial parts production and ensures the best feasible accuracy fit for the customer. This technology gives us a chance to design flexible shaped structures resulting in lower weight, less material usage, and fewer assembly steps (Varsha Shree et al., 2019).

Remanufacturing, recycling and environmentally conscious manufacturing have gained importance because of growing demand for a cleaner environment. After disassembly, using recycled components in remanufacturing operations provides cost savings to manufacturers. Recycling of waste products and distribution of recycled components to remanufacturers in order to use in new products are also essential for environment-friendly production. Remanufacturing helps to diminish pollution and production costs by reusing EOL products (Liu et al., 2020). In addition to this, with the developing technology, there has been a growing demand for production systems such as AM which makes production in a shorter time. This thesis focuses on the integration of DLB problem and VRP, and effects and contributions of AM technology on the integration of these two well-known optimization problems.

1.2. Thesis Organization

This thesis is divided into eight chapters. The next chapter analyses DLB problem and DL considerations, precedence relations in disassembly and differences between assembly and disassembly systems, respectively.

Chapter 2: DLB problem that is the main focus of this thesis is discussed in this section. Definition of DLB problem, precedence relations in disassembly and differences between assembly and disassembly systems are reviewed, respectively.

Chapter 3: This section first presents a brief review of the DLB problem and VRP literature. Most relevant and recent literature on 3DP technology in SCM are then presented. Finally, integrated DLB and distribution planning literature are reviewed in detail.

Chapter 4: Integrated DLB and routing problem (I-DLB-RP) is introduced and analysed in this chapter. Different mathematical formulations are presented for different scenarios such as single-component distribution, multi-component distribution, inventory cost, and multi-period conditions. Several scenario analysis are conducted on mathematical models and results shows that integrating the two problems provide optimal solutions for small-sized test beds.

Chapter 5: This chapter defines the I-DLB-RP with 3D printers (I-DLB-RP-3DP) and proposes a mixed integer non-linear mathematical formulation for solving the novel problem. Different scenario analysis are conducted on the presented mathematical model. This chapter focuses on the integration of 3DP technology with the DLB and VRP within the context of smart factories.

Chapter 6: This chapter introduces the I-CDDP and presents two mathematical formulations to solve the problem. The first mathematical formulation is for single-component distribution case and the second formulation is for multi-component distribution case. Different analysis are conducted on the formulations and managerial insights are presented. The optimization of RSC network cooperating with DLB and VRP is analysed and results are presented in detail.

Chapter 7: In this chapter, the I-DLB-RP with mobile AM (I-DLB-RP-MAM) is introduced. A non-linear mathematical programming model is presented and a numerical example is considered to illustrate the applicability of the model. Scenario analysis is conducted on test beds and results show that AM has several positive effects on SC.

Chapter 8: The summary of the thesis and our conclusions are given in the last chapter. Some aspects for the future work are also discussed.

CHAPTER II
DISASSEMBLY LINE BALANCING PROBLEM AND ITS SPECIFICATIONS

In this section of the thesis, DL and DLB problem are analysed in detail. DLB problem, precedence relations in disassembly and differences between assembly and disassembly systems are presented, respectively.

2.1. Disassembly Line Balancing Problem

There are three main problems in the disassembly literature, like disassembly planning, scheduling and balancing. This thesis focuses mainly on DLB problem and the integration with VRP.

DL is a part of disassembly systems in which the EOL products are separated their components with the aim of recycling and remanufacturing. DL comprises of many workstations and a material handling system in which sub-assembled product is transported from one workstation to another. The configuration of a DL takes a long time and a large investment. For this reason, balancing such a system as efficiently as possible is very important (Güngör and Gupta, 1999b). The DLB problem can be defined as the assignment of disassembly tasks to workstations such that all the disassembly precedence relations are satisfied and some measures are optimized (Altekin et al., 2008). Some of basic definitions used in this thesis are presented as follows (Güngör and Gupta, 2001).

Disassembly: Disassembly is a process that separates an EOL product to its components or subassemblies. Disassembly may be complete or partial.

Complete disassembly: The EOL products is completely disassembled.

Partial disassembly: The EOL product is not completely disassembled. Components and subassemblies occur in partial disassembly.

Component: A component is a part of a product that cannot be separated into smaller parts.

Subassembly: A subassembly is a part of a product that contains two or more components.

Task: A task is the smallest and indivisible part of a product in DL systems.

Task time: Task time is the time required to perform the task completely at a workstation.

Workstation: Workstation is a part of DL in which a set of tasks is performed.

Cycle time: Cycle time is the total time needed to perform a task or tasks in a workstation.

TAOG: Transformed AND/OR Graph (TAOG) contains full information of a product on all the disassembly trees (DT). A DT represents a way of completely disassembling a product.

Artificial node: The artificial nodes represent subassemblies in TAOG.

Normal node: The normal nodes represent tasks in TAOG.

Precedence relations: Precedence relations are the task sequence where serial tasks must be performed.

Predecessors of a Task: Set of tasks that must be performed before starting time of the task.

Successors of a Task: Set of tasks that cannot be processed before the completion time the task.

2.2. Precedence Relations in Disassembly

Precedence relations types in disassembly are analysed in this section. Precedence relations can be classified as '*AND*', '*OR*', *"OR successors"*, "*complex AND/OR*", "*AND within OR*", "*OR within AND*" in DLB problem (Moore et al., 2001; Altekin et al., 2008; Koc et al., 2009). These relations are explained and illustrated as follows. "i" denotes the disassembly task.

“*AND” precedence relations*: As seen in Figure 2.1, in order to disassemble component 4 screws 5 and 6 must be removed first. Consequently, components 5 and 6 are linked to component 4 with *“AND”* precedence relationship.

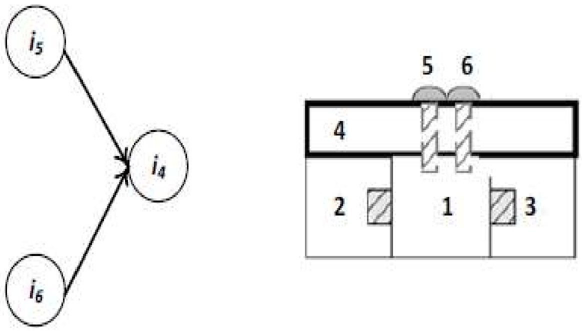

Figure 2.1 *“AND”* precedence relation (Özceylan, 2013)

“*OR” precedence relations*: In “*OR”* relationship, it is sufficient to disassemble any component from components 2 or 3 to disassemble component 1 as seen in Figure 2.2. The arc shape is used to show “*OR”* relationships.

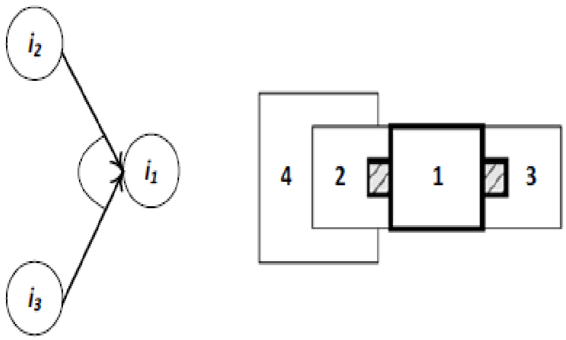

Figure 2.2*“OR”* precedence relation (Özceylan, 2013)

*“OR successors”*relations: *“OR”* relationship can be a successor as well as a predecessor. As seen in Figure 2.3, any of the components 1 or 4 can be disassembled after removal of the 5 components.

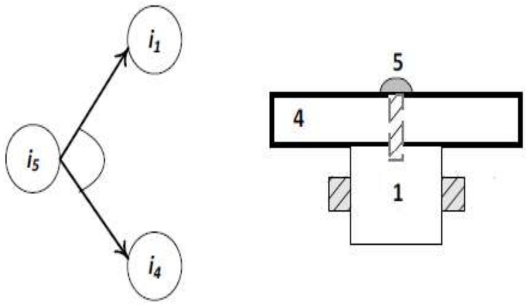

Figure 2.3 *"OR successors"* relation (Özceylan, 2013)

<u>*"complex AND/OR"* precedence relations*:*</u> *In a* "*complex AND/OR*" precedence relationship, both *"AND"* and *"OR"* precedence relationships exist at the same time. If we explain this precedence relationship with Figure 2.4, in order to disassemble component 1, we need to disassemble component 5 and component 2 or 3.

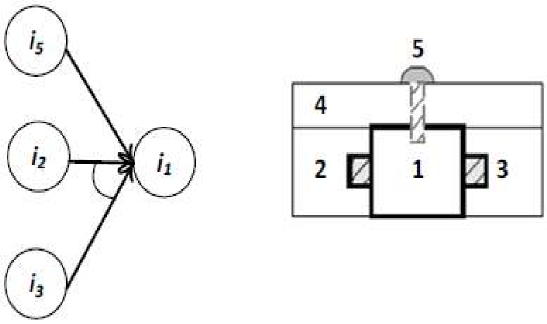

Figure 2.4 *"complex AND/OR"* relation (Özceylan, 2013)

<u>*"AND within OR" precedence relations:*</u> In these precedence relationships, first *"AND"*, then *"OR"* precedence relationship is observed. In the product shown in Figure 2.5, in order to disassemble component 1, components 2 and 4 or 3 and 5 must be removed first. Therefore, the components (2 and 4) and (3 and 5) are connected to each other by *"AND"* precedence relationship. The *"AND"* groups are connected to component 1 by *"OR"* precedence relationship.

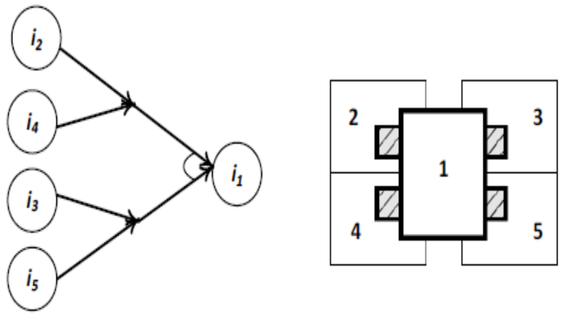

Figure 2.5 *"AND within OR"* relation (Özceylan, 2013)

"OR within AND" precedence relations: In this relationship, first *"OR"* precedence relation, then "*AND"* precedence relation is observed. In the product shown in Figure 2.6, to disassemble component 1, components 5 or 4 and 2 or 3 must be removed first. Therefore, the components (2 and 3) and (4 and 5) are connected to each other by *"OR"* precedence relationship. *"OR"* groups are connected to component 1 by *"AND"* precedence relationship.

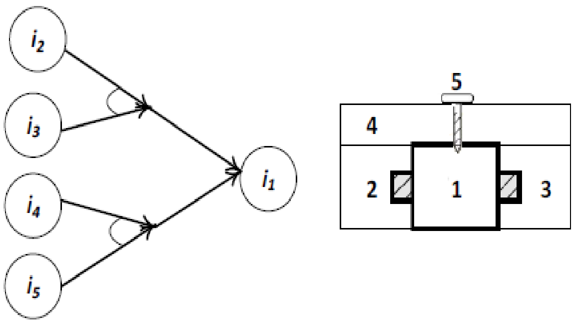

Figure 2.6 *"OR within AND"* relation (Özceylan, 2013)

2.3. Differences Between Assembly and Disassembly Systems

Disassembly operations cannot be considered as the reverse of assembly operations due to having unique characteristics (Kalayci and Gupta, 2013a). Assembly and disassembly processes are quite different both from technical and operational points of view. Several characteristics such as demand sources, complexity of performance measures, complexity of precedence relationship, and required line robustness are different in assembly and DL (Güngör and Gupta, 1999a; Güngör and Gupta, 2001; Özceylan et al., 2019). Differences between assembly and DL are summarized in Table 2.1.

Table 2.1 Differences between assembly and disassembly lines as regards technical and operational features (Güngör and Gupta, 2001; Lambert and Gupta 2004).

Line Consideration	***Assembly Line***	***Disassembly Line***
Demand sources	Single	Multiple
Demand entity	End product	Individual components
Complexity related to precedence relationships	High (includes physical and functional precedence constraints)	Moderate (mostly physical constraints)
Uncertainty related to quality of parts	Low	High
Uncertainty related to quantity of parts	Low	High
Uncertainty related to workstations and material handling system	Low to Moderate	High
Reliability of the workstations and the material handling system	High	Low
Complexity of performance measures	Moderate	High
Line flexibility	Low to Moderate	High
Design orientation	Design for assembly	Design for disassembly
Flow process	Convergent	Divergent
Direction of material flow	Forward	Reverse
Known techniques for line optimization	Numerous	Some

CHAPTER III

LITERATURE REVIEW

DLB Problem has been studied since 2000's years and many studies on the DLB have been made during this time. In this section, firstly, DLB and VRP are reviewed briefly and then AM literature related to SC is investigated. Finally, integrated DLB and distribution planning problem are analyzed. Detailed literature review is available in Chapters 4, 5, 6, 7.

3.1. Disassembly Line Balancing Literature

DLB problem that is a new study field became popular in the 2000's. The increasing importance of recycling also leads to an increase in the importance of disassembly. Because disassembly is the first stage of the recycling process. In this section, DLB problem literature is investigated.

Gungor and Gupta (2001) consider DLB problem in terms of task failures and analyse their effects on the line. This study is the first attempt to search and analyse task failures and to propose a model to decrease their effects on the line. Since then, several new ideas and studies have emerged that consider DLB problem. All these studies are reviewed in Özceylan et al. (2019) and Deniz and Ozcelik, (2019)'s studies.

Özceylan et al. (2019) classify DLB problem according to line types, objectives, product types, the structure of parameters, disassembly levels, models and solution approaches, complications, disassembly process and disassembled product and a comprehensive literature review is presented. Also, the current gaps related to DLB problem are discussed and several future research areas are provided in the direction of current gaps.

Deniz and Ozcelik (2019) review the DLB problem literature according to journals that most of the articles published, research areas, work together, articles that mostly cited, words that mostly stated in article titles together and whether the future directions of the published articles are realized. Bibliometric review and social network analysis are used for a comprehensive analysis of DLB problem literature. In addition, future study realization analysis is presented to see all future research suggestions in all studies and if they were studied or not.

3.2. Vehicle Routing Problem Literature

VRP is introduced by Dantzig and Ramser, (1959) and since then a lot of studies have been done related to VRP. Many ideas and classes are occurred by adding new remarks to the problem. Every day, the number of components obtained from DL are increasing due to the economic issues and environmental importance of recycling. These components are considered as raw materials by companies. Effective distribution of them to the RC is also important similar to the disassembly process. Thus, the VRP plays an important role in the distribution of recycled components. The classical VRP aims to determine a routing plan for a homogeneous fleet of vehicles to serve a range of customers.

The VRP and its variants have been intensively studied in the last sixty years and in this section an up-to-date review of the existing studies on the VRP is presented.

Montoya-Torres et al. (2015) present a state-of-the-art survey on VRP with multiple depots. Papers published between 1988 and 2014, in which several variants of the model are studied: split delivery, time windows, periodic deliveries, heterogeneous fleet, and pickup and delivery, are reviewed. The study also classifies approaches consistent with the single or multiple objectives that are optimized.

Koç et al. (2016) classify the studies on heterogeneous VRP. The heterogeneous VRP is investigated under two main categories: unlimited fleet and limited fleet. A comprehensive review of the existing studies is presented and also the performance of the state-of-the-art metaheuristic algorithms is analysed in detail.

Braekers et al. (2016) classifies VRP articles published between 2009 and 2015 and presents an electronic classification table to enable future researchers to get relevant literature, leaving only articles tailored to their interests.

Koç and Laporte (2018) review the existing literature on VRP with backhauls, containing exact and heuristic algorithms, models, variants, and industrial applications. A comparative analysis of the performance of heuristics for the problem is submitted. Also, both several extensions of the VRP with backhauls and a number of case studies are described.

Vidal et al. (2020) present a brief summary of current research in the field of VRP. The study discusses the VRP's attributes and research directions, determining recent successes, current shortcomings, and emerging challenges. The VRP models are investigated according to three categories: 1) considering relevant side metrics, objectives, or combinations of objectives; 2) progressing toward more precise and fine-grained models; 3) integrating routing optimization with other business decisions.

Elshaer and Awad (2020) present a taxonomic review including two-fold objectives. The first is to classify the VRP and its versions solved using metaheuristic algorithms. The second is to analyze the contribution of each metaheuristic in solving the VRP problems. The aim of the study is to reveal the utilization tends of the algorithms and the solved VRP versions to indicate the ones that are most popular.

Koç et al. (2020) show a comprehensive review of the existing studies on the VRP with simultaneous pickup and delivery. The survey paper presents the variants, algorithms, mathematical formulations, case studies, and industrial applications, and provides the trending topics and several promising research areas related to VRP.

3.3. A Brief Review on the 3D Printers In Supply Chain Management

The history of AM technology dates back to 1980s (Khajavi et al. 2014). From then on, many variants of 3DP technology have emerged. In this section, studies related with impacts of AM technology on SCM are investigated.

Huang et al. (2013) survey the AM literature and consider the societal impact of AM on SCM from a technical perspective. The study identifies many positive impacts of AM technology on customized healthcare products, manufacturing sustainability, and SCM. Also, two future research recommendations are identified in the areas of potential occupation hazard assessment and life-cycle energy consumption evaluation for AM.

Rogers et al. (2016) identify and classify the 3DP services and present a research agenda for future research on how 3DP services will affect the SC. The study firstly reviews the 3DP services-related literature and then conducts market analysis in European markets. The results show that there is now a necessity for more research, to clear how 3DP services could replace, complement or create entirely new SC due to the increasing importance of AM technology.

Pour et al. (2016) present a taxonomic review of the existing literature to show how AM technology could create differentiation from traditional manufacturing. The main aim is to analyse the AM system in isolation and to explain several features of AM technology impacts on the structure and characteristics of SCM. Finally, a set of recommendations is presented to reorganize the production system.

Sasson and Johnson (2016) aim to introduce an alternative where AM technology cooperates with and completes traditional manufacturing. The study investigates the potential scenario for this case and evaluates potential supply chain (SC) reconfigurations. The results show that firms that produce heterogeneous products are in a unique position to develop AM technology capabilities to increase the efficiency of their traditional manufacturing processes.

Ford and Despeisse (2016) provide insights into the effects of AM on SC. The paper claims that AM technology has positive impacts on improvements to material input processing, product and material life cycles through product and process redesign, make-to-order component and product manufacturing, and closing the loop. However, they state that AM technology has negative effects as an immature technology, as well as positive effects.

Li et al. (2016) deal with the impact of AM technology on spare parts SC. Three SC scenarios, conventional SC, distributed AM-based SC and centralized AM-based SC are investigated and compared with each other based on system dynamics simulations. The results show the spare part SC using AM is outstanding to the traditional manufacturing.

Chan et al. (2018) investigate the challenges arisen in the improvement of AM technology in terms of manufacturing and legal perspectives and focus on China. The main aim of the study is to reveal the barriers that stand mass-scale applications of AM technology. The results show that many companies can utilize the advantages of AM technology, but its potential is not promised due to the fact that 3DP has not been integrated well in SC.

3.4. Integrated Disassembly Line Balancing Problem and Distribution Planning Literature

In literature there are just a few studies which consider DLB problem and distribution planning together. These studies are introduced in this section and gap in literature is indicated.

Özceylan and Paksoy (2013) consider integrated reverse supply chain (RSC) and DLB problem in their study. A non-linear mathematical formulation is developed for problem under the objective of minimizing total transportation and total fixed cost of workstations.

Özceylan et al. (2014) combine closed loop supply chain (CLSC) and DLB problem. A non-linear mathematical formulation is presented in order to minimize total cost. The objective is to minimize costs of refurbishing, transportation, purchasing, and operating the disassembly workstations.

Özceylan and Paksoy (2014) propose two different fuzzy mathematical programming models for DLB problem and RSC integration problem. The objective of the study is to optimize the RSC and DLB problem, concurrently. The proposed models are run on test problems and the results are compared with each other.

Habibi et al. (2017a) deal with the disassembly of EOL products after collecting from certain points and integrate RSC and disassembly process. They consider the problem in two cases with coordination (case I) and without coordination (case II). Different mathematical formulations are presented for case I and case II. Since there is no data set in the literature to solve the problem, three benchmark data sets are produced for the current problem and case I and case II are compared by using these data sets.

Habibi et al. (2017b) consider the same problem with Habibi et al. (2017a) and propose a two-phase iterative heuristic for the current problem. This approach solves the Collection-Disassembly Problem in two steps. The proposed method is compared with the original form of Two-Phase Iterative Heuristic and results show that the proposed method gives the best solutions for test instances.

Kannan et al. (2017) integrate multi-product DLB problem in the planning recovery network from the perspective of a third-party provider. A mixed integer non-linear programming model is proposed for the problem and is validated on several real products from the liquid crystal displays industry. Also, sensitivity analysis is conducted to obtain insights from the presented model.

Habibi et al. (2018) deal with multi-vehicle stochastic collection-disassembly problem. The problem considers the number of EOL products and the uncertainty of the quality as well as the demands of the components. A mathematical formulation and sample average approximation are proposed to solve the problem.

Liu et al. (2020) search the collection-disassembly problem under uncertainty. They consider disassembly equipment selection and partial distributional information of demands of components. Recycled components' demands are assumed to be stochastic. A sample average approximation-based model and an approximated MIP model are presented to minimize cost and maximize the customer service level. Performance of the two models is evaluated on numerical examples.

Considering the above studies, it is observed that transportation of components formed after the disassembly process to remanufacturers by means of vehicle routing, has not been considered, yet. Therefore, in this chapter, I-DLB-RP, in which EOL products are disassembled first and then distributing recycled components to remanufacturers, is first considered. Then AM technology is cooperated with this system both in disassembly centre (DC) and in vehicle en-route.

In this thesis, nine different linear and non-linear mathematical formulations are presented for the I-DLB-RP, I-DLB-RP-3DP, I-CDDP, and I-DLB-RP-MAM. A summary and comparison of the presented mathematical formulations are shown in Figure 3.1. For example, model #6.2 is presented for I-CDDP. It is a linear formulation for multi-component case and considers both collection of EOL products and distribution of recycled components. However, the model #6.2 does not consider the inventory, 3DP technology and multi-period. Only, model #4.1 and #6.1 consider the single-component case, the other formulations are presented for distribution of multi-component. Model #5.1 and #7.1 take the AM technology into consideration.

Nevertheless, when 3D printer is available in DC for model #5.1; it is used in vehicle during distribution for model #7.1.

Table 3.1 Comparison of presented mathematical models

Problem	Models	Component	Model type	Inventory	Multi-period	3D	Collection
I-DLB-RP	#4.1	Single	Linear	-	-	-	-
	#4.2	Multi	Linear	-	-	-	-
	#4.3	Multi	Non-linear	-	-	-	-
	#4.4	Multi	Non-linear	+	-	-	-
	#4.5	Multi	Non-linear	+	+	-	-
I-DLB-RP-3DP	#5.1	Multi	Non-linear	-	-	+	-
I-CDDP	#6.1	Single	Linear	-	-	-	+
	#6.2	Multi	Linear	-	-	-	+
I-DLB-RP-MAM	#7.1	Multi	Non-linear	+	-	+	-

CHAPTER IV
INTEGRATED DISASSEMBLY LINE BALANCING AND ROUTING PROBLEM[1]

This chapter introduces the I-DLB-RP. The I-DLB-RP simultaneously optimizes two well-known optimization problems. The former one balances the DL in the DCs, whereas the latter one constructs a routing plan to distribute the usable components, generated by the disassembly process, from DC to the RC, i.e., customers. With the increasing importance of disassembly process for tackling with the burden of waste and the number of disassembled products, the distribution planning of usable components released after the disassembly process becomes essential. This chapter considers several scenarios; single-component distribution, multi-component distribution, inventory cost, and multi-period conditions. We propose five linear and non-linear mathematical models. Extensive computational experiments conducted on generated realistic benchmark instances. The analysis quantify the benefits of integrating the two problems.

4.1. Introduction

Rapid technological developments result in a continuous increase in the amount of consumption and consequently increase the amount of waste. Effective management of the recycling of wastes is quite important to ensure the protection of environment and economic development. Environmentally conscious remanufacturing and recycling have gain importance due to growing demand for a cleaner environment. Several companies, such as Apple, Panasonic, HP, GM, Kodak, Xerox, transform their operations to ensure sustainable production (Deniz and Ozcelik, 2019). Apple invented a recycling robot, called Liam, which can quickly disassemble the iPhone 6. Two Liam

[1] This chapter is based on a paper titled "*Integrated Disassembly Line Balancing and Routing Problem*" that is published in the International Journal of Production Research, doi: 10.1080/00207543.2020.1740346 by Diri Kenger, Z., Koç, Ç., Özceylan, E.

robots disassemble 2.4 million phones each year (Rujanavech et al., 2016). In 2019, Panasonic provided 93% recycling in washing machines, 81% in refrigerators, 95% in air conditioners, 87% in plasma televisions, and used them in new products (Panasonic 2019).

Disassembly is the first essential step on product recovery. It is a systematic separation of valuable components from discarded products through a series of operations. In order to increase the disassembly efficiency, the DL is an ideal choice for automated removal of products (Güngör and Gupta, 2002). The DLB problem has received much interest by researchers in the last two decades. The DLB problem can be defined as assigning of the disassembly tasks of a product to sequential workstations to provide certain conditions. The DLB problem uses the resources of the line in a way efficient while meeting the demand (Güngör and Gupta 2002; Altekin et al., 2008).

Logistics sector gains more importance depending on the increase in international trade volume, removing the borders between countries and the development of globalization in the recent period. Now goods and services that are designed in any geographical area of the world, can be produced in another place and can be demanded elsewhere. Therefore, the factor that makes goods and service producing companies prominent and advantageous in the global markets emerges as speed and on time delivery. These rapid changes force companies to simultaneously consider complex SC optimization problems instead of individually.

4.1.1. A Brief Literature Review

Every day, the number of components obtained from DL is increasing due to the economic issues and environmental importance of recycling. These components are considered as raw materials by companies. Effective distribution of them to the RC is also crucial similar to the disassembly process. Thus, the VRP plays an important role in the distribution of recycled components. The classical VRP aims to determine to construct a routing plan for a homogeneous fleet of vehicles to serve a range of customers. The VRP and its variants have been intensively studied in the last 60 years (Toth and Vigo, 2014; Koç et al., 2016; Koç and Laporte, 2018; Vidal et al., 2020). Several studies considered the simultaneous optimisation of the VRP with other problems such as production scheduling (Fu et al., 2017; Karaoğlan and Kesen, 2017;

Lacomme et al., 2018). In the last two decades, classical DLB problem and its many variations have been intensively studied due to the importance of recycling. Güngör and Gupta, (2001) introduced the DLB, analysed task failures, and proposed a model to decrease their effects on the line. For further details on the DLB and its variants, the reader is referred to the survey papers of (Özceylan et al., 2019) and Deniz and Ozcelik, (2019). Several papers considered simultaneous optimisation of line balancing with another problem (Brahimi and Aouam, 2016; Hamta et al., 2015; Koç, 2017; Paksoy et al., 2012; Paksoy and Özceylan, 2012). Though considering disassembly seems like the reverse of assembly, for complex products, the operational characteristics of disassembly and assembly are quite different from both technical and operational points of view (Özceylan et al., 2019). Several characteristics such as demand sources, the complexity of precedence relationship, the complexity of performance measures, and required line robustness are different in the assembly and DL (Güngör and Gupta, 2001). In addition, there are some specific objectives for the DLB such as removing highly demanded parts early, removing hazardous parts early, minimising the effect of the defective parts, removing easily accessible parts early, and removal of the parts with longer disassembly task times early. Even though there are various papers that consider the integration of line balancing with another problem, few studies focused on the integration of DLB and transportation planning. Özceylan and Paksoy, (2013) consider the integrated RSC and the DLB problem in their study. A non-linear mathematical formulation is developed for the problem under the objective of minimising total transportation and total fixed cost of workstations. Özceylan et al., (2014) combined CLSC and DLB problem. A non-linear mathematical formulation is presented in order to minimise the total cost. Özceylan and Paksoy, (2014) proposed two fuzzy mathematical formulations for the integrated problem of DLB and RSC. The objective of the study is to optimise the RSC and DLB problem. Habibi et al., (2017a) studied the RSC and the disassembly of EOL products after collecting from certain points. They considered two cases, with coordination and without coordination, and presented mathematical formulations for each case. However, balancing of DL and workstation opening cost are not considered. For the same problem, Habibi et al., (2017b) proposed a two-phase iterative heuristic. Kannan et al., (2017) integrated multi-product DLB problem in the planning recovery network. The authors proposed a mixed-integer non-linear programming (MINLP) model for the problem. Habibi et al., (2018) later considered a multi-vehicle stochastic collection-disassembly problem. A mathematical formulation and sample average approximation are proposed to solve the problem.

4.1.2. Scientific Contributions and Structure of the Chapter

We believe that there exists merit in the simultaneous optimization of the DLB and VRP. To our knowledge, the integrated problem has not been investigated in the literature.

We make three main scientific contributions. We first introduce the integrated DLB and VRP (I-DLB-RP). Our second contribution is to propose five linear and non-linear mathematical formulations and to consider several scenarios; single-component distribution, multi-component distribution, inventory cost, and multi-period conditions. Our third contribution is to conduct extensive computational experiments on generated benchmark instances, and to provide several insights on the I-DLB-RP.

The rest of the chapter is structured as follows. Section 4.2 presents the problem definition and mathematical formulations. Section 4.3 provides the computational experiments. Section 4.4 finally presents our concluding remarks.

4.2. Problem Definition and Mathematical Formulations

In the I-DLB-RP, a single DC first disassembles EOL products. A vehicle with fixed capacity then dispatches usable disassembled components to remanufacturers. Figure 4.1 illustrates the I-DLB-RP as part of a closed-loop SC network.

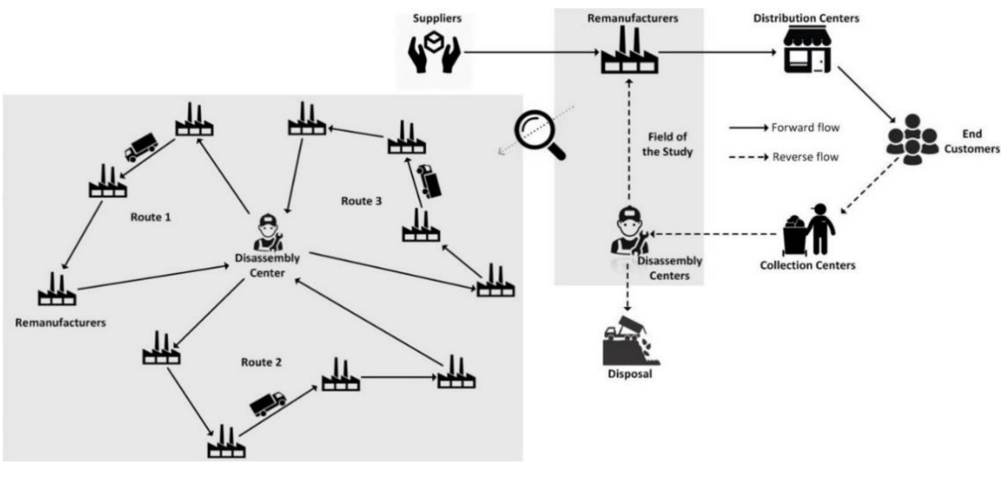

Figure 4.1 The illustration of the I-DLB-RP as part of a closed-loop supply chain network.

We now present five mathematical models for the I-DLB-RP. We order them from the most basic and simple form to the most comprehensive one. The main features of each model are given below:

- Model #4.1 is a linear model with single component, single period and without inventory.
- Model #4.2 is a linear model with multi component, single period and without inventory.
- Model #4.3 is a non-linear model with multi component, single period and without inventory.
- Model #4.4 is a non-linear model with multi component, single period and inventory.
- Model #4.5 is a non-linear model with multi component, multi period and inventory.

4.2.1. Notations and TAOG

In this section notations and TAOG are introduced for the proposed model. Also, some additional definitions are presented to better come out the problem.

The indices, sets and parameters, and variables are as follows:

Notations

Indices

c,g	remanufacturing centre, $c,g=\{1,2,\ldots,N\}$
I	task
j,h	workstation
A	artificial task

Sets and parameters

A_a	artificial nodes of a
B_i	normal nodes of i

$P(A_a), P(B_i)$	immediate predecessor set of A_a, B_i, respectively
$S(A_a), S(B_i)$	immediate successor set of artificial node A_a, B_i, respectively
d_{B_i}	task time (normal node) of B_i
J	number of workstations (upper bound)
W_{time}	working time
De_g	demand of remanufacturing centre *g*
Ct	fixed cost of shipping from disassembly centre to remanufacturing centre *g*
D_{cg}	distance between disassembly centre and remanufacturing centre or between remanufacturing centres
O	fixed cost to open a workstation in the disassembly line
Q	vehicle capacity
Cyc	cycle time

Variables

U_g	load of vehicle upon leaving disassembly centre
x_{ij}	1, if task B_i is assigned to workstation *j*; 0 otherwise
y_{cg}	1, if vehicle travels from disassembly centre to remanufacturing centre or between remanufacturing centres; 0 otherwise
z_i	1, if task B_i is performed; 0 otherwise
F_j	1, if workstation *j* is opened; 0 otherwise

The DLB parts of mathematical models are developed by using the formulation of Koc et al., (2009). They introduce a graph called TAOG which contains full information on all the DT. A DT represents a way of completely disassembling a product. The artificial nodes A_{is} represent subassemblies. The normal nodes B_{is} represent tasks.

Figure 4.2 illustrates the TAOG of the sample product that includes 23 tasks (indicated in white circles) and 13 artificial nodes (indicated in blue circles) with all disassembly task times.

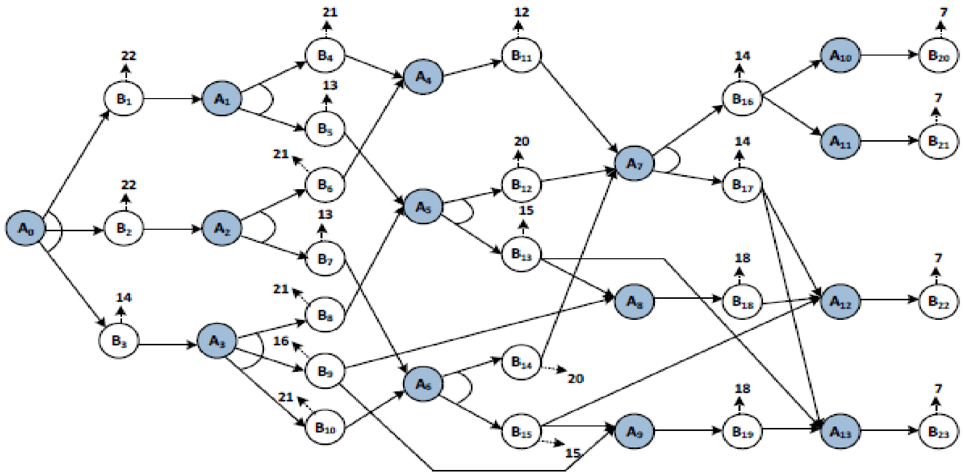

Figure 4.2 TAOG of the sample product (Koc et al., 2009).

4.2.2. Mathematical Model #4.1

This section presents a mixed-integer linear mathematical model, called model #4.1, for the I-DLB-RP. The disassembly process is performed in single DC and one-type of component is requested by RC. The model #4.1 is developed by using the formulation of Koc et al., (2009) and classical capacitated VRP. Assumptions of the model #4.1 are as follows:

(a1) A single type of product is completely disassembled.

(a2) A task cannot be split among two or more workstations.

(a3) All workstations can process any of tasks and all have the same associated costs.

(a4) Each disassembly takes apart the product or sub-assembly into exactly two or more new sub-assemblies.

(a5) All RC demand only one type and the same product.

(a6) Capacities of vehicles are known and are ready for service to customers in the RC.

(a7) The demand of each RC for a component is known and must be fully satisfied.

The mathematical model #4.1 is then:

$$min\ O * \sum_{j}^{J} F_j + Ct * \sum_{c}^{N} \sum_{g,g \neq c}^{N} D_{cg} * y_{cg} \tag{4.1}$$

The objective function (4.1) minimizes the total traveling cost of vehicles and the total fixed cost of operating disassembly workstations.

Subject to

$$\sum_{i:B_i \in S(A_0)} Z_i = 1 \tag{4.2}$$

$$\sum_{i:B_i \in S(A_a)} Z_i = \sum_{i:B_i \in P(A_a)} Z_i \qquad \forall a, a \neq 0 \tag{4.3}$$

$$\sum_{j=1}^{J} x_{ij} = z_i \quad \forall\, i \tag{4.4}$$

$$\sum_{i:B_i \in S(A_a)} x_{ih} \leq \sum_{i:B_i \in P(A_a)} \sum_{j=1}^{h} x_{ij} \qquad \forall\, a, a \neq 0, h \in J \tag{4.5}$$

$$\sum_{i=1}^{I} x_{ij} * d_{Bi} \leq Cyc * F_j \ \ \forall j, j = 1, \ldots, J \tag{4.6}$$

$$F_{j+1} \leq F_j \quad \forall j, j = 1, \ldots, J-1 \tag{4.7}$$

Constraints (4.2) and (4.3) guarantee that exactly one of the OR-successors is selected in the DC. Constraints (4.4) ensure that each task is assigned to exactly one workstation in the DC. Constraints (4.5) are precedence constraints. Constraints (4.6) prevent the cycle time being exceeded by a disassembly workstation. Constraints (4.7) ensure that workstations open sequentially.

$$\sum_{g=1,g\neq c}^{N} y_{cg} = 1 \ \forall c, c = 2, \ldots, N \tag{4.8}$$

$$\sum_{c=1,c\neq g}^{N} y_{cg} - \sum_{c=1,c\neq g}^{N} y_{gc} = 0 \quad \forall g, g = 1, \ldots, N \tag{4.9}$$

$$U_c - U_g + Q * y_{cg} \leq Q - De_g \quad \forall c, g, c, g = 2, \ldots, N, c \neq g \tag{4.10}$$

$$De_g \leq U_g \leq Q \qquad \forall g \tag{4.11}$$

$$x_{ij}, z_i\ , y_{cg}, F_j \in \{0,1\} \qquad \forall i, j, c, g \tag{4.12}$$

Constraints (4.8) and (4.9) are general assignment constraints for the VRP. Constraints (4.8) guarantee that each customer must be visited once. Constraints (4.9) define the flow. Constraints (4.10) are capacity constraints. Constraints (4.11) enforce the non-negativity restriction on the decision variables. Finally, constraints (4.12) represent the binary variables.

The cycle time in DC is calculated by dividing the total working time to the total demand of RC. Since working time and total demand of components are known, Constraints (4.13) is linear:

$$Cyc = (W_{time}/(\sum_{g=2}^{N} De_g)) \tag{4.13}$$

4.2.3. Mathematical Models #4.2 and #4.3

We now present a linear (model #4.2) and a non-linear (model #4.3) mixed-integer mathematical model for the I-DLB-RP with single DC and multi-component. More than one-type of components are requested by RC. The assumptions of model #4.2 are as follows:

(a8) All RC demand more than one type of component.

(a9) Total demand of a RC cannot exceed vehicle capacity, and the assumptions of (a1-a4), (a6), and (a7).

Additional notations for model #4.2 and model #4.3 are given below.

Notations

Indices

k	component

Parameters

De_{gk}	demand of remanufacturing centre g for component k
μ	big number
St	disassembling cost of a product
Pr	demand satisfying profit

Variables

P	maximum number of disassembled products

The mathematical model #4.2 is then:

$$\min O * \sum_{j}^{J} F_j + Ct * \sum_{c}^{N} \sum_{g,g\neq c}^{N} D_{cg} * y_{cg} + St * Max_{Demand} - Pr * \sum_{c}^{N} \sum_{g,g\neq c}^{N} \sum_{k}^{K} De_{ck} * y_{cg} \tag{4.14}$$

The objective function (4.14) minimizes the total cost considering profit of satisfying demands.

Subject to

$$U_c - U_g + Q * y_{cg} \leq Q - \sum_{k=1}^{K} De_{gk} \qquad \forall c, g, c, g = 2, \ldots, N, c \neq g \tag{4.15}$$

$$\sum_{k=1}^{K} De_{gk} \leq U_g \leq Q \qquad \forall g \tag{4.16}$$

Constraints (4.2)-(4.9) and (4.12).

Constraints (4.15) are the capacity constraints. The non-negativity restriction is provided by constraints (4.16). Since all demand will be provided, cycle time can be calculated based on given formulations as follows:

$$Max_{Demand} = \max\{\sum_{g=1}^{N} De_{gk} |\ k = 1, \ldots, K\} \tag{4.17}$$

$$Cyc = \frac{W_{time}}{Max_{Demand}} \tag{4.18}$$

If we relax the assumption "The demand of each RC for a component is known and must be fully satisfied" model will be non-linear. The assumptions of models #4.3 are as follows:
(a10) The demand of all RC does not have to be satisfied, and the assumptions (a1-a4), (a6), (a8), and (a9).

The mathematical model #4.3 is then:

$$\min O * \sum_{j}^{J} F_j + Ct * \sum_{c}^{N} \sum_{g, g \neq c}^{N} D_{cg} * y_{cg} + St * P - Pr * \sum_{c}^{N} \sum_{g, g \neq c}^{N} \sum_{k}^{K} De_{ck} * y_{cg} \tag{4.19}$$

The objective function (4.19) minimizes the total costs of workstations, routing and disassembly of products considering profit of satisfying demands.

Subject to

$$Cyc * P = W_{time} \tag{4.20}$$

$$\sum_{i=1}^{I} x_{ij} * d_{B_i} \leq Cyc \qquad \forall j \tag{4.21}$$

$$\sum_{i=1}^{I} x_{ij} \leq \mu * F_j \qquad \forall j \tag{4.22}$$

Constraints (4.20) and (4.21) are cycle time constraints. Constraints (4.22) are workstation constraints.

$$\sum_{g=1, g\neq c}^{N} y_{cg} \leq 1 \qquad \forall c, c = 2, \dots, N \tag{4.23}$$

$$\sum_{c=2}^{N} \sum_{g=1, g\neq c}^{N} De_{ck} * y_{cg} \leq P \qquad \forall k, k = 1, \dots, K \tag{4.24}$$

$$Cyc \geq 0 \tag{4.25}$$

Constraints (4.2)-(4.5), (4.7), (4.9), (4.12), (4.15) and (4.16).
Constraints (4.23) state that demand of all RC does not need to be fully satisfied. Constraints (4.24) guarantee that total demand cannot exceed the maximum number of disassembled products. Constraints (4.25) indicate the non-negativity restrictions on decision variables.

4.2.4. Mathematical Model #4.4

We now present model #4.4 for the I-DLB-RP considering inventory. Assumptions of model #4.3 are also valid for model #4.4. The notations are as follows:

Notations

Parameters

CI	inventory cost of component k

Variables

I_k	inventory level of component k

The mathematical model #4.4 is then:

$$min\, O * \sum_{j}^{J} F_j + Ct * \sum_{c}^{N} \sum_{g,g \neq c}^{N} D_{cg} * y_{cg} + St * P + CI * \sum_{k}^{K} I_k - Pr * \sum_{c}^{N} \sum_{g,g \neq c}^{N} \sum_{k}^{K} De_{ck} * y_{cg} \tag{4.26}$$

The objective function (4.26) minimizes the workstation cost, routing cost, disassembly cost of product and inventory cost.

Subject to

$$I_k = P - \sum_{c=2}^{N} \sum_{g=1,g \neq c}^{N} De_{ck} * y_{cg} \quad \forall k, k = 1, \dots, K \tag{4.27}$$

Constraints (4.2)-(4.5), (4.7), (4.9), (4.12), (4.15), (4.20)-(4.23) and (4.25).

Constraints (4.27) ensure the inventory balance of the DC.

4.2.5. Mathematical Model #4.5

We finally present the model #4.5 which is non-linear and considers inventory cost and multi-period. Assumptions of model #4.2 are also valid for model #4.5. The notations are as follows:

Notations

Indices

t	Period

Variables

P_t	maximum number of disassembled product at period *t*
De_{gkt}	demand of remanufacturing centre *g* from component *k* at period *t*
I_{kt}	inventory level of component *k* at period *t*
C_t	cycle time at period *t*
U_{gt}	load of a vehicle just after leaving cluster at period *t*
x_{ijt}	1, if task B_i is assigned to workstation *j* at period *t*; 0 otherwise
y_{cgt}	1, if vehicle travels from disassembly centre to remanufacturing centre or between remanufacturing centres at period *t*; 0 otherwise
z_{it}	1, if task B_i is performed at period *t*; 0 otherwise
F_{jt}	1, if workstation *j* is opened at period *t*; 0 otherwise

The mathematical model #4.5 is then:

$$\min \quad \begin{aligned} & O * \sum_{j}^{J} \sum_{t}^{T} F_{jt} + Ct * \sum_{c}^{N} \sum_{g,g \neq c}^{N} \sum_{t}^{T} D_{cg} * y_{cgt} \\ & + St * \sum_{t}^{T} P_t + CI * \sum_{k}^{K} \sum_{t}^{T} I_{kt} \\ & - Pr * \sum_{c}^{N} \sum_{g,g \neq c}^{N} \sum_{k}^{K} \sum_{t}^{T} De_{ckt} * y_{cgt} \end{aligned} \tag{4.28}$$

The objective function (4.28) minimizes total cost of workstation, routing, product disassembling and inventory.

Subject to

$$\sum_{i:B_i \in S(A_0)} z_{it} = 1 \quad \forall t \tag{4.29}$$

$$\sum_{i:B_i \in S(A_a)} z_{it} = \sum_{i:B_i \in P(A_a)} z_{it} \qquad \forall\, t, a, a \neq 0 \tag{4.30}$$

$$\sum_{j=1}^{J} x_{ijt} = z_{it} \qquad \forall\, i, t \tag{4.31}$$

$$\sum_{i:B_i \in S(A_a)} x_{iht} \leq \sum_{i:B_i \in P(A_a)} \sum_{j=1}^{h} x_{ijt} \qquad \forall a, t, h \in J, a \neq 0 \tag{4.32}$$

$$\sum_{i=1}^{I} x_{ijt} * d_{B_i} \leq Cyc_t \quad \forall j, t, j = 1, \dots, J \tag{4.33}$$

$$Cyc_t * P_t = W_{time} \quad \forall t \tag{4.34}$$

$$\sum_{i=1}^{I} x_{ijt} \leq \mu * F_{jt} \ \ \forall j, t \tag{4.35}$$

$$F_{j+1,t} \leq F_{jt} \quad \forall j, t, \text{ j=1,…,J-1} \tag{4.36}$$

Constraints (4.29) and (4.30) guarantee that exactly one OR-successor is selected in DC at period t. Constraints (4.31) ensure that each disassembly task is assigned to exactly one workstation during a period. Constraints (4.32) impose precedence relations at period t. Constraints (4.33) guarantee that the disassembly time of tasks in the workstation does not exceed the cycle time for all periods. Constraints (4.34) calculate the cycle time by dividing total working time to maximum number of disassembled products for all periods. Constraints (4.35) are workstation constraints. Constraints (4.36) force that workstations open sequentially.

$$\sum_{g=1, g\neq c}^{N} y_{cgt} = 1 \ \ \forall t, c, c = 2, \dots, N \tag{4.37}$$

$$\sum_{c=1, c\neq g}^{N} y_{cgt} - \sum_{c=1, c\neq g}^{N} y_{gct} = 0 \ \ \forall t, g, g = 1, \dots, N \tag{4.38}$$

$$U_{ct} - U_{gt} + Q * y_{cgt} \leq Q - \sum_{k=1}^{K} De_{gkt} \quad \forall t, c, g, c, g = 2, \dots, N, c \neq g \tag{4.39}$$

$$I_{kt} = P_t - \sum_{c=2}^{N} De_{ckt} \quad \forall k, t | t = 1 \tag{4.40}$$

$$I_{kt} = P_t - \sum_{c=2}^{N} De_{ckt} + I_{k,t-1} \quad \forall k, t | t > 1 \tag{4.41}$$

$$Cyc_t \geq 0 \qquad \forall g, t \tag{4.42}$$

$$\sum_{k=1}^{K} De_{gkt} \leq U_{gt} \leq Q \qquad \forall g, t \tag{4.43}$$

$$x_{ijt}, z_{it}, y_{cgt}, F_{jt} \in \{0,1\} \qquad \forall i, j, c, g, t \tag{4.44}$$

Constraints (4.37) and (4.38) are classical assignment constraints for the VRP. Constraints (4.39) define the capacity constraint at period t. Constraints (4.40) and (4.41) ensure the inventory balance of the DC for all periods. Constraints (4.42)-(4.44) present the non-negative and binary decision variables, respectively.

4.3. Computational Results

This section presents the results of our extensive computational experiments for models #4.1, #4.2, #4.3, #4.4 and #4.5. All experiments were conducted on a server with Intel Core i7-2630QM 2.0 GHz dual processor and 6.00 GB memories. We used GAMS/GUROBI and GAMS/SCIP with its default settings as the optimizer to solve the linear and non-linear models, respectively.

We first present the data generation and benchmark instances in Section 4.3.1, we then present the results of each mathematical model in Section 4.3.2, and we finally present scenario analysis in Section 4.3.3.

4.3.1. Data Generation and Benchmark Instances

To generate our benchmark instances, we consider well-known data sets in the literature. For the DLB, we used a set of a sample product from Koc et al., (2009). Table 4.1 presents the disassembly task times and demands of RC.

For the VRP part, we modify the classical VRP instances of Augerat et al., (1995) to generate our test bed. In particular, we adjust the smallest data set (P_n16_k8) of Set P, and for simplicity 16 nodes are decreased to 9 nodes (1 DC and 8 RC) without changing the coordinate of nodes and vehicle capacity. All demand characteristics were generated using discrete uniform distributions. Demands for single-component case are in the range [5-10] which are presented in Table 4.1.

Table 4.1 Disassembly task times of sample product and demands of RCs.

Task	Task time	Task	Task time	Task	Task time	RC	Demand
1	22	9	16	17	14	2	6
2	22	10	21	18	18	3	8
3	14	11	12	19	18	4	6
4	21	12	20	20	7	5	8
5	13	13	15	21	7	6	5
6	21	14	20	22	7	7	7
7	13	15	15	23	7	8	5
8	21	16	14	-	-	9	10

Demands of RC for multi-component case are in the range [1-6]. Table 4.2 presents the first and second period demands for multi-component case. C1, C2, C3, C4, C5, C6, and C7 denote component 1, 2, 3, 4, 5, 6, and 7, respectively.
Unit shipping cost (*Ct*) and cost of opening a workstation (*O*) were set as in Özceylan and Paksoy (2013). Ct is fixed to 5.23 cents per tonne-km for a general freight truck. *O* in the DL is fixed to 100 $/workstation. *Wtime* is set to 1000 minutes. Number of maximum workstation (*J*) is set to 5. Disassembling cost of a product (*St*) is fixed to 10$/product and inventory cost per component (*CI*) is fixed to 5$/component. Profit of satisfying demands is fixed to 3$/component for models #4.1, #4.2, and #4.5. Since the demands of RC are not needed to be fully satisfied for models #4.3 and #4.4, changing demand satisfying profit results in changing cycle time and number of opened workstations. Therefore, profit of satisfying demands is fixed to 6$/component for models #4.3 and #4.4.

Table 4.2 First and second period demands for multi-component case.

RC	First period							Second period						
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
2	3	1	4	3	2	1	2	5	1	2	1	2	4	2
3	2	4	3	2	3	1	2	2	5	3	1	2	3	2
4	1	1	6	2	2	1	3	4	1	3	2	4	2	4
5	2	1	2	3	4	3	4	1	4	3	2	4	3	1
6	1	1	5	2	1	2	1	3	2	4	1	2	3	2
7	5	2	1	1	3	3	4	2	3	1	2	5	6	3
8	2	1	3	3	4	2	1	6	4	6	4	3	5	5
9	1	3	2	1	3	3	2	2	1	3	2	4	2	1

4.3.2. Results

This section presents the detailed experimental results. Table 3 shows the optimal results for illustrative examples. Obj is the objective function value, NS is the number of workstations, CT is the cycle time in minutes, TN is the number of vehicle tour, CPU is run time in seconds, and T is period. The demand quantities of components are the same for the multi-component cases (models #4.3 and #4.4), and maximum station times of balances is 47 at Figure 4.3, but cycle times in Table 4.3 are different. The main reason of this difference is a variety of objective functions. The objective function of model #4.4 includes the cost of inventory in addition to model #4.3. Therefore, disassembled number of products at the solution of model #4.4 is one unit less than the solution of model #4.3, and actual cycle times are different.

Table 4.3 Optimal results for presented models.

	Model #4.1	**Model #4.2**	**Model #4.3**	**Model #4.4**	**Model #4.5**	
					T=1	T=2
Obj	507.74$	178.501$	287.746$	155.048$	816.52$	
NS	5	3	2	2	3	2
CT	18.18	38.46	47.619	50	35.71	43.47
TN	2	4	4	4	4	5
CPU	3.078	0.768	12.51	4.88	11.35	

For the single-component case, cycle time is calculated by dividing working time to demand quantity of single-component. Figure 4.3 illustrates the optimal line balances of five models. The calculation of cycle times for each model is as follows:

$CT_1 = (W_{time}/(\sum_{g}^{G} De_g))$ =1000/55=18.18 minutes

$CT_2 = W_{time}/Max\_Demand = 1000/26 = 38.46$ minutes

$CT_3 = W_{time}$/P=1000/21=47.619 minutes

$CT_4 = W_{time}$/P=1000/20=50 minutes

$CT_{5,T1} = W_{time}/P_1 = 1000/28 = 35.71$ minutes

$CT_{5,T2} = W_{time}/P_2 = 1000/23 = 43.47$ minutes

Model1	3 Stime=14	9 Stime=16	19 Stime=18	18 Stime=18	22 23 Stime=14	CT=18.18
Model2	1 5 Stime=35	13 23 Stime=22	18 22 Stime=25			CT=38.46
Model3	2 7 Stime=35	15 19 22 23 Stime=47				CT=47.619
Model4	1 5 Stime=35	13 18 22 23 Stime=47				CT=50
Model5_T1	3 8 Stime=35	12 17 Stime=34	22 23 Stime=14			CT=35.71
Model5_T2	1 4 Stime=43	11 16 Stime=26	20 21 Stime=14			CT=43.47

Figure 4.3 Balanced disassembly workstations for all models.

Figures 4.4-4.6 illustrate the optimal distribution of components for illustrative examples for five different models. Since we relax the demand of each RC for a component is known and must be fully satisfied assumption for models #4.3 and #4.4, demand of all RC is not satisfied.

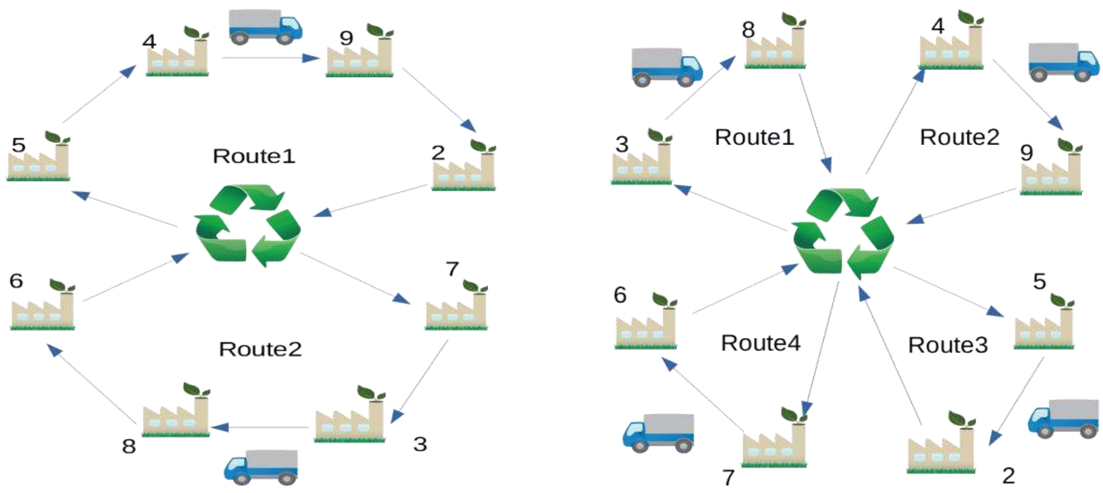

Figure 4.4 Optimal distribution of model #4.1 (left) and model #4.2 (right).

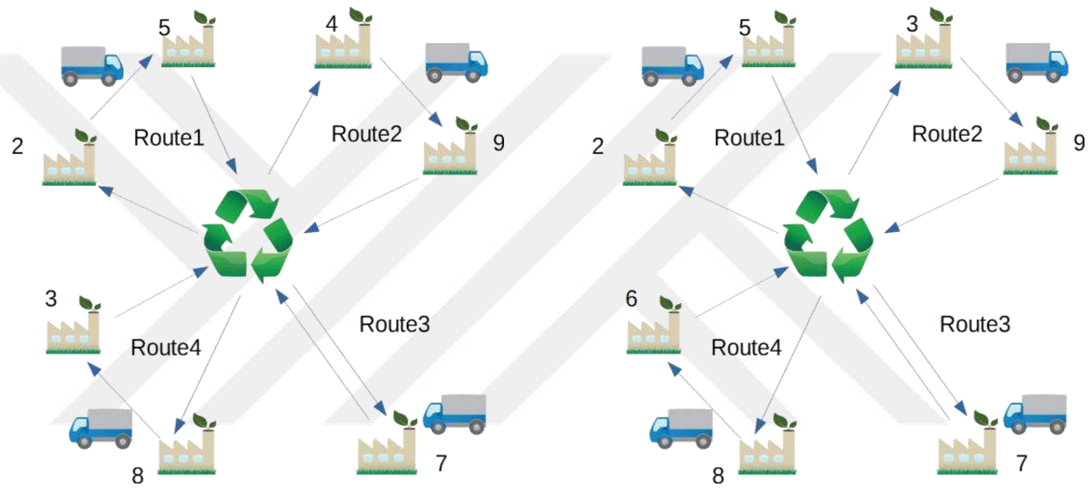

Figure 4.5 Optimal distribution of model #4.3 (left) and model #4.4 (right).

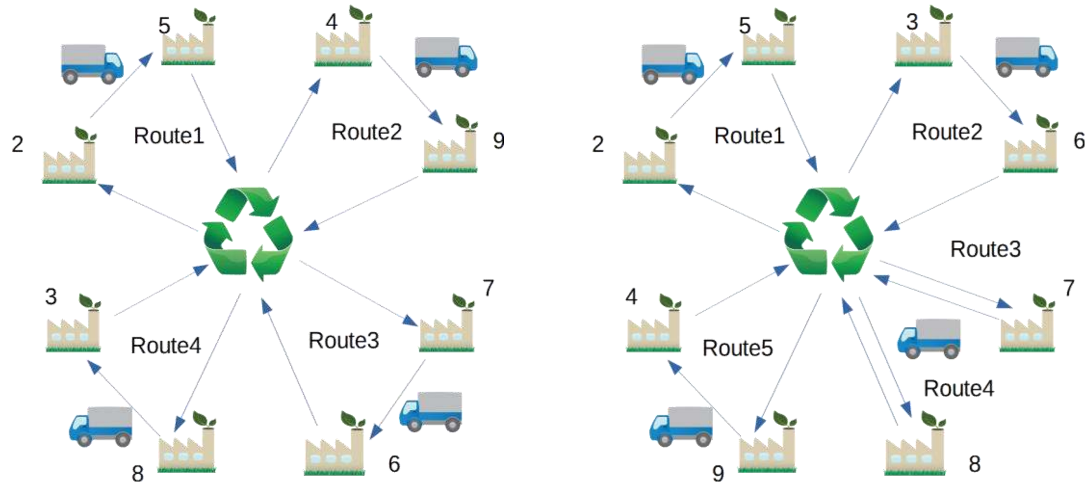

Figure 4.6 Optimal distribution of first (left) and second (right) periods of model #4.5.

Since inventory constraint is considered for the case of model #4.4 and model #4.5, inventory level is occurred for each component. The disassembly process is performed according to the number of maximum demanded component for both cases and inventory cost occurs for some products. Table 4.4 shows that inventory level of components in DC after distributing of components to remanufacturers. In Table 4.4, component is denoted by Comp and inventory level is denoted by IL.

Table 4.4 Inventory level of components in disassembly centre.

IL / Comp	Model4	Model5	
		T=1	T=2
1	4	11	9
2	7	14	16
3	-	2	-
4	5	11	19
5	-	6	3
6	5	12	7
7	4	9	12

4.3.3. Scenario analysis

In this section, we first investigate the effect of changing profit of satisfying demand, then the effect of changing demand quantity of RC, effects of changes in complexity of the product, limit analysis is conducted and finally the effects of changing penalty cost are analysed on model #4.4. Since the assumption the demand of each RC for a component is known and must be fully satisfied is relaxed for models #4.3 and #4.4, the first sensitivity analysis is realized on these models. The other sensitivity analyses are executed on model#4.4, because model#4.4 is the most comprehensive model for single period among presented models.

4.3.3.1. The Effect of Changing Profit of Satisfying Demand

We now investigate the effect of changing profit of satisfying demand on disassembled product, cycle time, number of workstations and component distribution to RC for models #4.3 and #4.4. The demand of each RC for each component is known. However, it is not necessary to satisfy these demands for models #4.3 and #4.4. Therefore, the number of RC whose demands are satisfied varies according to the demand satisfying profit. Furthermore, the number of disassembled products, cycle time and number of opened workstation changes.

Table 4.5 presents the results of scenario analysis for model #4.3 and model #4.4. It is indicated that the profit of satisfying demand increases, and the number of disassembled products and the number of RC also increases. The number of workstations increases as cycle time decreases in the same working time. Model #4.4 allows keeping inventory different from model #4.3. Higher demand satisfying profit is required to meet the demand of all RC for model #4.4. This implies that keeping inventory is more profitable than satisfying the demands.

Table 4.5 Results of model #4.3 and #4.4 on changing profit of satisfying demand.

Profit of satisfying demand ($)	**Disassembled product (unit)**	**CT**	**NS**	**Remanufacturing centres**
				Model #4.3
3	11	90.9	1	3, 5, 6, 7
4	12	83.33	1	2, 3, 5, 7
5	21	47.61	2	2,3,4,5,7,8,9
12	26	38.46	3	All nodes
				Model #4.4
3	11	90.9	1	3,5,6,7
5	20	50	2	2,3,5,6,7,8,9
11	21	47.61	2	2,3,4,5,7,8,9
21	26	38.46	3	All nodes

Figures 4.7 and 4.8 illustrate the relationship between cycle time, number of disassembled products, and number of satisfied RC. According to this scenario, while increasing the profit of satisfying demand, the number of disassembled product and number of satisfied RC increases in the same time. As the number of disassembled products increases, the number of components also increases.

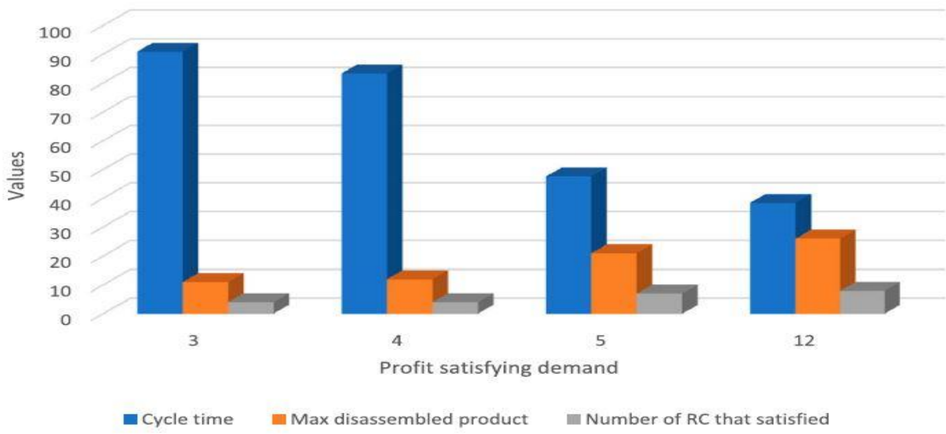

Figure 4.7 Relationship between the cycle time, maximum disassembled product, and number of RC that satisfied for model #4.3.

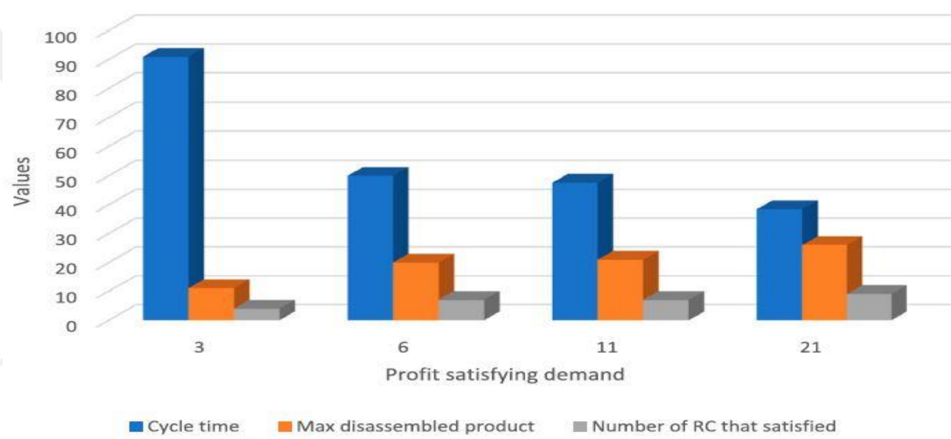

Figure 4.8 Relationship between the cycle time, maximum disassembled product, and number of RC that satisfied for model #4.4.

Figures 4.9 and 4.10 illustrate the relationship between number of disassembled products, cycle time and number of workstations. In this case, while increasing the profit of satisfying demand, the number of disassembled product and number of workstations also increases. However, increasing profit of satisfying demand decreases the cycle time, since number of disassembled product increases.

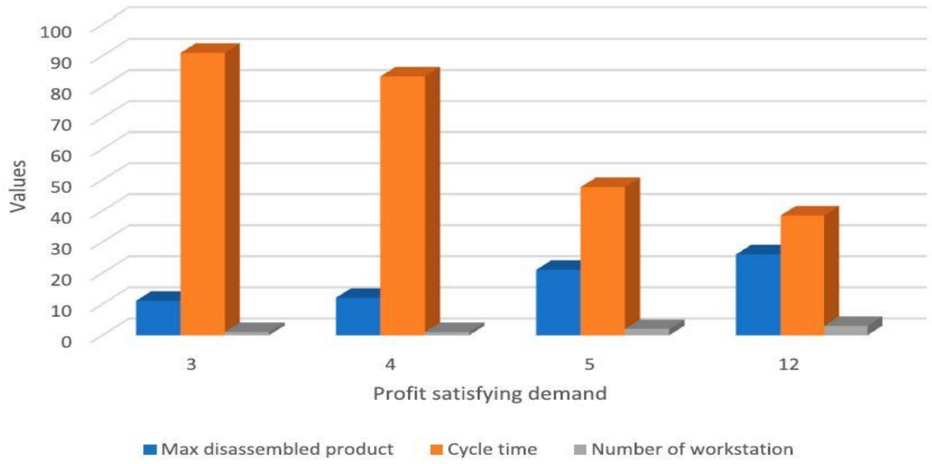

Figure 4.9 Relationship between max disassembled product, cycle time, and number of workstations for model #4.3.

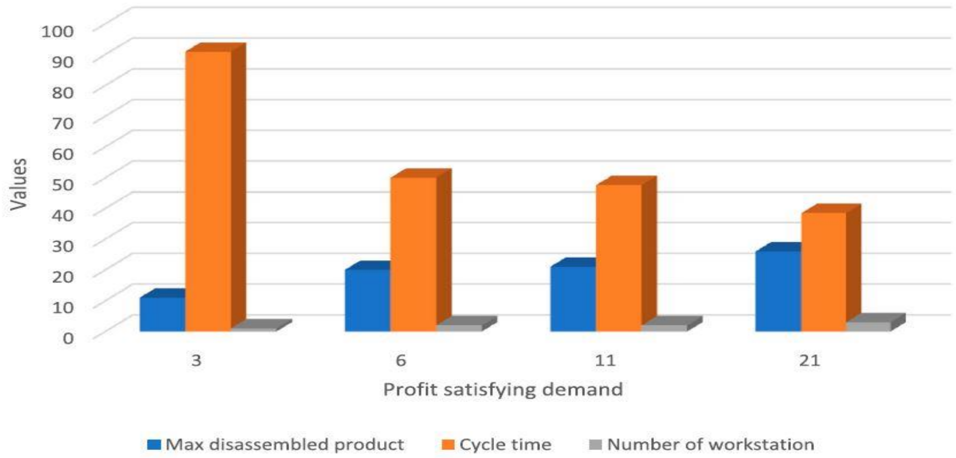

Figure 4.10 Relationship between max disassembled product, cycle time, and number of workstations for model #4.4.

4.3.3.2. The Effect of Changing Demand Quantity of Remanufacturing Centres

The second scenario aims to analyse the effects of changing demand of RC quantity on line balance and the number of satisfied RC. We doubled the demand of RC quantity. For example, only the first demand of RC is doubled for the first trial, and others remained constant. The demand of second RC is then doubled, and the others remained steady. In this way, the line balances that may occur in the case of a changing the demands of eight RC are examined and the results are presented in Table 4.6.

Table 4.6 Results of model #4.4 on changing demand quantity of remanufacturing centres.

	RC2	RC3	RC4	RC5	RC6	RC7	RC8	RC9
Obj	148.5	206	155	No solution	142.7	No solution	146.2	188.7
NS	2	2	2	No solution	2	No solution	1	2
S_RC	5	7	7	No solution	7	No solution	4	6
CT	58.8	43.4	50	No solution	47.6	No solution	99.9	52.6
P	17	23	20	No solution	21	No solution	11	19

According to solution results, a slight change in the demand of RC can stimulate the change in DL balance and the number of satisfied RC. Change in each demand of RC lead to different line balance and profit amount (Obj). In the case of demand of RC 5 and 7 are doubled, there is no solution due to vehicle capacity is exceeded.

4.3.3.3. Effects of Changes in Complexity of The Product

In this section, the effects of changes in product complexity are investigated and a realistic product is considered to measure the performance of model #4.4. A radio sample with 30 disassembly tasks and 10 parts is considered from Altekin and Akkan, (2012). The VRP data is the same with numerical examples. Figure 4.11 shows the TAOG of the radio which contains 30 normal nodes and 19 artificial nodes, with all disassembly task times. The optimal solution value is $328.04 with two opened workstations. Figure 4.12 illustrates the balanced disassembly workstations for radio example with opened workstations and their tasks. Figure 4.13 illustrates the optimal distribution of model #4.4 for radio example.

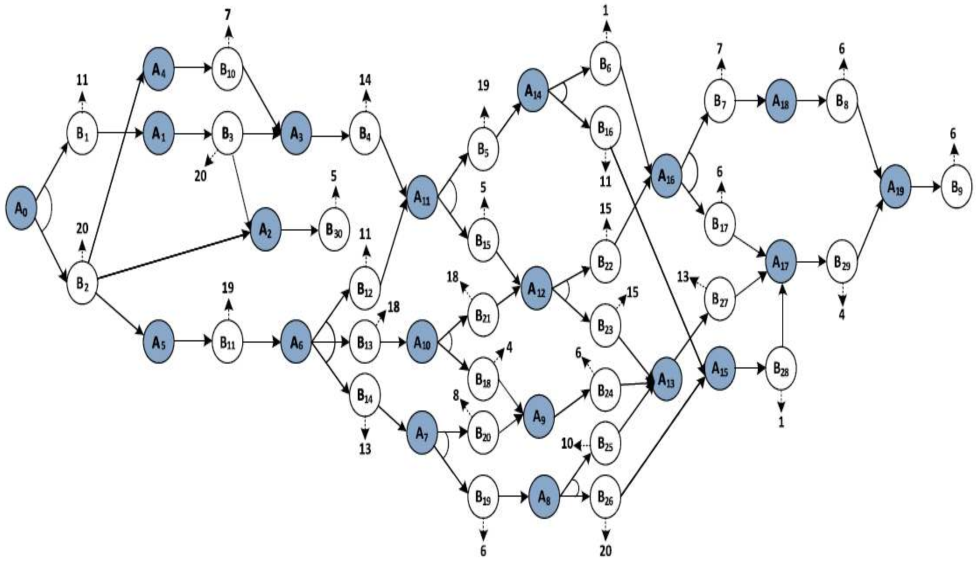

Figure 4.11 The transferred AND/OR graph of the radio example (Altekin and Akkan, 2012).

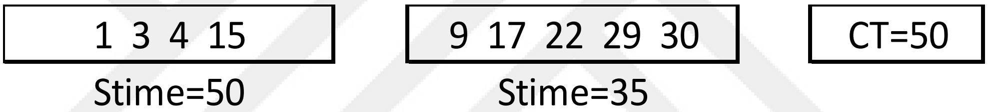

Figure 4.12 Balanced disassembly workstations for radio example.

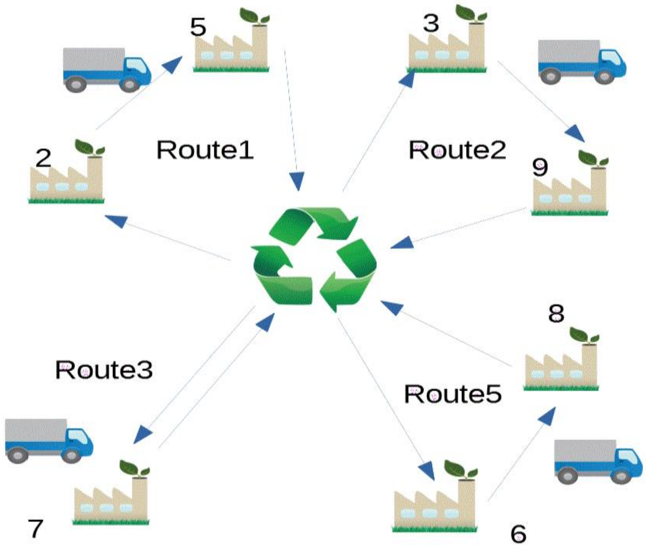

Figure 4.13 Optimal distribution of model #4.4 for radio example.

4.3.3.4. Limit Analysis for Computational Model

We now investigate the limit of I-DLB-RP. To do so, we consider model #4.4 for analysis since it is the most comprehensive one for the single period in all models. For the VRP part, we modify the instances of Augerat et al., (1995) by considering the data set (P_n16_k8) of Set P and nodes are adjusted to 13, 14, 15 and 16 nodes. For the DLB part, we use a part of the test instances ((3,2,6); (3,2,7); (3,2,8); (3,2,9)) of Hezer and Kara, (2015). The demands of RC are generated using discrete uniform distributions within the range of [1,6]. The solver time is limited to 7200 s. Table 4.7 presents the experimental results. In the table, TL and NN denote the exceeding of the time limit and the number of nodes, respectively.

Table 4.7 Experimental results of model #4.4 for the integrated problem.

DLB	VRP	NN	NS	CT	P	CPU	TN
3-2-6	P-n16	13	1	37	27	109	2
	P-n16	14	1	33.3	30	1455	3
	P-n16	15	1	33.3	30	5848	3
	P-n16	16	TL				
3-2-7	P-n16	13	1	43.47	23	21	2
	P-n16	14	1	31.25	32	3844	3
	P-n16	15	1	38.4	26	2568	3
	P-n16	16	TL				
3-2-8	P-n16	13	1	47.6	21	62	3
	P-n16	14	1	45.45	22	1943	3
	P-n16	15	1	38.4	26	977	3
	P-n16	16	TL				
3-2-9	P-n16	13	1	43.47	23	225	3
	P-n16	14	TL				
	P-n16	15	1	38.4	26	2080	3
	P-n16	16	TL				

MINLP problems are very difficult to solve, due to combining all the difficulties of both of their subclasses: the mixed integer programs (MIP) and non-linear programs (NLP). Since both the DLB and VRP are in the NP-hard class, the I-DLB-RP is also NP-hard. Therefore, it is not surprising that small-size instances reach to optimal solution while large-size instances do not reach to optimal solution within the time limit.

4.3.3.5. The Effect of Penalty Cost

In this section, the effect of the penalty cost on the number of disassembled products, cycle time and the number of satisfied RC is analysed. The unsatisfied demand may cause problems in certain conditions. Therefore, penalty cost is considered for unsatisfied demand and an analysis is conducted on model #4.4. The equation (4.45) is added to the objective function of model #4.4 and the results are shown in Table 4.8. *Pc* denotes the penalty cost.

$$Pc * \sum_{c}^{N} \sum_{g,g\neq c}^{N} \sum_{k}^{K} De_{ck} * (1 - y_{cg}) \quad (4.45)$$

Table 4.8 Results of model #4.4 on changing penalty cost

Penalty cost ($)	Disassembled product (unit)	CT	NS	Remanufacturing centres
3	20	50	2	2, 3, 5, 6, 7, 8, 9
6	21	47.6	2	2, 3, 4, 5, 7, 8, 9
9	21	47.6	2	2, 3, 4, 5, 7, 8, 9
12	21	47.6	2	2, 3, 4, 5, 7, 8, 9
15	26	38.4	3	All nodes

According to solution results, changing penalty cost causes the change in line balance and the number of satisfied RC. While penalty cost increases, the number of disassembled products and satisfied RC also tend to increase.

4.3.3.6. Summary of Applied Scenario Analysis

This section presents a summary of the scenario analyses. The effects of each scenario analysis are briefly given and precautions are presented for existing effects. The summary of all scenario analyses, effects of them and countermeasures/suggestions to them are given in Table 4.9.

Table 4.9 The summary of scenario analyses

Scenario	Effects	Countermeasures/Suggestions
The effect of changing profit	The change in line balance and the number of satisfied remanufacturing centres	Rebalancing (Altekin and Akkan, 2012; Mete et al. 2019)
The effect of changing demand quantity	The change in line balance and the number of satisfied remanufacturing centres	Rebalancing (Altekin and Akkan, 2012; Mete et al. 2019)
The effect of changing complexity of the product	The model also achieved an optimal result for a different product	The proposed model can be applied to different sized products.
Computational analysis of the model	Large-size instances cannot be reach to optimal solution	Heuristic/Metaheuristic algorithms such as beam search, genetic algorithm, ant colony optimization, artifical bee colony algorithm etc. (Kalaycı and Gupta, 2013a; Kalaycı and Gupta, 2013b; Kalaycı, Polat and Gupta, 2016; Mete et al. 2016b) can be applied.
The effect of adding penalty cost	The change in line balance and the number of satisfied remanufacturing centres	As the penalty cost creates an extra cost, the model without the penalty cost can be preferred.

4.4. Chapter Results and Findings

The rapid global increase in consumption of all products and unconscious exploitation of natural resources makes recycling process necessary. Designing and balancing the DL is crucial in terms of productivity and environmental awareness. Furthermore, effective and optimized distribution and transportation plans provide companies with a significant cost advantage.

We have introduced the integrated DLB and VRP (I-DLB-RP) as a new practical optimization problem. We have proposed five mathematical formulations. We have considered several scenarios; single-component distribution, multi-component distribution, inventory cost, and multi-period conditions. We presented these mathematical models from the most basic and simple form to the most comprehensive one. We have generated a new set of benchmark instances ranges from small-size to large-size. We have conducted extensive computational experiments on these instances. We have provided several managerial and policy insights. The effect of demand satisfying profit is investigated by changing corresponding values and results are discussed. The effect of changing demand quantity of RC is also investigated and a realistic product is considered to measure the performance of model #4.4. The effects of changes in product complexity are investigated on a realistic product and limit analysis is conducted on model #4.4. Also, we investigate the effects of penalty cost on model #4.4. We summarize our main findings as follows:

- The proposed mathematical models for the I-DLB-RP obtained robust solutions on benchmark instances.
- Scenario analyses have shown that costs directly affect the results. When the profit of satisfying demand is 12, demand of all RC are fully satisfied for the model #4.3. However, demand of all RC fully satisfied for model #4.4, when the profit of satisfying demand is 21.
- For model #4.4, higher demand satisfying profit is required to meet the demands of all RC since keeping inventory is more profitable than satisfying the demands.
- A slight change in the demand of RC can stimulate the DL balance and the number of satisfied RC.
- Limit analysis has clearly indicated the difficulties of solving MINLP models for the I-DLB-RP.
- For model #4.4, increasing penalty cost causes the change in line balances and the number of satisfied RC.

CHAPTER V

INTEGRATED DISASSEMBLY LINE BALANCING AND ROUTING PROBLEM WITH 3D PRINTERS[2]

3DP is one of the most influential technological developments in the last decades, and the usage of this technology in SCM has become an area of ever-increasing interest. This chapter investigates the effect of 3D printers in a single-echelon SC network. A single DC first disassembles EOL products and produces new components by using 3D printers. A fleet of vehicles with fixed capacities then transport components to (re)manufacturers. 3D printers in DC provide the opportunity to increase productivity and decrease costs by disassembling fewer products. This chapter introduces the I-DLB-RP with 3D printers (I-DLB-RP-3DP), and proposes a mixed integer non-linear mathematical formulation. Extensive computational experiments conducted to analyse the transformation of disassembly operations in smart factories.

5.1. Introduction

As consumption is rapidly increasing in the world, discarded devices produce a huge amount of electronic waste. Disassembly of EOL products helps to reduce this waste which promotes recycling. Disassembly phase generates the desired components via separation of EOL products into its units. The DLB is a crucial member of RSC and highly effective to successfully deal with EOL products to a great extent (Deniz and Ozcelik, 2019). Balancing the DL is critical in terms of recycling and remanufacturing.

The 3DP technology is one of the current SC trends which is also considered as AM (Khajavi et al. 2014). This technology provides new opportunities in SC operations. In recent years, many manufacturers heavily invested in 3D printers. For example, General Electric manufactures nozzles obtained by assembling 20 different parts in

[2] This chapter is based on a paper titled "*Integrated Disassembly Line Balancing and Routing Problem with 3D Printers*" that is in press in the CRC Book: Logistics 4.0: Digital Transformation of Supply Chain Management, by Diri Kenger, Z., Koç, Ç., Özceylan, E.

one step using 3DP technology (Catts, 2013). This helps General Electric to take the advantage of creating prototype part designs in a faster and more efficient way than before. Airbus produces aircraft components for its jetliners. They are working on spare parts production on demand with 3D printers (Airbus, 2014). In 2017, Siemens achieved to produce gas turbine wings using completely AM (Siemens, 2017). The common reasons why all these companies use 3DP technology are that less material and more economical parts will be produced in a shorter time. NASA has announced that 70 parts produced by AM are used on Mars Rover test vehicles (Kucukkoc, 2019). In addition, it is possible for the manufacturing system to be functional during the transportation, allowing the products to be produced en-route. Although this form of production is rare in traditional manufacturing, Amazon has received a patent for a system that performs 3DP during en-route (Ryan et al., 2017).

In logistics and SCM, determining the position of the delivery points and constructing routes is crucial. Optimization of distribution operations saves large amounts of cost and time. The VRP, one of the most well-known and studied optimization problems, aims to distribute goods between depots and customers (Toth and Vigo, 2014). Integration of disassembly and distribution planning problems gains interest by researchers because of the significant importance in practice (see Özceylan and Paksoy 2013; Özceylan and Paksoy 2014; Özceylan et al. 2014; Koç 2017; Habibi et al. 2017a; Habibi et al. 2017b; Kannan et al. 2017; Habibi et al. 2018).

Both the DLB and 3DP technology are current subject areas and have many significant implications on SC. However, while the DLB is generally effective on the RSC, 3DP technology is commonly effective on the forward SC. The DLB and 3DP technology have common advantages such as sustainable clean environment, cost and time savings, and raw material saving. Furthermore, less labor and inventory cost, process simplifications, high efficiency and flexibility are among potential advantages of 3DP technology (Li et al. 2016; Chan et al. 2018). For example, instead of assembling several components, using 3DP technology simplifies the process by producing required part in one level. Integration of SC and DLB is also popular and among current study fields. The biggest challenge in SCM is the delivery of more precious products and services to customers efficiently and effectively (Holmström et al. 2010).

The VRP is a very critical issue for the delivery of components formed after disassembly process. In addition, AM technology has a significant effect on producing more precious and solid products. Hence, co-operation of the VRP and AM technology gains importance in this manner. 3DP technology is now more accessible since the cost of processing has reached the level everyone can afford (Chan et al., 2018a). The 3DP technology saves time up to 75% of the old development time in component production time and consumes up to 65% fever resources, reducing gas emissions by up to 30%, resulting in longer-life components (Siemens, 2017). The presence of 3DP technology speeds up the progress of industries such as spare parts manufacturing (Khajavi et al. 2014). Although 3DP is a popular study field and an affordable technology, utilization in the literature and industry is still very limited. In the VRP integrated problems, vehicles are used to collect EOL products. However, we use vehicles for the distribution of the components formed after disassembly process. To our knowledge, the current literature has not been investigated the 3D printers within the studied integrated problems.

This chapter makes three main scientific contributions. The first contribution is to introduction of the I-DLB-RP with 3DP printers (I-DLB-RP-3DP) within the context of smart factories. The second contribution is to propose a MINLP formulation for the I-DLB-RP-3DP. The third contribution is to conduct extensive computational experiments to investigate the I-DLB-RP-3DP, and to provide several policy and managerial implications.

The rest of the chapter is structured as follows. Section 5.2 reviews the related literature. Section 5.3 formally defines the I-DLB-RP-3DP and presents the mathematical formulation. Computational experiments are presented in Section 5.4. Conclusions are presented in Section 5.5.

5.2. Literature Review

In this section, we first review the DLB and the VRP in Section 5.2.1, we then review the 3D printers in SCM in Section 5.2.2, we finally review the integrated disassembly and distribution planning problem in Section 5.2.3.

5.2.1. A Brief Review on the DLB and the VRP

The DLB problem introduced by Gungor and Gupta (2001). Özceylan et al. (2019) and Deniz and Ozcelik (2019) reviewed the related literature on the DLB in detail. Özceylan et al. (2019) classified the literature in nine main aspects: Models and solution approaches, objectives, product types, the parameter structure, disassembly levels, complications in DLs, line types, disassembly process, and disassembled product. Deniz and Ozcelik (2019) applied bibliometric and social network analysis to systematically define the trend and key direction. The authors also implemented future study realization analysis to observe if the future work promises of published studies are accomplished or not.

For about sixty years, the VRP and its rich variations have been intensively studied in the literature by researchers. For more details, we refer the readers to the following survey papers of Braekers et al., (2016); Koç et al., (2016); Koç and Laporte, (2018), and to the book of Toth and Vigo, (2014).

5.2.2. A Brief Review on the 3D Printers in Supply Chain Management

The history of AM technology dates back to 1980s (Khajavi et al. 2014). Huang et al. (2013) surveyed the AM literature and analysed the impact on population health and wellbeing, energy consumption and environmental impact, impact on manufacturing SC, and potential health and occupational hazards. Rogers et al. (2016) reviewed the studies related with implications of 3DP technology on SC, and assessed the firms provide 3DP services in selected European markets. They emphasize that the market can change as 3DP technology matures. Sasson and Johnson (2016) presented an alternative that combines 3DP technology with and completes traditional serial production. The authors discuss the economic reasons for modern manufacturing and for 3DP. A process for 3DP supercentres that focus on low volume, customized, and high emergency production is proposed, and implications of 3DP technology on SC are examined. Jia et al., (2016) suggested two business models for the 3D printed chocolate SC and evaluate the financial viability of these models by using modeling and simulation. Ford and Despeisse (2016) focused on advantages and challenges of AM and their implications on sustainability. Li et al. (2016) considered impact of AM technology on spare parts SC. Conventional, distributed AM-based and centralized AM-based SCs are compared and superiority of AM technology is detected for spare parts SC. Chan et al. (2018) discussed the impacts of 3DP technology on SC and evaluate in terms of manufacturing and legal perspective. The authors focused on challenges that resist mass-scale applications of 3DP.

5.2.3. A Brief Review on The Integrated Disassembly and Distribution Planning Problem

This section presents the literature on the integrated disassembly problem and distribution planning. These studies and solution methods are summarized in Table 5.1.

Table 5.1 The literature on the integrated disassembly problem and distribution planning.

Study	Disassembly	DLB	VRP	CLSC	RSC	Solution Method
Özceylan and Paksoy (2013)		✔			✔	NLP
Özceylan et al. (2014)		✔		✔		NLP
Özceylan and Paksoy (2014)		✔			✔	Fuzzy mathematical programming
Habibi et al. (2014)		✔	✔		✔	LP
Habibi et al. (2017a)	✔		✔		✔	LP
Habibi et al. (2017b)	✔		✔		✔	Two-phase iterative heuristic
Kannan et al. (2017)		✔			✔	NLP
Habibi et al. (2018)	✔		✔		✔	Stochastic mathematical programming, Two-phase iterative heuristic
I-DLB-RP-3DP		✔	✔			NLP

CLSC: Closed loop supply chain, RSC: Reverse supply chain, LP: Linear programming; NLP: Non-linear programming

5.3. Problem Definition and Modeling

In our problem, a SC network consists of DCs with 3DP machines and RC. In DCs, EOL products are disassembled by balancing DL and missing components are produced by 3DP machines. Then vehicles with fixed capacities deliver components to RC. 3DP machine in DC, working simultaneously with DL, is used in the production of missing components. Since the current problem provides spare parts to RC through disassembly process, the cooperation of 3DP technology and DL gains highly importance. Figure 5.1 illustrates the I-DLB-RP-3DP.

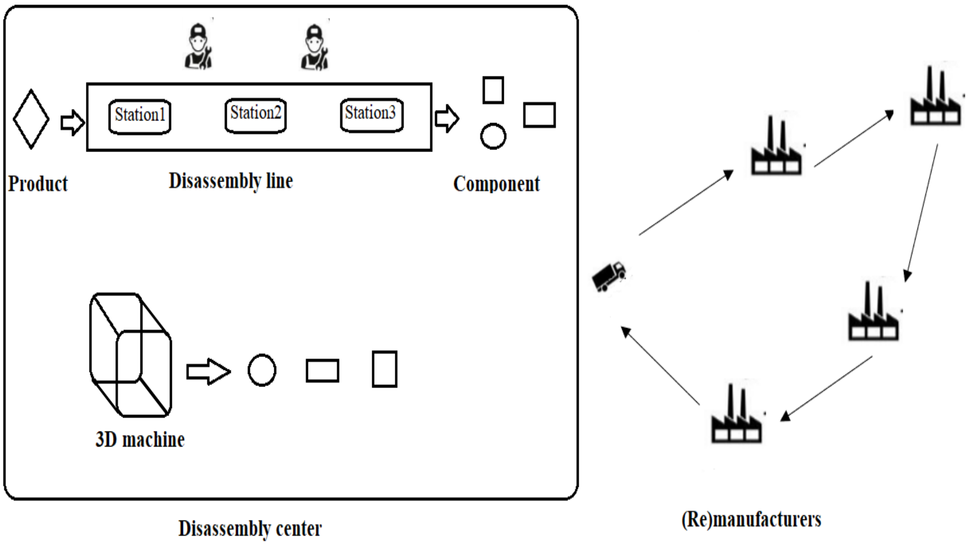

Figure 5.1 Illustration of the I-DLB-RP-3DP.

We now present a non-linear mathematical formulation for the I-DLB-RP-3DP which considers a single DC, a single 3DP machine, single-type of product, and multi-component. Mathematical model is developed by extending the formulation of Koc et al., (2009) and integrated with formulation of the classical capacitated VRP. Our assumptions are as follows:

- The demand of each RC for a component is known and must be fully satisfied.
- Distances between DC and RC and between RC are known.
- A single-type of product are completely disassembled.
- Setup times are ignored.
- No work-in-process inventory is allowed.
- A task cannot be split among two or more workstations.
- The precedence relations of the problem are known.
- All workstations can process any of the tasks and all have the same associated costs.
- The task process times are not sequence dependent.
- One DC responsible for disassembling of EOL products.
- Each disassembly takes apart the product or sub-assembly into exactly two or more new sub-assemblies.
- Any task can be processed at any workstation.
- Waste is ignored.

- All RC demand more than one type of component.
- Capacity of vehicles are known and are ready for service to customers in the RC.
- Inventory is ignored.
- 3DP machine has the ability of producing different components.
- Each component is different from each other.

Notations

Indices

c,g	remanufacturing centre, *c,g={*1,2,…,*N}*
i	task
j,h	workstation
a	artificial task
k	component

Sets and Parameters

A_a	artificial nodes of *a*
B_i	nodes of *i*
$P(A_a), P(B_i)$	immediate predecessor set of A_a and B_i, respectively
$S(A_a), S(B_i)$	immediate successor set of artificial node set of A_a and B_i respectively
d_{B_i}	task time (normal node) of B_i
J	number of workstations (upper bound)
W_{time}	working time
De_{gk}	demand of remanufacturing centre *g*
Ct	fixed cost of shipping from disassembly centre to remanufacturing centre *g*

D_{cg}	distance between disassembly centre and remanufacturing centre or between remanufacturing centres
O	fixed cost to open a workstation in the disassembly line
Cap	vehicle capacity
St	fixed cost to disassembly a product
Tt	fixed cost to operate 3DP machine
t_k	operating time of part *k* on 3DP machine

Variables

CT	cycle time
U_g	load of vehicle just after leaving cluster
Dp	the number of disassembled products on disassembly line
TD_k	the number of component *k* produced by 3DP machine
x_{ij}	1, if task B_i is assigned to workstation *j*; 0 otherwise
y_{cg}	1, if vehicle travels from disassembly centre to remanufacturing centre or between remanufacturing centres; 0 otherwise
z_i	1, if task B_i is performed; 0 otherwise
F_j	1, if workstation *j* is opened; 0 otherwise

The mathematical formulation of the I-DLB-RP-3DP (model #5.1) is then:

$$\text{minZ} = O * \sum_{j}^{J} F_j + Ct * \sum_{c}^{N} \sum_{g}^{N} D_{cg} * y_{cg} + St * Dp + Tt * \sum_{k}^{K} t_k * TD_k \quad (5.1)$$

$$\sum_{i:B_i \in S(A_0)} z_i = 1 \tag{5.2}$$

$$\sum_{i:B_i \in S(A_a)} z_i = \sum_{i:B_i \in P(A_a)} z_i \qquad \forall\, a, a \neq 0 \tag{5.3}$$

$$\sum_{j=1}^{J} x_{ij} = z_i \qquad \forall\, i \tag{5.4}$$

$$\sum_{i:B_i \in S(A_a)} x_{ih} \leq \sum_{i:B_i \in P(A_a)} \sum_{j=1}^{h} x_{ij} \qquad \forall\, a, a \neq 0, h \in J \tag{5.5}$$

$$\sum_{i=1}^{I} x_{ij} * d_{B_i} \leq CT * F_j \qquad \forall j, j = 1, \dots, J \tag{5.6}$$

$$CT * Dp = W_{time} \tag{5.7}$$

$$F_{j+1} \leq F_j \qquad \forall j, j = 1, \dots, J-1 \tag{5.8}$$

$$\sum_{g=1, g \neq c}^{N} y_{cg} = 1 \qquad \forall c, c = 2, \dots, N \tag{5.9}$$

$$\sum_{c=1, c \neq g}^{N} y_{cg} - \sum_{c=1, c \neq g}^{N} y_{gc} = 0 \qquad \forall g, g = 1, \ldots, N \tag{5.10}$$

$$U_c - U_g + Cap * y_{cg} \leq Cap - \sum_{k=1}^{K} De_{gk} \qquad \forall c, g, c, g = 2, \ldots, N, c \neq g \tag{5.11}$$

$$\sum_{k=1}^{K} t_k * TD_k \leq W_{time} \tag{5.12}$$

$$Dp + TD_k \geq \sum_{g=2}^{N} De_{gk} \qquad \forall k \tag{5.13}$$

$$CT, Dp, TD_k \geq 0 \qquad \forall g, k \tag{5.14}$$

$$\sum_{k=1}^{K} De_{gk} \leq U_g \leq Cap \quad \forall g \tag{5.15}$$

$$x_{ij}, z_i, y_{cg}, F_j \in \{0,1\} \qquad \forall i, j, c, g \tag{5.16}$$

The objective function (5.1) minimizes the total traveling cost of vehicles, the total fixed cost of operating disassembly workstations, total disassembly cost of products, and total fixed cost of operating 3DP machine. Constraints (5.2) and (5.3) guarantee that exactly one of the OR successors is selected. Constraints (5.4) ensure that each selected task is assigned to at most one workstation in the DC. Constraints (5.5) tackle with the precedence relations between the nodes. Constraints (5.6) prevent the cycle time being exceeded by a disassembly workstation. Constraints (5.7) show that the cycle time in the DC is equal to the total working time divided by the number of disassembled products. Constraints (5.8) ensures that workstations open sequentially. Constraints (5.9) guarantee that each customer must be visited once. Constraints (5.10) define the flow. Constraints (5.11) are the capacity constraints. Constraints (5.12) ensure that the time required for components produced by the 3DP machine does not exceed the total working time. Constraints (5.13) ensure that sum of the number of disassembled products and the component *k* produced by the 3DP machine cannot be less than the total demand of the component *k*. Constraints (5.14)-(5.16) define the domain of the decision variables.

5.4. Computational Experiments

This section presents the results of our computational experiments. We first present the details of the benchmark instance, and we then present the results obtained on a numerical example by applying the proposed mathematical model. We finally present the detailed results of the analyses of the effect of changing working time and fixed cost for 3DP machine.

5.4.1. Benchmark Instance

We generated the benchmark instance for the I-DLB-RP-3DP by considering the well-known test problems from literature. For the DLB part, we used a set of a sample product from the study of Koc et al., (2009). For the VRP part, we modify the classical VRP instances of Augerat et al., (1995). In particular, we selected the smallest data set (P_n16_k8) of Set P, and for simplicity we selected 9 nodes (1 DC and 8 RC) without changing the coordinate of nodes and vehicle capacity. All demand characteristics were generated by using the discrete uniform distributions. Demands of RC are in the range [1, 6]. Operating time of component *k* on 3DP machine is in the range [5-20]. The details about the benchmark instance are presented in Appendix.

Unit shipping cost (*Ct*) and cost of opening a workstation (*O*) were set as in Özceylan and Paksoy, (2013). *Ct* is fixed to 5.23 cents per tonne-km for a general freight truck, and *O* is fixed to 100 USD per each workstation in the DL. W_{time} is set to 1000min. Number of maximum workstations (*J*) is set to 5. Disassembling cost of a product (*St*) is fixed to 50USD per product, and fixed cost of operating 3DP machine (Tt) is fixed to 2USD per component.

5.4.2. Results Obtained on a Numerical Example

Since presented model is non-linear, GAMS/SCIP with its default settings as the optimizer is used to solve the model and experiments are conducted on a computer Intel Corei5 1.60 GHz processor with 8 GB RAM.

Table 5.2 and Figure 5.2 present the obtained results. In Table 5.2, C1, C2, C3, C4, C5, C6, and C7 denote component 1, 2, 3, 4, 5, 6, and 7, respectively. 3D-NC denotes the number of components produced by 3DP machine and DL-NC denotes the number of components obtained via the DL. The optimal objective function value is obtained as 1327.5 USD for the numerical example. According to the optimal result, the number of disassembled products is 17, the number of opened workstations is 2, and the cycle time is determined as follows:

$$CT = W_{time}/Dp = 1000/17 = 58.82 \text{ min}$$

Table 5.2 The number of components obtained from 3DP machine and disassembly line.

	3D-NC	DL-NC
C1	-	17
C2	-	17
C3	9	17
C4	-	17
C5	5	17
C6	-	17
C7	2	17

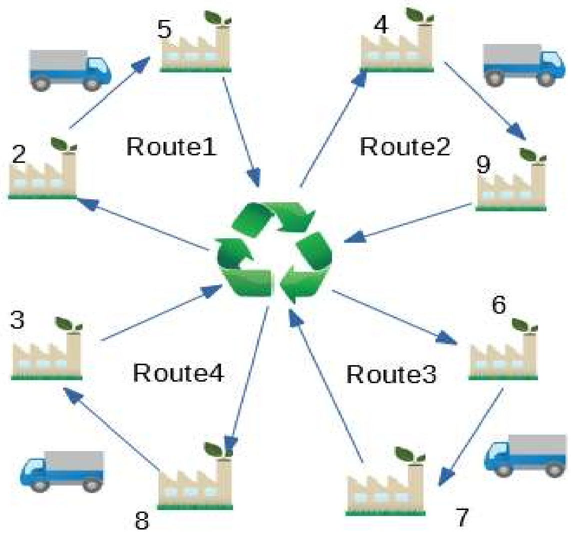

Figure 5.2 Optimal distribution for the numerical example.

5.4.3. Scenario Analysis

In order to investigate the impact of several parameters on the solution, we now analyse two different scenarios: (i) the effect of changing working time on the performance measures (total cost, number of workstations, cycle time, the number of disassembled products and the number of components produced by 3DP machine), (ii) the effect of changing fixed cost of operating 3DP machine without changing the disassembling cost of a product on performance measures (total cost, number of workstations, cycle time, the number of disassembled products and the number of components produced by 3DP machine).

We first analysed the effect of changing working time. Working time of initial problem increased by +%25 and +%50, and decreased by -%25 and -%50. Table 5.2 presents the details of all solutions. WT, FC-3D, NS, TN denote the working time, fixed cost to operate 3DP machine, the number of workstations and the number of vehicle tours, respectively. Results show that increasing working time increases the number of components produced by 3DP machine (3DP in Table 5.2), and decreases the number of disassembled products (DP in Table 5.2). Furthermore, as working time is decreased objective function value is increased, and the number of workstations is tented to increase.

Table 5.3 Results of the effect of changing working time.

WT	FC-3D	*Obj*	NS	*CT*	TN	CPU	DP	3DP
500	0.5	1140	3	83.3	4	2.160	12	47
750	0.5	882.02	1	125	4	0.920	8	75
1000	0.5	838.5	1	200	4	1.540	5	96
1250	0.5	780.5	1	1000	4	0.870	1	124
1500	0.5	666	-	-	4	0.560	-	131

Figure 5.3 presents the changing objective function value and cycle time according to variation of working time. When the working time is increased, objective function value decreases and cycle time increases. The reason behind decreasing of the objective function value as the working time increases probably depends on the assumed costs. This is because, fixed disassembling cost of a product may be much more than fixed cost of operating 3DP machine due to several costs such as labor and opening workstations in DL.

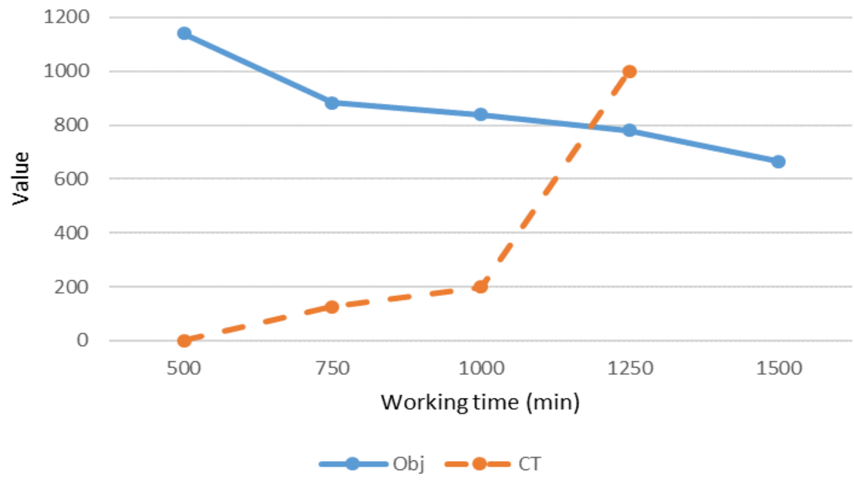

Figure 5.3 Relationship between objective function value and the cycle time.

Figure 5.4 presents the relationship between the number of disassembled products and components produced by 3DP machine. In this case, as working time is increased, the number of disassembled products decreases and the number of components produced by 3DP machine increases. Since the fixed cost of operating 3DP machine is much lower, the model tends to increase the number of components produced through the

3DP machine to minimize the value of the objective function. Most of the demanded components cannot be produced with the 3DP machine due to the limited working time for the numerical example, although the fixed cost of operating 3DP machine is lower. Increasing the working time makes it possible to produce components in 3DP machine and decreases the value of the objective function.

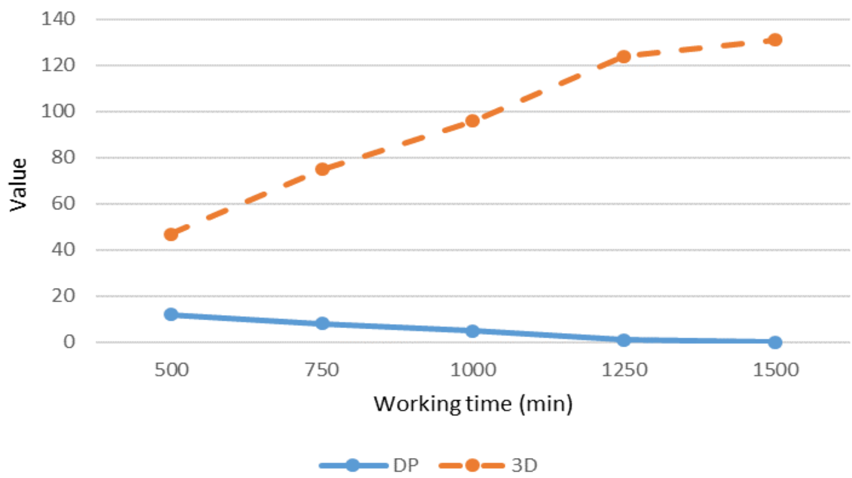

Figure 5.4 Relationship between the number of disassembled products and components produced by 3DP machine.

In the second scenario, we investigate the effect of changing fixed cost of operating 3DP machine without changing the disassembling cost of a product. Fixed cost of operating 3DP machine of initial problem is increased up to 16USD/component and decreased down to 0.5USD/component for scenario analysis. Table 5.4 presents the obtained results. In the frame of this scenario, as fixed cost of operating 3DP machine increases, objective function value, the number of workstations and the number of disassembled products also increases. However, cycle time and the number of components produced by 3DP machine decrease.

Table 5.4 shows that as the fixed cost of the 3DP machine increases, the model tends to increase the number of disassembled products in the DL. This also causes an increase in the value of the objective function. In these conditions, the total cost is higher due to obtaining components via the DL.

Table 5.4 Results of fixed cost change for 3DP machine.

FC-3D	*Obj*	NS	*CT*	CPU	DP	3DP
0.5	838.5	1	200	1.540	5	96
1	1168.5	1	83.3	1.530	12	47
2	1327.5	2	58.82	0.840	17	16
4	1471.5	2	45.45	1.140	22	4
8	1601.5	2	43.47	1.240	23	3
16	1611.5	3	38.46	1.060	26	-

Figure 5.5 shows the variation of the number of disassembled products and the number of components produced by 3DP machine according to changing fixed cost of 3DP machine. The scenario analysis results show that when we increase the fixed cost of operating 3DP machine, the number of disassembled products through the DL increases and the number of components produced by 3DP machine decreases. This is because the DL and the 3DP machine run in parallel at the same working time, and affect each other in opposite directions.

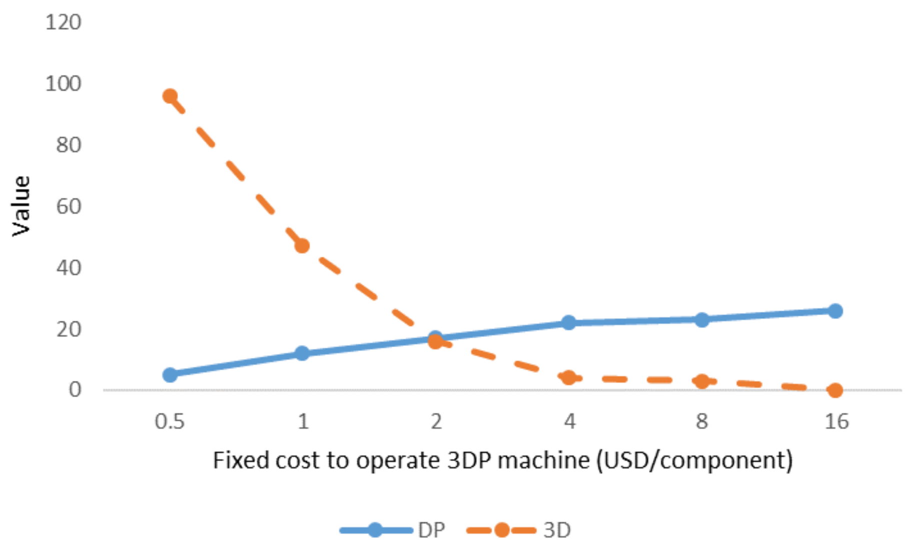

Figure 5.5 Relationship between the number of disassembled products and components produced by 3DP machine according to fixed cost of operating 3DP machine.

5.5. Chapter Results and Findings

This chapter focused on the integration of 3DP technology with the DLB and VRP within the context of smart factories. Disassembly process sustains a clean environment, time and cost saving as it promotes the recycling process. The effective distribution of components formed after disassembly process is a challenging operation. The 3DP technology is an essential part of smart factories since it reduces the cost of inventory, saves time and provides quicker response to demands. It is also highly effective process for creating new designs and producing better quality products when compared with the traditional production techniques.

We have proposed a mixed integer non-linear mathematical formulation for the I-DLB-RP-3DP. We have conducted extensive computational experiments to investigate the I-DLB-RP-3DP, and we have provided several policy and managerial insights. Scenario analyses show that costs and working time are an important factor on the results. When the fixed cost of the 3DP machine increases, the number of disassembled products and the value of the objective function also increase for the current test problem and vice versa. In addition, increasing the working time causes to increase the number of components produced by 3DP machine and cycle time; decrease the number of disassembled products and objective function value.

CHAPTER VI
INTEGRATED COLLECTION-DISASSEMBLY-DISTRIBUTION PROBLEM[3]

Optimized collection of EOL products from collection centres, disassembling of them and then distributing recycled components on demand are crucial for a sustainable RSC. This chapter introduces the I-CDDP which deals with a RSC consists of a DC, collection centres, and RC. In the I-CDDP, EOL products in the collection centres are first transported to the DC. These products are then disassembled in DC and recycled components are delivered to RC on demand. The VRP arises in the collection of EOL products and distribution of recycled parts. The I-CDDP is the optimization of RSC network cooperating with DLB and VRP. We propose two mixed-integer mathematical formulations for several problem cases. The first model deals with the case in which one type component is demanded, and the second model deals with the multi-component case. The chapter conducts extensive scenario analyses on formulations to provide managerial and policy insights.

6.1. Introduction

Increased consumption and depletion of natural resources are becoming a rapidly growing danger affecting the environment. Enterprises are aware of the dangers around them and adopt recycling and remanufacturing as an important business strategy. Along with this sense, recycling and remanufacturing provide both economic advantages and environmentally conscious manufacturing. Therefore, successful reverse logistics (RL) management is crucial in the sense of a sustainable clean environment, lower cost, and shorter response time. RSC network optimization is a

[3] This chapter is based on a paper titled "*Integrated Collection-Disassembly-Distribution Problem*" that is in press in the Sustainable Production and Logistics: Modeling and Analysis, by Diri Kenger, Z., Koç, Ç., Özceylan, E.

subgroup of RL management where all used and discarded products, components and materials are efficiently managed (Özceylan and Paksoy, 2013). One of the crucial steps of RSC processes is disassembly. The DL is the best option for automated systems. It is also a part of a disassembly system in which the EOL products are taken apart for the purpose of recycling and remanufacturing (Güngör and Gupta, 2001).

The disassembly process has become an active study field in the last two decades due to the role in product recovery (Mete et al., 2016). The returned products save cost and energy as a result of providing cheaper components. From the environmental point of view, it decreases the need for new resources and prevents waste burial (Habibi et al., 2017b). The DLB problem can be defined as assigning of the disassembly tasks of a product to sequential workstations to provide certain conditions (Altekin and Akkan, 2012; Güngör and Gupta, 2001). Collecting EOL products is considered as a compulsory operation coming before the disassembly process (Habibi et al., 2017a). The DLB problem has been considered for several factors such as line types (straight, U-type, two-sided, etc.), performance measures (removing hazardous parts early, maximization profit, minimization workstations etc.), and product types (single, mixed, multi) (Özceylan et al., 2019). However, a few studies consider integration of the DLB with other problems (Habibi et al., 2018, 2017a, 2017d; Kannan et al., 2017; Özceylan et al., 2014; Özceylan and Paksoy, 2014, 2013). To the best of our knowledge, the VRP has not been considered for both collections of EOL products and distribution of recycled components.

Diri Kenger et al., (2020) introduce an optimization problem called the I-DLB-RP. The I-DLB-RP simultaneously optimizes two well-known problems. The former one balances the DL in the DCs, whereas the latter one constructs a routing plan to distribute the usable components, generated by the disassembly process, from DC to the RC. While I-DLB-RP does not consider the collection of EOL products from collection centres, I-CDDP consider this issue. In this chapter, we make three main scientific contributions to the literature. (*i*) We introduce the I-CDDP. (*ii*) We develop two mixed integer mathematical formulations for a RSC network cooperating with DLB and VRP. The first model is presented for the case in which one type component is demanded, and the second model is for multi-component case. (*iii*) We conduct computational experiments on a realistic case study including several scenario analyses on models.

The rest of the chapter is structured as follows. In Section 6.2, we provide a brief literature review on the DLB and the VRP. In Section 6.3, the current problem is defined, and our assumptions and the mixed-integer mathematical formulations are provided. Section 6.4 presents the experimental results and scenario analyses. Finally, the conclusions are summarized in Section 6.5.

6.2. Literature Review

The VRP was introduced about sixty years ago and it has been intensively studied in the literature. For further details on the VRP and its rich variants, we refer the reader to the book of Toth and Vigo, (2014), and the surveys of Koç et al., (2016); Koç and Laporte, (2018); Vidal et al., (2020).

In the last two decades, classical DLB problem and its many variations have been studied due to the importance of recycling. Güngör and Gupta, (2001) introduced the DLB, analysed task failures, and described a formulation to decrease their effects on the line. Özceylan et al., (2019), and Deniz and Ozcelik, (2019) provide a detailed review on the DLB and its variants.

Due to resource scarcity and pollution, recycling and remanufacturing have great attention in recent years. Although, the DLB is an essential step for RSC, the integration with RSC is rarely studied in the literature. Özceylan and Paksoy, (2013) considered a RSC network consists of collection/DC and plants, and proposed a mathematical formulation to optimize the problem. Özceylan and Paksoy, (2014) studied the integration of RSC and DLB problem, and proposed a fuzzy programming approach. Habibi et al., (2017a) introduced collection-disassembly problem in RSC and proposed several formulations. Habibi et al., (2017b) proposed two-phase iterative heuristic for collection-disassembly problem. Kannan et al., (2017) integrated DLB and RSC in terms of a third party provider for multiple types of products. Habibi et al., (2018) considered collection-disassembly problem under uncertainty and propose sample average approximation for solving the problem. The problem includes the VRP both in collection of EOL products and distribution of components. Diri Kenger et al., (2020) introduce the I-DLB-RP simultaneously optimizes the DLB and VRPs. In the I-DLB-RP, a single DC first disassembles EOL products. A vehicle with fixed capacity then dispatches usable disassembled components to remanufacturers. While I-DLB-

RP does not consider the collection of EOL products from collection centres, I-CDDP consider this issue.

6.3. Problem Definition and Modelling

We developed two mathematical formulations for different cases of the current problem. In model #6.1, all RC demand one type of component. In model #6.2, all RC demand more than one type of component.

We consider a two-phase RSC network. In the first phase, EOL products are transported from collection centres to DC. In the second phase, recycled components via line balancing in the DC are distributed to RC. The current problem is a two-echelon VRP, one is for collection of EOL products and other is for distributing recycled components after disassembly operation. The I-CDDP is illustrated in Figure 6.1.

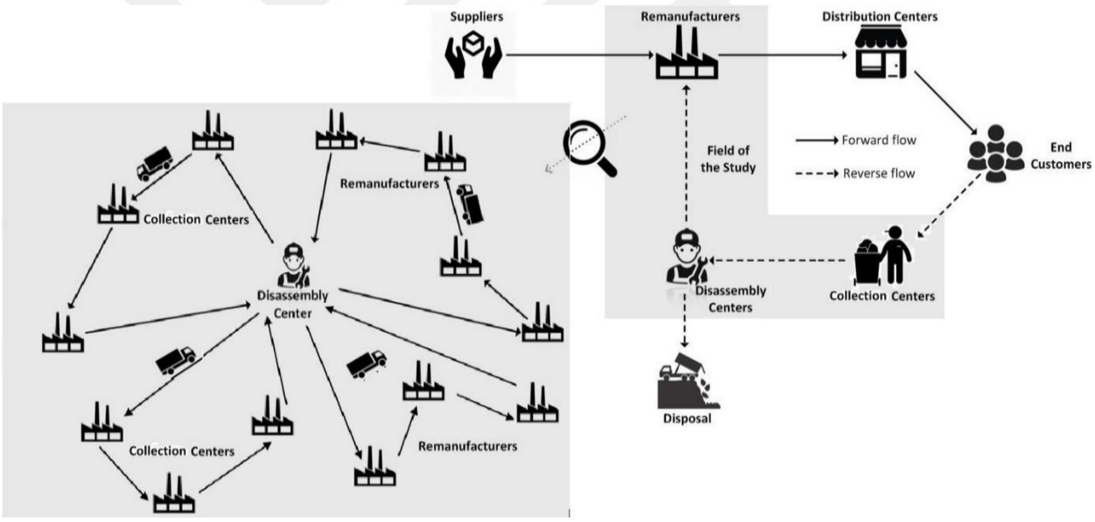

Figure 6.1 The illustration of the I-CDDP.

6.3.1. Mathematical Model #6.1

The first problem considers a single DC, single type of product and multi-component. Mathematical formulation is developed by extending the classical capacitated VRP and integrated with formulation of Koc et al., (2009). The assumptions of model #6.1 are as follows.

- A single type of product is completely disassembled.
- A task cannot be split among two or more workstations.

- All workstations can process any of tasks and all have the same associated costs.
- Each disassembly takes apart the product or sub-assembly into exactly two or more new sub-assemblies.
- Capacities of vehicles are known.
- Vehicles are ready for service to customers in the RC.
- The demand of each RC for a component is known and must be fully satisfied.
- All RCs demand only one type and the same component.
- Total demand of a RC cannot exceed the vehicle capacity.
- Collection centres supply one type of EOL product to the DC.

Notations

Indices

c, g	remanufacturing centre, *c,* $g=\{1,2,\ldots,N\}$
m, t	collection centre, *m,* $t=\{1,2,\ldots,E\}$
I	Task
j, h	workstation
A	artificial task

Sets and parameters

A_a	artificial nodes of *a*
B_i	normal nodes of *i*
$P(A_a)$	immediate predecessor set of A_a
$P(B_i)$	immediate predecessor set of B_i
$S(A_a)$	immediate successor set of artificial node A_a
$S(B_i)$	immediate successor set of artificial node B_i
d_{B_i}	task time (normal node) of B_i (s)

J	number of workstations (upper bound)
W_{time}	working time (s)
De_g	demand of remanufacturing centre *g* (unit)
Ct	fixed cost of shipping from disassembly centre to remanufacturing centre *g* or collection centre *t* (cents)
D_{cg}	distance between disassembly centre and remanufacturing centre or between remanufacturing centres (km)
O	fixed cost to open a workstation in the disassembly line ($/workstation)
Q	vehicle capacity (unit)
Cyc	cycle time (s)
S_t	supply of collection centre *t* (unit)
DC_{mt}	distance between disassembly centre and collection or between collection centres (km)

Variables

U_g	load of vehicle after visiting remanufacturing centre *c*
UU_t	load of vehicle after visiting collection centre *m*
x_{ij}	1, if task B_i is assigned to workstation *j*; 0 otherwise
y_{cg}	1, if vehicle travels from disassembly centre to remanufacturing centre or between remanufacturing centres; 0 otherwise
yy_{mt}	1, if vehicle travels from disassembly centre to collection centre or between collection centres; 0 otherwise
z_i	1, if task B_i is performed; 0 otherwise

F_j 1, if workstation *j* is opened; 0 otherwise

The mathematical model #6.1:

$$Minimize\ O * \sum_{j}^{J} F_j + Ct * \sum_{c}^{N} \sum_{g,g \neq c}^{N} D_{cg} * y_{cg} + Ct * \sum_{m}^{E} \sum_{t,m \neq t}^{E} DC_{mt} * yy_{mt} \quad (6.1)$$

subject to

$$\sum_{i:B_i \in S(A_0)} z_i = 1 \quad (6.2)$$

$$\sum_{i:B_i \in S(A_a)} z_i = \sum_{i:B_i \in P(A_a)} z_i \qquad \forall a, a \neq 0 \quad (6.3)$$

$$\sum_{j=1}^{J} x_{ij} = z_i \qquad \forall\ i \quad (6.4)$$

$$\sum_{i:B_i \in S(A_a)} x_{ih} \leq \sum_{i:B_i \in P(A_a)} \sum_{j=1}^{h} x_{ij} \qquad \forall\ a, a \neq 0, h \in J \quad (6.5)$$

$$\sum_{i=1}^{I} x_{ij} * d_{Bi} \leq Cyc * F_j \qquad \forall j, j = 1, \dots, J \quad (6.6)$$

$$Cyc = (W_{time}/(\sum_{g=2}^{N} De_g)) \tag{6.7}$$

$$F_{j+1} \leq F_j \qquad \forall j, j = 1, \dots, J-1 \tag{6.8}$$

$$\sum_{t=1, t\neq m}^{E} yy_{mt} \leq 1 \qquad \forall m, m = 2, \dots, E \tag{6.9}$$

$$\sum_{m=1, m\neq t}^{E} yy_{mt} - \sum_{m=1, m\neq t}^{E} yy_{tm} = 0 \qquad \forall t, t = 1, \dots, E \tag{6.10}$$

$$UU_m - UU_t + Q * yy_{mt} \leq Q - S_t * yy_{mt} \qquad \forall m, t, m, t = 2, \dots, E, m \neq t \tag{6.11}$$

$$S_m * yy_{1m} \leq UU_m \qquad \forall m, m = 2, \dots, E \tag{6.12}$$

$$S_m * \sum_{t=1}^{E} yy_{mt} \leq UU_m \qquad \forall m, m = 2, \dots, E \tag{6.13}$$

$$\sum_{g=2}^{N} De_g \leq \sum_{m=2}^{E} \sum_{t=1}^{E} S_t * yy_{mt} \tag{6.14}$$

$$\sum_{g=1, g\neq c}^{N} y_{cg} = 1 \qquad \forall c, c = 2, \ldots, N \tag{6.15}$$

$$\sum_{c=1, c\neq g}^{N} y_{cg} - \sum_{c=1, c\neq g}^{N} y_{gc} = 0 \qquad \forall g, g = 1, \ldots, N \tag{6.16}$$

$$U_c - U_g + Q * y_{cg} \leq Q - De_g \qquad \forall c, g, c, g = 2, \ldots, N, c \neq g \tag{6.17}$$

$$De_g \leq U_g \leq Q \qquad \forall g \tag{6.18}$$

$$0 \leq UU_t \leq Q \qquad \forall t \tag{6.19}$$

$$x_{ij}, z_i, y_{cg}, yy_{mt}\ F_j \in \{0,1\} \qquad \forall i, j, c, g. \tag{6.20}$$

The objective function (6.1) minimizes the total traveling cost of vehicles and the total fixed cost of operating disassembly workstations. Constraints (6.2) and (6.3) guarantee that exactly one of the OR-successors is selected in the DC. Constraints (6.4) ensure that each task is assigned to exactly one workstation in the DC. Constraints (6.5) ensure the precedence relationships. Constraints (6.6) prevent the cycle time being exceeded by a disassembly workstation. Constraints (6.7) show the cycle time calculated by dividing the total working time to the total demand of RC. Constraints (6.8) ensure that workstations open sequentially. Constraints (6.9) state that all collection centres do not need to be visited. Constraints (6.10) define the flow for collection centres. Constraints (6.11)-(6.13) are capacity constraints. Constraints (6.14) ensure that the total supply of collection centres must not be less than the demand of RC. Constraints (6.15) guarantee that each RC must be visited once. Constraint (6.16) define the flow for RC. Constraints (6.17) are capacity constraints. Constraints (6.18) and (6.19) enforce the non-negativity restriction on the decision variables. Finally, constraints (6.20) represent the binary variables.

6.3.2. Mathematical Model #6.2

We now present the model #6.2 for the I-CDDP. In this case, the DL is balanced according to maximum demand among RC to satisfy the demand of all RC. Therefore, the demand of all RC can be satisfied. Assumptions and additional notations are as follows.

- All valid assumptions of model #6.1 are valid except “All RC demand only one type and same component”.
- All RC demand more than one type of component.

Notations

Indices

k	component

Parameters

De_{gk}	demand of remanufacturing centre *g* for component *k*

The model #6.2:

$$Max_{Demand} = \max\{\sum_{g=1}^{N} De_{gk} |\ k = 1, \dots, K\} \qquad (6.21)$$

$$Cyc = \frac{W_{time}}{Max_{Demand}} \qquad (6.22)$$

$$U_c - U_g + Q * y_{cg} \leq Q - \sum_{k=1}^{K} De_{gk} \qquad \forall c, g, c, g = 2, \dots, N, c \neq g \qquad (6.23)$$

$$Max_{Demand} \leq \sum_{m=2}^{E} \sum_{t=1}^{E} S_t * yy_{mt} \qquad (6.24)$$

$$\sum_{k=1}^{K} De_{gk} \leq U_g \leq Q \qquad \forall g \qquad (6.25)$$

Objective function (6.1), constraints (6.2)-(6.6), (6.8), (6.9)-(6.13), (6.15), (6.16), (6.19), and (6.20).

Constraints (6.21) and (6.22) calculate the cycle time since demand of all RC will be provided. Constraints (6.23) are capacity constraints. Constraints (6.24) ensure that the total supply of collection centres must not be less than the maximum demand of RC. Constraints (6.25) state the non-negativity restriction.

6.4. Computational Experiments

This section provides the results of computational experiments for models #6.1 and #6.2 on test instances. All experiments were conducted on a server with Intel Core i5-8250U 1.6 GHz dual processor and 8.00 GB memories. We used GAMS/CPLEX to solve the models #6.1 and #6.2.

We consider the realistic product, a toy car sample, of Mete et al. (2018) for the DLB with 97 tasks and 12 components. Figure 6.2 shows the toy car and its components. Figure 6.3 illustrates the TAOG for the toy car.

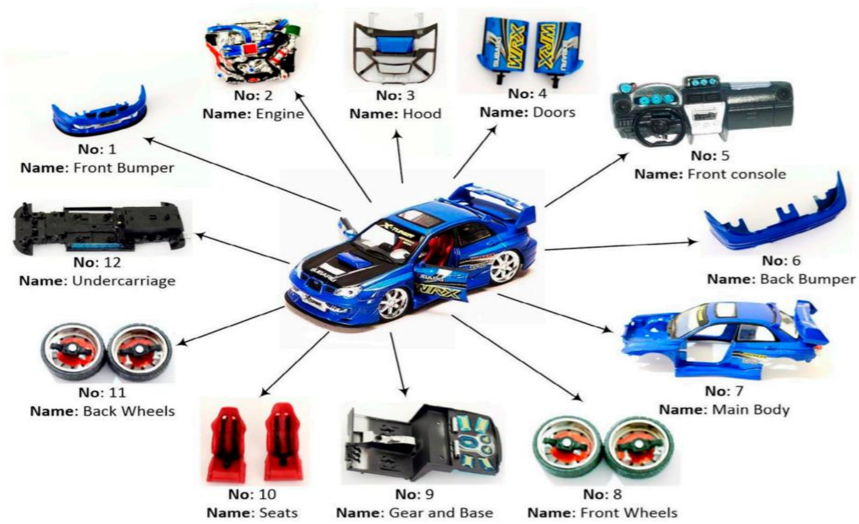

Figure 6.2 Toy car and its components (Mete et al. 2018).

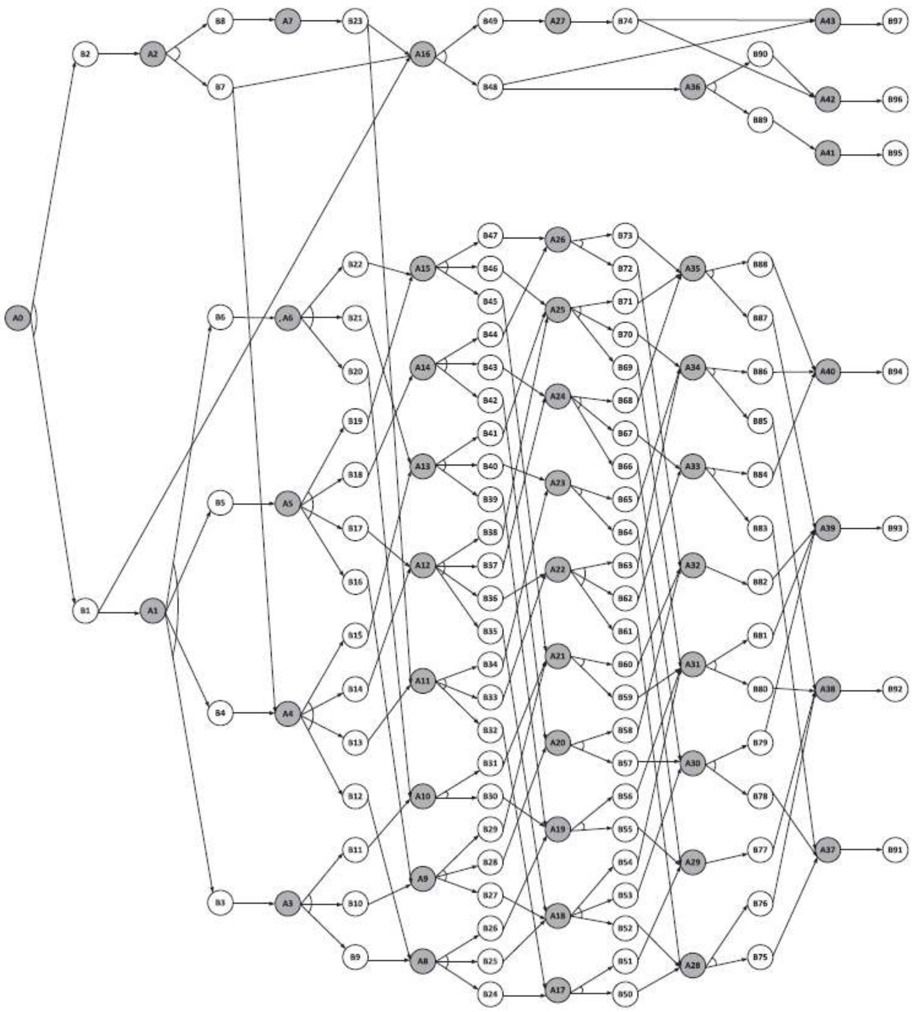

Figure 6.3 The transferred AND/OR graph of the toy car (Mete et al. 2018).

For the VRP phase, we consider the classical VRP instances of Augerat et al., (1995) and modify them to generate our test instances. We arrange the smallest data set (P_n16_k8) from Set P, and divide the nodes as collection centres and RC. The first node is considered as DC and the next eight nodes are considered as RC without changing the coordinate of nodes. Remaining seven nodes are considered as collection centres. Demand and supply characteristics are generated using discrete uniform distribution. Demand for single-component and multi-component cases are generated within the range [1-5] and [1-6], respectively. Table 6.1 presents the demands where C1, C2, C3, C4, C4, C5, C6, C7, C8, C9, C10, C11, and C12 denote component 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12, respectively. RC denotes the RC. Table 6.2 presents the supply for both two cases which are generated in the range [5-10].

Table 6.1 Demands for single component and multi-component cases.

RC	One component case	Multi-component case											
	Demand	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
2	1	3	1	4	3	2	1	2	2	3	5	4	2
3	5	2	4	3	2	3	1	2	1	1	3	2	6
4	4	1	1	6	2	2	1	3	2	2	1	1	4
5	2	2	1	2	3	4	3	4	1	1	2	3	1
6	3	1	1	5	2	1	2	1	3	2	1	2	3
7	5	5	2	1	1	3	3	4	2	1	4	1	2
8	5	2	1	3	3	4	2	1	1	3	2	3	1
9	4	1	3	2	1	3	3	2	4	2	1	1	3

Table 6.2 Supply quantities for single-component and multi-component cases.

Collection Centres	2	3	4	5	6	7	8
Supply	6	8	7	8	10	9	5

Ct is fixed to 5.23 cents per ton-km for a general freight truck. *O* in the DL is fixed to 100 $/workstation. *Wtime* is set to 1250 seconds (s). Number of maximum workstation (*J*) is set to 10. For model #6.1, the vehicle capacity is 35 units for both collection and distribution processes. For model #6.2, the vehicle capacity is 35 units for collection and 70 units for the distribution process.

6.4.1. Results for the Numerical Example

This section presents the results for models #6.1 and #6.2. Table 6.3 presents the details of optimal results. Obj denotes the objective function value. NS denotes the number of workstations. CT denotes the cycle time in seconds. CPU denotes the run time in seconds.

Table 6.3 Optimal results for models #6.1 and #6.2.

	Obj ($)	NS	CT (sec)	CPU (sec)
Model #6.1	410.40	4	43.10	0.312
Model #6.2	415.30	4	48.07	0.297

Figures 6.4 and 6.5 show the optimal distribution plans for models #6.1 and #6.2, respectively. “C” denotes the collection centre, “DC” denotes the disassembly centre and “R” denotes the RC. Since the total products in the collection centres much higher than demand of RC, not all collection centres are visited. Therefore, collection centre 2, 3, 6, and 7 are only visited for single-component case and 3, 4, 5, and 8 are only visited for multi-component case. Since the demand of each RC must be fully satisfied, all RC are visited.

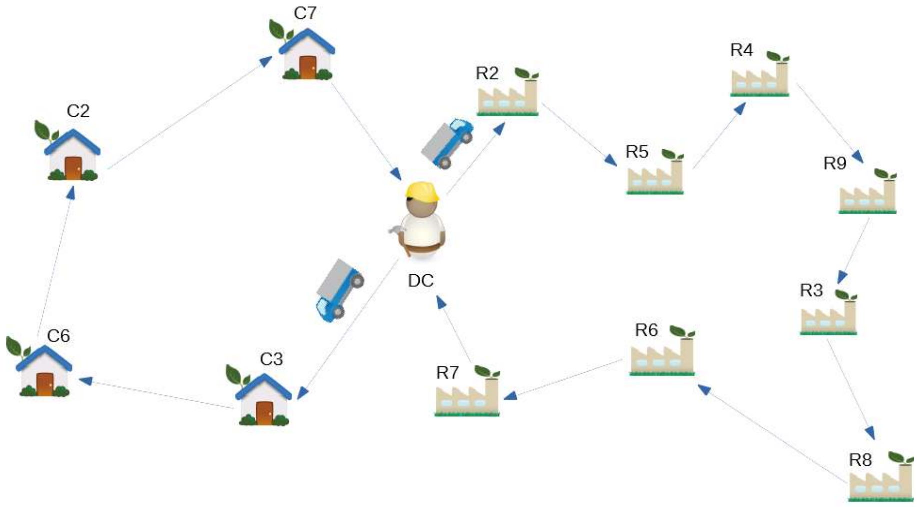

Figure 6.4 Optimal distribution plan for model #6.1.

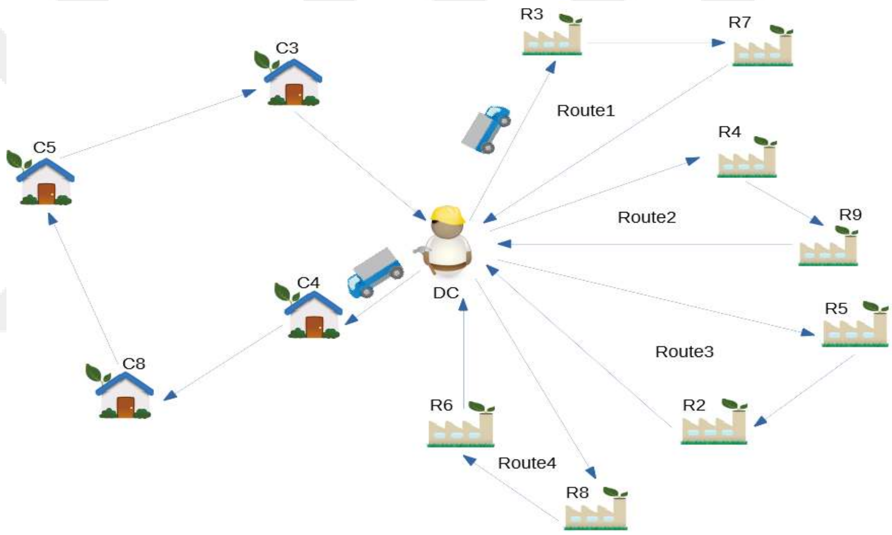

Figure 6.5 Optimal distribution plan for model #6.2.

6.4.2. Scenario Analysis

We now present the managerial insights for models #6.1 and #6.2. The effects of changing working time on performance measures are considered and results are analysed. For this scenario, working time is increased by 500 s at every turn. Since the supply and demand quantities are not changed for scenario analysis, the results of routing are same for each time.

Table 6.4 and Figure 6.6 present the obtained results for model #6.1. It is clear that increasing working time decreases objective function value and number of workstations. However, the cycle time systematically increases. A new disassembly workstation is opened to satisfy the demand of RC under decreasing working time.

Table 6.4 Results of model #6.1 on changing working time.

WT	Obj	NS	CT	CPU
1250	410.40	4	43.10	0.312
1750	310.40	3	60.30	0.297
2250	310.40	3	77.50	0.312
2750	210.40	2	94.80	0.297
3250	210.40	2	112.06	0.297
3750	210.40	2	129.30	0.453

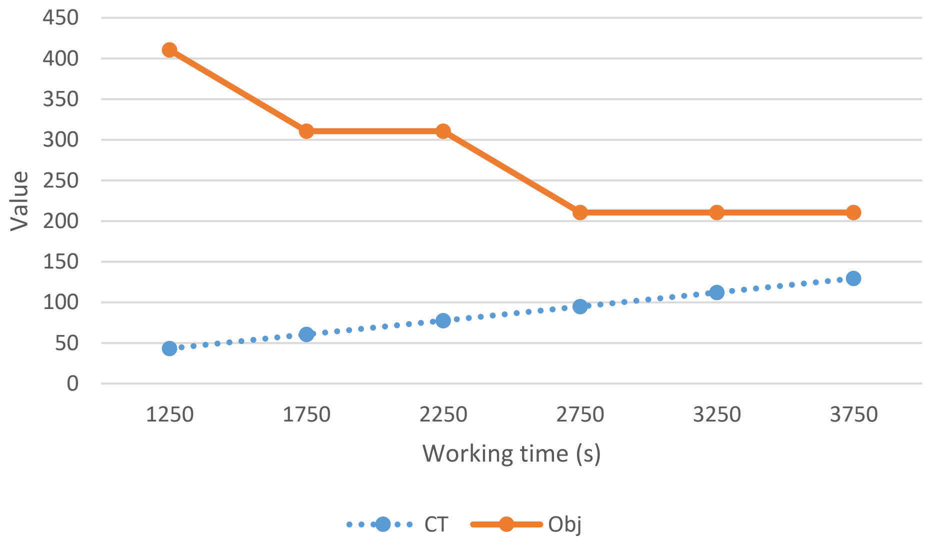

Figure 6.6 Relationship between cycle time, objective function, and working time for model #6.1.

Table 6.5 and Figure 6.7 present the obtained results for model #6.2. When we increase the working time, objective function value and the number of workstations decrease. However, cycle time increases. Since the size of test problem is not changed, a significant change in CPU time is not observed.

Table 6.5 Results of model #6.2 on changing working time.

WT	Obj	NS	CT	CPU
1250	415.30	4	48.07	0.297
1750	315.30	3	67.30	0.297
2250	215.30	2	86.50	0.297
2750	215.30	2	105.70	0.297
3250	215.30	2	125.00	0.282
3750	215.30	2	144.20	0.297

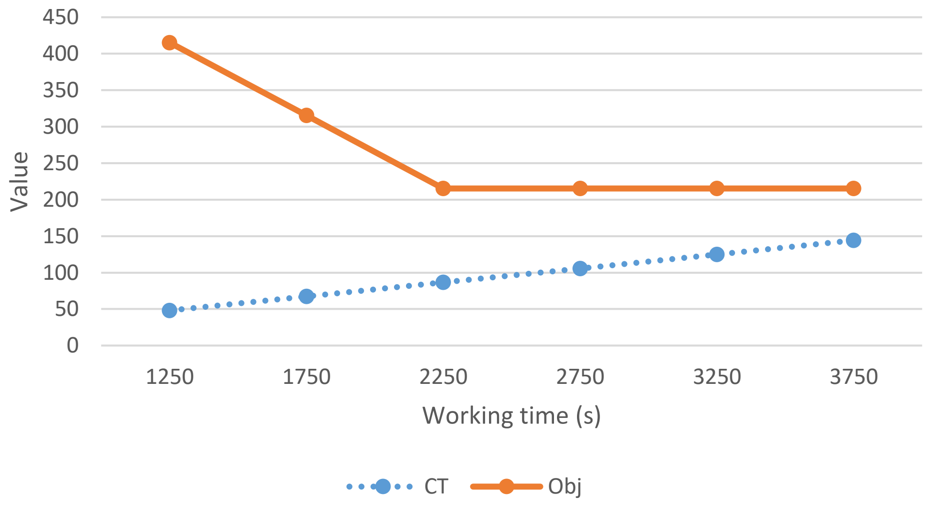

Figure 6.7 Relationship between cycle time, objective function and working time for model #6.2

6.5. Chapter Results and Findings

Due to economic, legislative and environmental reasons, the need for RSC has increased in recent years which has a great potential for tackling the waste. Disassembly is one of the most important elements of RSC, and DLB is highly used in disassembly operations due to its high productivity. The VRP arises and plays a crucial role in the collection of EOL products and the distribution of recycled components in product recovery.

We have studied the optimization of RSC network consists of collection, disassembly, and RC. We have introduced the I-CDDP. We have considered two different scenarios for the I-CDDP, and we have presented two mixed-integer mathematical formulations. The first one is for single-component case and the second one is for multi-component case. We have considered a case study and have conducted scenario analyses with using mathematical models to see the impact of changing working time. Results have shown that both models tend to open new disassembly workstations to satisfy the demand of RC under decreasing working time. Furthermore, as working time increases, the objective function value tends to decrease.

CHAPTER VII
INTEGRATED DISASSEMBLY LINE BALANCING AND ROUTING PROBLEM WITH MOBILE ADDITIVE MANUFACTURING[4]

This chapter introduces the I-DLB-RP with mobile AM (I-DLB-RP-MAM). One of the most significant recent technological developments is AM. In the I-DLB-RP-MAM, end-of-life products are first disassembled in a single DC, and a vehicle equipped with a 3D printer is then dispatches both recycled and 3D printed components to the customers (RC). Several demanded components are obtained in DC and the remaining amounts are produced by 3D printer en-route. We formulate a non-linear mathematical programming model for the novel I-DLB-RP-MAM and present a numerical example to illustrate the applicability of the model. Scenario analyses are conducted on benchmark instances and results have shown that AM technology can be incorporated into the SC and has several positive effects such as reducing inventory and total cost.

7.1. Introduction

Competition between companies in any industrial sector is rapidly increasing. Companies aim to decrease lead times and costs while delivering high quality products. AM, also known as 3DP technology, provides many advantages to companies due to its less labor, transportation, inventory cost, and delivery time, raw material saving, process simplifications, high efficiency and flexibility (Li et al., 2016; Chan et al., 2018; Pereira, Gasi, and Lourenço 2019; Delic and Eyers, 2020; Schniederjans et al., 2020; Afshari et al., 2020). AM has a very wide range of applications in various industries such as aerospace, aircraft, car, medicine, dentistry,

[4] This chapter is based on a paper titled "*Integrated Disassembly Line Balancing and Routing Problem with Mobile Additive Manufacturing*" that is under review in International Journal of Production Economics, by Diri Kenger, Z., Koç, Ç., Özceylan, E.

medical, art, and fashion (Beltagui et al., 2020; Pereira et al., 2019). General Electric, Ford Motor Company, Airbus, Siemens, NASA are prominent manufacturers invested in 3D printers (Mohr and Khan, 2015; Kucukkoc, 2019). Furthermore, Amazon promoted the concept of AM and granted a patent for manufacturing 3D printed products en-route (Amazon Technologies, Inc., 2015; Ryan et al., 2017; Malladi et al., 2020). The idea that the 3D printers could be mobile, maybe even situated in the same vehicle that would, at last, deliver the order to the customer's door, is brought forward by Amazon (3ders, 2018). The company perceives this as an innovator way of saving time and money, with a reduction in inventory space and labor costs. The topic of mobile AM started to gain more attention in this respect and emerged as a new potential research area.

More recently, Diri Kenger et al., (2020) introduced the I-DLB-RP. This novel problem considers disassembling of EOL products and then distributing recycled components to the RCs on demand via routing of vehicles. It is the first study to integrate DLB and VRP. The authors developed five linear and non-linear mathematical models. The presented models are arranged from the most basic and simple form to the most comprehensive one to show the development of novel problem. The I-DLB-RP obtained good solutions on benchmark instances.

The world is rapidly digitizing, and as a consequence communication and information technology is getting essential in SCM. The concept of AM, an innovation in the digitalized world, introduced in 1980s and applications emerged in 1990s (Khajavi et al., 2014b; Verboeket and Krikke, 2019). AM technology have many significant impacts on SC such as cost, time, and raw material savings (Holmström et al., 2017a). AM technology also provides sustainable clean environment, process simplifications, high efficiency and flexibility (Li et al., 2016; Chan et al., 2018). For more details about the impacts of AM on SC, we refer the readers to the papers of Mohr and Khan (2015), Chen (2016), Ryan et al. (2017), Chan et al. (2018), Özceylan et al. (2018), and Varsha Shree et al. (2019), and the surveys of Oettmeier and Hofmann (2017), Khorram Niaki and Nonino (2017), Pereira, Gasi, and Lourenço (2019), Verboeket and Krikke (2019), and Caviggioli and Ughetto, (2019).

A number of papers considered DLB (Özceylan and Paksoy, 2013; Özceylan et al., 2014; Kannan et al., 2017), several papers considered disassembly (Habibi et al., 2017a, 2017b, 2018), and few of them considered DLB with routing of vehicles (Habibi et al., 2017a, 2017b, 2018; Diri Kenger et al., 2020). Various types of solution methods are used such as linear programming (Diri Kenger et al., 2020; Habibi et al., 2017a), non-linear programming (Diri Kenger et al., 2020; Kannan et al., 2017b; Özceylan et al., 2014b; Özceylan and Paksoy, 2013b), and heuristic algorithms (Habibi et al., 2017b, 2018).

Our literature analysis shows that AM has not been considered in these studies. AM is not yet an alternative technology, but is instead an application that supports conventional manufacturing (Holmström et al., 2017b). Increased space to store additional inventory may increase costs. Time delays between receiving an order and transporting the demand may decrease customer satisfaction and profits (Krassenstein, 2015). In this chapter, we consider an extension of the I-DLB-RP where the distribution is carried out through vehicles equipped with 3D printer. The missing components in DC are produced by 3D printers in a vehicle en-route. The main focus is to see the effects of 3DP technology on the I-DLB-RP. AM technology is operated to promote DL to satisfy the demands of RCs.

This chapter makes three main scientific contributions. The first contribution is to introduce the I-DLB-RP-MAM. The second contribution is to develop a mixed integer non-linear mathematical formulation for the I-DLB-RP-MAM. The third contribution is to provide several managerial insights on the I-DLB-RP-MAM considering practical products.

The rest of the chapter is organized as follows. Section 7.2 presents the description of the I-DLB-RP-MAM and presents the mathematical formulation. Section 7.3 provides the computational results and scenario analyses. Section 7.4 presents the conclusions.

7.2. Problem Description and Formulation

Consider a SC network consists of DCs and RCs. EOL products are first disassembled in a single DC. A vehicle equipped with 3D printer then dispatches both the recycled components and 3D printed components to RCs. Some of the components demanded by RCs are obtained by DL in DC, and the remaining components are produced en-route by 3D printer in the vehicle. We follow the idea of Amazon where a truck fleet equipped with 3D printer technology to shorten the time between order and delivery (Amazon Technologies, Inc., 2015). Figure 7.1 illustrates the I-DLB-RP-MAM.

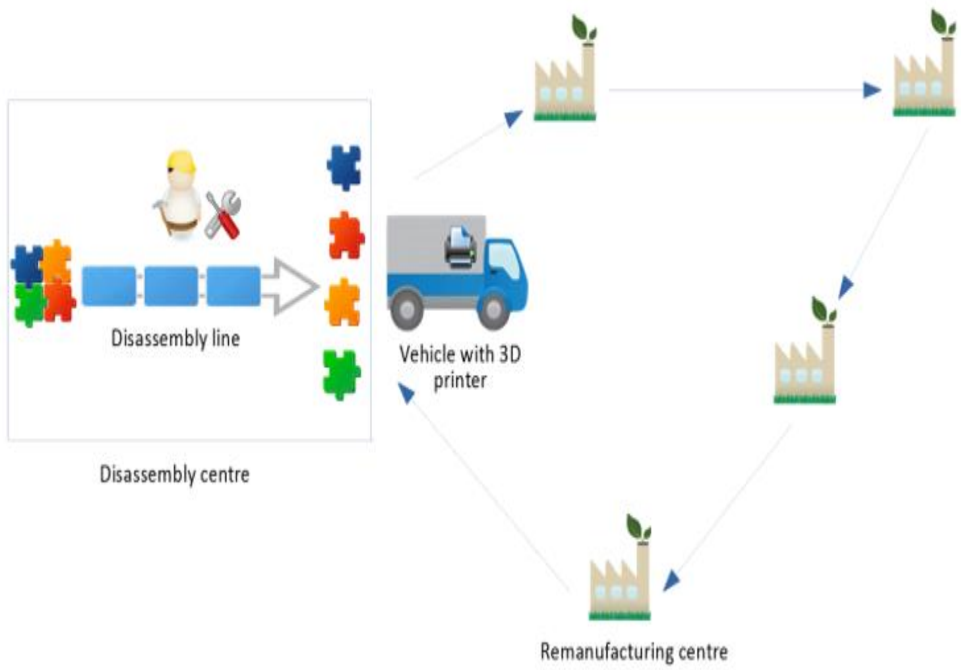

Figure 7.1 Illustration of the I-DLB-RP-MAM.

We now present a non-linear mathematical formulation for the I-DLB-RP-MAM. The novel problem is considered for a single DC, one-type of product, multi-component and a single 3D printer. Mathematical formulation is developed by using the formulation of Diri Kenger et al., (2020). Problem assumptions are as follows.

- A single type of product is completely disassembled.
- A task cannot be split among two or more workstations.
- All workstations can process any of tasks and all have the same associated costs.
- Each disassembly takes apart the product or sub-assembly into exactly two or more new sub-assemblies.
- All RCs demand more than one type component.
- All RCs do not demand all types of components.
- Vehicles are ready for service to customers in the RC.
- Some of the recycled components in DC are assumed to be defective.
- The demand for each RC for a component is known and must be fully satisfied.

- 3D printer can produce different components.
- Each component is different from each other.

Notations

Indices

c, g	remanufacturing centre, *c, g*={1, 2,…, *N*}
i	task
j, h	workstation
a	artificial task
k	component

Sets and Parameters

A_a	artificial nodes of *a*
B_i	nodes of *i*
$P(A_a), P(B_i)$	immediate predecessor set of A_a and B_i, respectively
$S(A_a), S(B_i)$	immediate successor set of artificial node set of A_a and B_i respectively
d_{B_i}	task time (normal node) of B_i
J	number of workstations (upper bound)
W_{time}	working time
De_{gk}	demand of remanufacturing centre *g*
Ct	fixed cost of shipping from DC to remanufacturing centre *g*
D_{cg}	distance between DC and remanufacturing centre or between remanufacturing centres
O	fixed cost to open a workstation in the disassembly line
Q	vehicle capacity

St	fixed cost to disassembly a product
Tt	fixed cost to operate 3D printer
CI	fixed cost to stock a component
$Time_{cg}$	time to produce 3D printed components while traveling from c to g
t_k	operating time in 3D printer for component k
$\mu(k)$	defect rate in DC for component k
M	big number

Variables

Cyc	cycle time
U_g	load of vehicle just after leaving g
P	the number of disassembled products on disassembly line
Dl_{gk}	the number of component k delivered from the DC to RC g
TD_{gk}	the number of component k produced by 3D printer for RC g
I_k	inventory level of component k
x_{ij}	1, if task B_i is assigned to workstation j; 0 otherwise
y_{cg}	1, if a vehicle travels from DC to RC or between RCs; 0 otherwise
z_i	1, if task B_i is performed; 0 otherwise
F_j	1, if workstation j is opened; 0 otherwise

The mathematical formulation of the I-DLB-RP-MAM (model #7.1) is then:

$$\min \quad O * \sum_{j}^{J} F_j + Ct * \sum_{c}^{N} \sum_{g,g \neq c}^{N} D_{cg} * y_{cg} + St * P + Tt * \sum_{g=2}^{N} \sum_{k}^{K} TD_{gk} + CI * \sum_{k}^{K} I_k \tag{7.1}$$

$$\sum_{i:B_i \in S(A_0)} z_i = 1 \tag{7.2}$$

$$\sum_{i:B_i \in S(A_a)} z_i = \sum_{i:B_i \in P(A_a)} z_i \qquad \forall\, a, a \neq 0 \tag{7.3}$$

$$\sum^{J} x_{ij} = z_i \qquad \forall\, i \tag{7.4}$$

$$\sum \quad x_{ih} \leq \sum \sum^{h} x_{ij} \qquad \forall\, a, a \neq 0, h \in J \tag{7.5}$$

$$Cyc * P = W_{time} \tag{7.6}$$

$$\sum_{i=1}^{I} x_{ij} * d_{B_i} \leq Cyc \qquad \forall j \tag{7.7}$$

$$F_{j+1} \leq F_j \quad \forall j, j = 1, \dots, J-1 \tag{7.8}$$

$$\sum_{i=1}^{I} x_{ij} \leq M * F_j \qquad \forall j \tag{7.9}$$

$$\sum_{g=1, g\neq c}^{N} y_{cg} = 1 \ \ \forall c, c = 2, \ldots, N \tag{7.10}$$

$$\sum_{c=1, c\neq g}^{N} y_{cg} - \sum_{c=1, c\neq g}^{N} y_{gc} = 0 \qquad \forall g, g = 1, \ldots, N \tag{7.11}$$

$$U_c - U_g + Q * y_{cg} \leq Q - \sum_{k=1}^{K} De_{gk} \qquad \forall c, g, \ \ c, g = 2, \ldots, N, c \neq g \tag{7.12}$$

$$\sum_{g=2}^{N} Dl_{gk} \leq \mu_k * P \qquad \forall k \tag{7.13}$$

$$TD_{gk} = De_{gk} - Dl_{gk} \quad \forall g, k, g = 2, \ldots, N \tag{7.14}$$

$$\sum_{k=1}^{K} t_k * TD_{gk} * y_{cg} \leq Time_{cg} \qquad \forall c, g, g = 2, \ldots, N, c \neq g \tag{7.15}$$

$$I_k = \mu_k * P - \sum_{g=2}^{N} Dl_{gk} \qquad \forall k \tag{7.16}$$

$$\sum_{k=1}^{K} De_{gk} \le U_g \le Q \quad \forall g \tag{7.17}$$

$$Cyc, P, Dl_{gk}, TD_{gk}, I_k \ge 0 \qquad \forall g, k \tag{7.18}$$

$$x_{ij}, z_i , y_{cg}, F_j \in \{0,1\} \qquad \forall i, j, c, g \tag{7.19}$$

The objective function (7.1) minimizes the total cost which consists of traveling cost, operating cost of disassembly workstations, disassembly cost of product, total cost of components produced by 3D printer, and inventory cost. Constraints (7.2) and (7.3) ensure that exactly one of the OR successors is selected. Constraints (7.4) guarantee that each selected task is assigned to one of the workstations in the DC. Constraints (7.5) provide the precedence relations. Constraints (7.6) and (7.7) deal with cycle time. Constraints (8) ensure that workstations open sequentially. Constraints (7.9) allows tasks to be assigned if the workstation is opened. Constraints (7.10) ensure each RC must be visited once. Constraints (7.11) define the flow. Constraints (7.12) are the capacity constraints. Constraints (7.13) state that total delivered components from DC do not exceed the disassembled product. Constraints (7.14) calculate the 3D printed components amount. Constraints (7.15) ensure that the time required for components produced by the 3D printer does not exceed the traveling time. Constraints (7.16) ensures the inventory balance in DC. Constraints (7.17)-(7.19) define the domain of decisions variables.

7.3. Computational Results

In this section, we first present an illustrative example to test the model in Section 3.1 and then present some managerial insights based on different scenarios in Section 3.2. All experiments are conducted on a server with Intel Core i5-8250U 1.6 GHz dual processor and 8.00 GB memories. We used GAMS/SCIP as the optimizer to solve the mathematical model.

7.3.1. Illustrative example

We first present the description of data in Section 7.3.1.1 and then present the results of illustrative example in Section 7.3.1.2.

7.3.1.1. Description of data

To generate our illustrative example, we consider well-known data sets in the literature. For the DLB, the flashlight example consists of 10 disassembly tasks and 7 components (Tang et al., 2002). In practice, components of flashlights are suitable to be produced by 3D printers. For example, Signify, a leader producer in lighting, produces 3D printed led lights on-demand allow easy modification and adaptation. The company indicates that significant saving can be achieved on time, energy, waste in manufacturing, packaging and transportation (Signify, 2020). Furthermore, 3D printers can now produce lithium-ion batteries (Reyes et al., 2018).

Figure 7.2 illustrates the flashlight with its components. Figure 7.3 presents the TAOG which includes 10 normal and 7 artificial nodes with all disassembly task times of the flashlight.

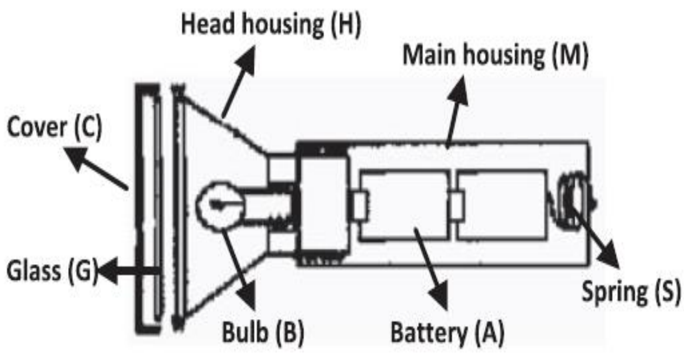

Figure 7.2 A flashlight with its components (Tang et al., 2002).

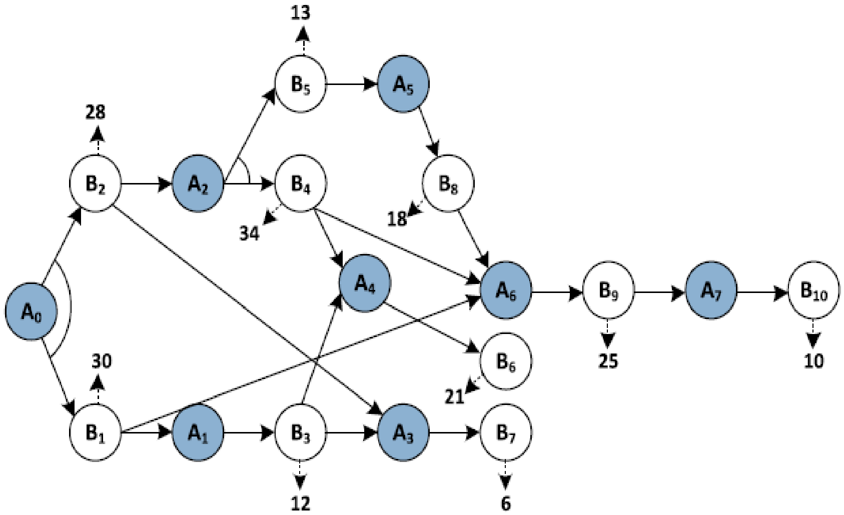

Figure 7.3 The TAOG of the flashlight (Paksoy et al. 2013).

For the VRP part, we modify the smallest data set (P_n16_k8) of Set P from classical VRP instances of Augerat et al., (1995). We adjust the data set as 9 nodes (1 DC and 8 RC) without changing the coordinate of nodes and vehicle capacity. We generate all parameters considering discrete uniform distribution. Operating times in 3D printer are in the range [1-4]. Defective rate of components in DC are in the range [0-1]. Table 7.1 presents the demands for RCs. C1–C7 denote component 1–7. Table 7.2 presents the operating times *t(k)* and defect rates of components $\mu(k)$. Demands are in the range [0–6] since all RCs do not demand all types of components. Table 7.3 presents time (min) between nodes (DC and RC or RC and RC) which are directly proportional to the distance between two nodes.

Table 7.1 Demands for remanufacturing centres.

	C1	C2	C3	C4	C5	C6	C7
RC1	3	-	4	3	-	1	6
RC2	2	4	3	-	3	-	2
RC3	-	4	6	2	-	5	4
RC4	4	5	-	4	4	3	4
RC5	-	1	5	-	1	2	1
RC6	5	2	-	1	3	3	4
RC7	2	-	3	3	4	-	-
RC8	4	3	3	4	3	3	2

Table 7.2 Operating times (min) and defect rate of components.

	C1	C2	C3	C4	C5	C6	C7
$t(k)$	1	2	1	3	4	3	1
$\mu(k)$	1	1	0.7	1	0.8	1	0.9

Table 7.3 Time (min) to travel between nodes for producing 3D printed components.

Nodes	DC	RC1	RC2	RC3	RC4	RC5	RC6	RC7	RC8
DC	-	13	21	32	22	23	12	22	32
RC1	13	-	12	19	11	24	12	18	20
RC2	21	12	-	15	22	16	10	8	12
RC3	32	19	15	-	21	31	25	23	7
RC4	22	11	22	21	-	35	23	29	26
RC5	23	24	16	31	35	-	12	8	25
RC6	12	12	10	25	23	12	-	10	22
RC7	22	18	8	23	29	8	10	-	17
RC8	32	20	12	7	26	25	22	17	-

W_{time} is fixed to 1000 minutes. The number of the maximum workstation (J) is fixed to 6. Unit shipping cost (Ct) is set to 5.23 cents per tonne-km for a general freight truck. Cost of opening a workstation (O) is set to 100 $/workstation (Özceylan and Paksoy, 2013). Disassembling cost of a product (St) is set to 5$/product. Cost of operating 3D printer (Tt) is set to 5$/component. Inventory cost per component (CI) is set to 40$/component.

7.3.1.2. Results of illustrative example

This section provides the results of illustrative example. Table 7.4 presents optimal component amount both delivered from DC and 3D printed en-route. 3D represents the 3D printed components en-route. DL represents the delivered components from DC.

Table 7.4 Results of the illustrated example.

	R1		R2		R3		R4		R5		R6		R7		R8	
	DL	3D	DL	3D	DL	3D	DL	3D	DL	3D	DL	3D	DL	3D	DL	3D
C1	2	1	2	-	-	-	2	2	-	-	-	5	2	-	2	2
C2	-	-	3	1	1	3	1	4	-	1	2	-	-	-	3	-
C3	4	-	-	3	1	5	-	-	2	3	-	-	-	3	-	3
C4	1	2	-	-	2	-	-	4	-	-	1	-	2	1	4	-
C5	-	-	2	1	-	-	4	-	-	1	2	1	-	4	-	3
C6	-	1	-	-	5	-	-	3	-	2	2	1	-	-	3	-
C7	3	3	-	2	-	4	-	4	-	1	4	-	-	-	2	-

Table 4 indicates that some of RCs demands are satisfied from DC and remaining are produced by 3D printer in vehicle en-route. These optimal results show that all demands of RCs are fully satisfied. Figure 4 illustrates the optimal distribution of the illustrative example. Objective function is 655.981 and solution time is 0.33 second for illustrative example. Table 7.5 shows the cost of traveling, workstation, disassembled product, 3D printed components, inventory, and percentages in total cost. TC, WOC, PDC, 3DPC, and IC denote traveling cost, operating cost of disassembly workstations, disassembly cost of products, total cost of components produced by 3D printer, and inventory cost, respectively.

Table 7.5 Costs and percentage for illustrative example.

	Result	%
TC	135.98	20.73
WOC	100.00	15.24
PDC	50.00	7.63
3DPC	370.00	56.40
IC	-	-
Total cost	655.98	100

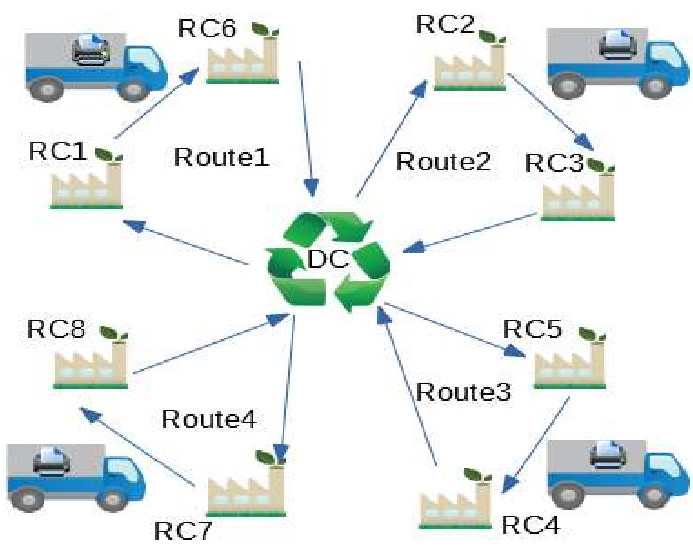

Figure 7.4 Optimal distribution of the illustrated example.

We calculate the cycle time by dividing working time to number of disassembled products in DC. The calculation of cycle time for mathematical model is as follows:

$$CT = \frac{Wtime}{Dp} = \frac{100}{10} = 100\,min$$

7.3.2. Scenario Analysis

In this section, our primary interest is to analyse the effects of AM technology on distribution plan. In particular, we aim (*i*) to investigate the effect of changing 3D printer operating cost on the model (Section 7.3.2.1); (*ii*) to analyse effect of AM technology on I-DLB-RP (Section 7.3.2.2); and finally (*iii*) to conduct limit analysis on the mathematical model (Section 7.3.2.3).

7.3.2.1. The Effect of Changing 3D Printer Operating Cost

Disassembled product cost is fixed to 1$/product and cost of operating 3D printer is doubled for each trial. Inventory cost is set to 20$/component and results are shown in Table 6. 3D, DP, CT, and OBJ denotes 3D printed component, disassembled product, cycle time, and the objective function value, respectively. Aim of this analysis is to indicate how changing the cost of 3D printer operating cost affects the solution results. As shown in Table 7.6, according as disassembled product amount increase in DC, cycle time tends to decrease. Figure 7.5 shows the relationship between 3D printed component and disassembled product amount. As cost of operating 3D printer increases, 3D printed component amount tends to decrease and disassembled product amount tends to increase. The main reason for this result is that the increasing cost of operating 3D printer will result in the delivering of many more components from DC to RCs.

Table 7.6 Results of cost analysis for illustrative example.

Cost of operating 3D printer ($)	3D (unit)	DP (unit)	CT (min)	OBJ ($)
1	74	10	100	319.98
5	17	20	50	615.98
10	17	20	50	765.98
20	17	20	50	935.98
40	17	20	50	1275.98
80	3	30	33.3	1945.98

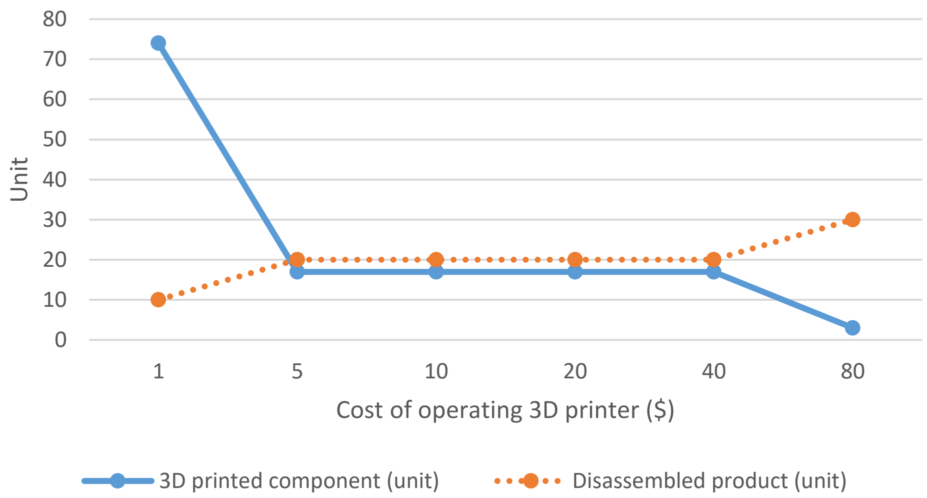

Figure 7.5 Relationship between 3D printed component and disassembled product.

7.3.2.2. Comparative Analysis

In this section, the effect of AM on I-DLB-RP is analysed. Therefore, the presented model conducted without considering AM constraints and solution results are compared. Constraints (14) and (15) are removed and constraints (13) and (16) are changed with constraint (20) and (21), respectively. So, all demands of RCs are met from only DC. For DLB part, we use the data set of 2-1-N from the Hezer and Kara

(2015)'s study. *N* denotes the number of components. We use the same data sets (1 DC and 8 RC) with illustrative example for VRP part. Vehicle capacity is fixed to 70. Solution results of I-DLB-RP and I-DLB-RP-MAM are compared with each other and optimal results are presented in Table 7.7. The results clearly show the benefits of AM technology on I-DLB-RP. According to the results, AM consideration significantly reduced total cost. The most important reason of this is the decrease in inventory cost in the DC. Comparison of the total cost for I-DLB-RP-MAM with I-DLB-RP is given in Figure 7.6. Also, considering AM technology decreases the disassembled product in DC as expected. Consequently, AM technology has positive effects on I-DLB-RP and plays an important part in reducing costs.

$$\sum_{g=2}^{N} De_{gk} \leq \mu_k * P \qquad \forall k \tag{20}$$

$$I_k = \mu_k * P - \sum_{g=2}^{N} De_{gk} \qquad \forall k \tag{21}$$

Table 7.7 Comparison of the I-DLB-RP-MAM with I-DLB-RP.

DLB	CT (min)		DP (unit)		CPU (sec)		OBJ ($)	
	I-DLB-RP-MAM	I-DLB-RP	I-DLB-RP-MAM	I-DLB-RP	I-DLB-RP-MAM	I-DLB-RP	I-DLB-RP-MAM	I-DLB-RP
2-1-5	50	25	20	40	4.20	3.00	403.50	2053.50
2-1-6	100	25	10	40	5.50	3.30	492.40	2617.40
2-1-7	100	25	10	40	3.50	2.30	522.40	3037.40
2-1-8	100	25	10	40	4.07	2.72	532.58	3622.58
2-1-9	100	25	10	40	5.60	3.60	550.66	4230.66
2-1-10	100	25	10	40	4.00	2.53	586.07	4571.07

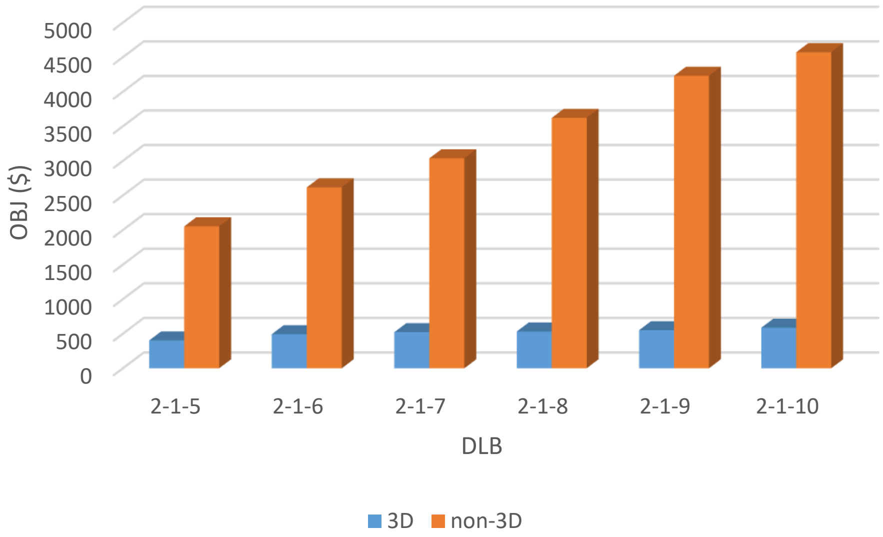

Figure 7.6 Comparison of the objective function value of presented model with non-3D model

7.3.2.3. Limit Analysis of the Computational Model

In this section, we investigate the limit of I-DLB-RP-MAM. For the VRP part, we modify the instances of Augerat et al. (1995) by considering the data set (P_n16_k8) of Set P and nodes are adjusted to 12, 13, 14, and 15 nodes. For the DLB part, we use the all test instances of Hezer and Kara, (2015). The demands for RCs are generated using discrete uniform distributions within the range of [0, 6]. The limit analysis is conducted by considering the cost of disassembly a product and operating 3D printer are equal. Vehicle capacity is increased to 70 unit. The solver time is limited to 7200 s. Table 7.8 presents the optimal solution results. NN and Inv denote the number of nodes and total inventory amounts of components, respectively. TL denotes exceeding of the time limit.

Table 7.8 Computational results for the limit analysis

DLB	NN	CT	DP	3D_P	CPU	OBJ	Inv	DLB	NN	CT	DP	3D_P	CPU	OBJ	Inv
1-2-5	12	50	20	24	365.3	412.1	-	2-2-6	12	50	20	24	297.8	513.9	5
	13	50	20	34	474.4	464.4	-		13	50	20	34	496.5	548.02	4
	14				TL				14				TL		
	15				TL				15				TL		
1-2-10	12	50	20	35	223.8	672.2	9	2-2-7	12	50	20	30	1160.7	556.04	5
	13	50	20	48	1026.7	666.4	5		13	50	20	42	2856.6	603.3	4
	14	50	20	58	5433.1	645.3	1		14				TL		
	15				TL				15				TL		

Table 7.8 Continuing

DLB	NN	CT	DP	3D_P	CPU	OBJ	Inv	DLB	NN	CT	DP	3D_P	CPU	OBJ	Inv
1-2-15	12	50	20	51	2.92	873.03	13	2-2-8	12	50	20	30	526.5	576.4	6
	13	50	20	71	425.5	850.4	6		13	50	20	42	719.4	603.6	4
	14	50	20	91	16.9	861.3			14	50	20	51	5112.8	592.02	1
	15				TL				15				TL		
1-3-5	12	50	20	24	393.3	412.1	-	2-2-9	12	50	20	30	274.7	636.4	9
	13	50	20	34	617.6	464.4	-		13	50	20	41	1295.3	628.6	5
	14	50	20	40	795	494.6	-		14				TL		
	15	33.3	30	10	2448.9	541.9	7		15				TL		
1-3-10	12	50	20	35	245.3	672.2	9	3-1-5	12	50	20	24	353.4	412.1	-
	13	50	20	48	955.04	666.4	5		13	50	20	34	483.2	464.4	-
	14				TL				14	50	20	40	1354.4	494.6	-
	15				TL				15	33.3	30	10	1250	541.9	7
1-3-15	12	50	20	51	2.3	873.03	13	3-1-6	12	50	20	24	180.7	513.9	5
	13	50	20	71	76.6	850.4	6		13	50	20	34	389.1	548.02	4
	14	50	20	91	28.9	861.3	1		14	50	20	40	4513.7	526.4	1
	15				TL				15				TL		
1-4-5	12	50	20	24	337.2	412.1	-	3-1-7	12	50	20	30	689.8	556.04	5
	13	50	20	34	515.3	464.4	-		13	50	20	42	2232.6	603.3	4
	14	50	20	40	629.8	494.6	-		14	50	20	49	6462.3	581.1	1
	15	33.3	30	10	1212.5	541.9	7		15				TL		
1-4-10	12	50	20	35	259.9	672.2	9	3-1-8	12	50	20	30	279.8	576.4	6
	13	50	20	48	905.2	666.4	5		13	50	20	42	592.9	603.6	4
	14				TL				14	50	20	51	2567	592.02	1
	15				TL				15				TL		
2-1-5	12	50	20	24	279.1	412.1	-	3-1-9	12	50	20	29	76.4	636.4	9
	13	50	20	34	494.9	464.4	-		13	50	20	42	1455.5	628.6	5
	14	50	20	40	405.1	494.6	-		14				TL		
	15	33.3	30	10	1338.2	541.9	7		15				TL		
2-1-6	12	50	20	24	334.8	513.9	5	3-1-10	12	50	20	35	452.08	672.2	9
	13	50	20	34	641.1	548.02	4		13	50	20	48	1557.3	666.4	5
	14	50	20	40	7161.9	526.4	1		14	50	20	58	6696.8	645.3	1
	15				TL				15				TL		
2-1-7	12	50	20	30	616.3	556.04	5	3-2-5	12	50	20	24	343.05	412.1	-
	13	50	20	42	2338.9	603.3	4		13	50	20	34	371.4	464.4	-
	14				TL				14	50	20	40	590.1	494.6	-
	15				TL				15	50	20	49	3915.06	541.9	-
2-1-8	12	50	20	30	291.2	576.4	6	3-2-6	12	50	20	24	255.06	513.9	5
	13	50	20	42	451.2	603.6	4		13	50	20	34	729.9	548.02	4
	14	50	20	51	2478.6	592.02	1		14	50	20	40	5531	526.4	1
	15				TL				15				TL		
2-1-9	12	50	20	30	84.5	636.4	9	3-2-7	12	50	20	30	816.8	556.04	5
	13	50	20	41	343.6	628.6	5		13	50	20	42	3016.9	603.3	4
	14				TL				14				TL		
	15				TL				15				TL		

Table 7.8 Continuing

DLB	NN	CT	DP	3D_P	CPU	OBJ	Inv	DLB	NN	CT	DP	3D_P	CPU	OBJ	Inv
2-1-10	12	50	20	35	206.8	672.2	9	3-2-8	12	50	20	30	229.8	576.4	6
	13	50	20	48	671.3	666.4	5		13	50	20	42	543.1	603.6	4
	14	50	20	58	5163.5	645.3	1		14	50	20	51	6290.8	592.02	1
	15				TL				15				TL		
2-2-5	12	50	20	24	352.04	412.1	-	3-2-9	12	50	20	30	227.4	636.4	9
	13	50	20	34	4130.3	464.4	-		13	50	20	41	953.9	628.6	5
	14	50	20	40	1552.6	494.6	-		14				TL		
	15	50	20	48	3726.8	541.9	-		15				TL		

The limit analysis has shown that non-linear programming models are too difficult to solve. One-unit increase in sample size significantly increases the solution time. Therefore, even small-size instances may not reach to the optimal solution. Also, we can say considering AM on the I-DLB-RP generally increases solution time when comparing with Diri Kenger et al., (2020)'s study. Additionally, as increasing sample size, total cost decreases in parallel with inventory cost for some test instances.

7.4. Chapter Results and Findings

AM is one of the numerous frame breaking technologies that the fourth industrial revolution brings along. Amazon promoted the concept of the 3D printers that are part of their service could be mobile. Few companies have had as great an impact on the SC in the last decade, as Amazon has. Therefore, this chapter is quite important for academia to reach the practical life. AM technology also leads to a cleaner environment around the world promoting less fuel consumption and recycling. The primary objective of this chapter is to shed light on the benefits behind the integration of I-DLB-RP and AM technology. This chapter is the first attempt to integrate I-DLB-RP with mobile AM. A non-linear mathematical model is presented for the novel problem and tested on benchmark instances. Several scenario analyses, cost analysis, a comparative analysis, and limit analysis, are conducted on the presented model and results has shown that:

- As operating cost of 3D printer increase, cycle time and 3D printed components tend to decrease.
- As operating cost of 3D printer increase, total cost and disassembled product amount tends to increase.

- AM consideration for I-DLB-RP has significant advantages such as decreasing disassembled product amount and inventory cost. As a consequence, the total cost decreases considerably.
- Limit analysis has clearly indicated the difficulties of solving the presented model for the I-DLB-RP-MAM.
- As the sample size increases, the solution time and total cost increase. However, total cost decreases for some test beds due to inventory cost.
- Finally, limit analysis shows that a one-unit increase in sample size significantly increases the solution time.

CHAPTER VIII

CONLUSIONS

8.1. Overview

This thesis has studied a number of integrated DLB and VRP models in cooperation with AM. Section 8.2 summarizes the scientific contributions and results of four main chapters. Section 8.3 presents an overview of research outputs of the thesis. Section 8.4 presents the limitations of the considered problems and methodologies. Section 8.5 define future research directions.

8.2. Scientific Contributions of the Thesis

The main purpose of this thesis is to simultaneously optimize several integrated versions of DLB and VRP which are well-known problems.

Specific contributions of each chapter are presented as follows:

In Chapter IV:

- This is the first attempt of integration DLB and VRP.
- Five different linear and non-linear mathematical formulations are presented for several scenarios (single-component distribution, multi-component distribution, inventory cost, and multi-period conditions).
- New benchmark instances are produced for demand section of integrated problem.
- Extensive computational experiments and several scenario analyses are conducted and results are analysed.
- A slight change in the demand of RC can stimulate the DL balance and the number of satisfied RC.
- Limit analysis has clearly indicated the difficulties of solving MINLP models for the I-DLB-RP.

- Scenario analyses have shown that costs directly affect the solution results.

In Chapter V:

- This is the first adaptation of 3DP technology to I-DLB-RP within the context of smart factories.
- A non-linear mathematical formulation is proposed.
- New test beds are generated for 3DP and demand section of the problem.
- Scenario analyses are realized and several insights are provided.
- Scenario analyses show that working time and costs are an essential factor on the results.
- Increasing the fixed cost of the 3DP machine increases the objective function value and the number of disassembled products for the current test problem and vice versa.
- When the working time increases, the number of components produced by 3DP machine and cycle time also increases. However, the number of disassembled products and objective function value decreases.

In chapter VI:

- The I-CDDP is introduced.
- Two different mathematical formulations are presented for two different conditions: single-component distribution, multi-component distribution.
- New test beds are produced for demand section of problem.
- Scenario analyses are conducted and managerial insights are presented.
- Results have shown that both models tend to open new disassembly workstations to satisfy the demand of RC under decreasing working time.
- As working time increases, the objective function value tends to decrease.

In chapter VII:

- The I-DLB-RP-MAM is introduced.
- A non-linear mathematical programming model is presented.
- Several managerial insights are derived and effects of AM technology on SC are investigated.

- AM consideration for the I-DLB-RP has significant advantages such as decreasing total cost depending on decreasing disassembled product amount and inventory cost.
- Limit analysis has clearly shown the complexities of solving the presented model for the I-DLB-RP-MAM.
- When sample size increases, the total cost and solution time increase. Nevertheless, due to inventory cost total cost decreases for some test beds.
- Finally, limit analysis shows that a one-unit increase in sample size significantly increases the solution time.

8.3. Research Outputs

An overview of the research outputs of the thesis is given below.

Four publications:

- Diri Kenger, Z., Koç, Ç., Özceylan, E., 2020. Integrated Disassembly Line Balancing and Routing", International Journal of Production Research, doi: 10.1080/00207543.2020.1740346 [Chapter 4].
- Diri Kenger, Z., Koç, Ç., Özceylan, E. Integrated Disassembly Line Balancing and Routing Problem with 3D Printers, that is published in the CRC Book: Logistics 4.0: Digital Transformation of Supply Chain Management, in press [Chapter 5].
- Diri Kenger, Z., Koç, Ç., Özceylan, E. Integrated Collection-Disassembly-Distribution Problem, that is published in the Sustainable Production and Logistics: Modeling and Analysis, in press [Chapter 6].
- Diri Kenger, Z., Koç, Ç., Özceylan, E. Integrated Disassembly Line Balancing and Routing Problem with Mobile Additive Manufacturing. International Journal of Production Economics, under first review [Chapter 7].

8.4. Limitations of the Research Results

We now present the limitations of this dissertation.

- Due to the difficulty for solving MINLP models considered in this thesis, only small size test problems are used to reach optimal solutions. However, heuristic/metaheuristic algorithms could be developed to effectively solve large-size test problems.

- We assumed that all parameters are deterministic for introduced problems. This study does not consider stochastic, fuzzy or dynamic environments. However, in DL, a component may be defective due to operation complexity or workers. Similarly, for the VRP, some parameters such as travel time and demand may show stochastic behavior.
- We assume that a single-type of product are completely disassembled in DC. Nevertheless, in practical more than one type of EOL products are collected to recycling.
- The presented mathematical models run on existing test problems in the literature. To validate the effectiveness of the algorithms, a real product including case studies, should be considered.
- We assume that we have one 3D printer for producing new components. However, a few 3D printers could be responsible to produce new components, simultaneously.

8.5. Future Research Directions

In order to fulfill the above limitations, we have determined the following future research areas:

- More realistic and large size benchmark instances could be generated. Metaheuristic algorithms could be developed to effectively solve the large-size instances.
- Using stochastic and fuzzy parameters could be considered in order to approach real-life application.
- We consider complete disassembly for all introduced problems. However, partial disassembly could also be considered.
- The presented models could be formulated for hazardous materials and presence of task failures.
- A case study could be conducted on a real industrial product or with real distances.
- Linearization of non-linear models could be considered.

- Different scenario cases such as inventory, multi-product, multi-period may be considered for current problems.
- More than one 3D printer could be considered to save time for manufacturing new components.

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ACADEMIC TRACK RECORD

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2. Diri Kenger, Z. Koç, Ç., Özceylan, E., (2020) Integrated disassembly line balancing and routing problem, International Journal of Production Research, doi:10.1080/00207543.2020.1740346.

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INTEREST AREAS

Optimization, Mathematical Modelling, Assembly and disassembly line balancing problem, Vehicle Routing Problem, Additive Manufacturing Technology.