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Disassembly line balancing problem: a review of the state of the art and future directions

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The disassembly line balancing (DLB) problem assigns the set of tasks to each workstation for each product to be disassembled and aims at attaining several objectives, such as minimising the number of workstations, ensuring similar idle time at each workstation and removing hazardous parts/highly demanded components at the earliest moments possible. Over the past two decades, the DLB problem and its variants have grown ever more popular for researchers and practitioners of environmentally conscious manufacturing. Yet, the problem characteristics and assumptions vary widely and there is no literature review to classify the existing articles accordingly. Hence, a comprehensive literature review of recent and state-of-the-art papers is vital to draw a framework of the past, and to shed light on future directions. To do so, 116 studies published in proceedings and journals since 1999 are selected and reviewed. The papers are then analysed and categorised to construct a useful foundation of past research. Finally, trends and gaps in the literature are identified to clarify and to suggest future research opportunities.

Keywords: disassembly; disassembly line; line balancing; state of the art; survey

1. Introduction

Product recovery has become an obligation to the environment and to the society itself, enforced primarily by governmental regulations and customer perspective on environmental issues (Güngör and Gupta 1999a). Product recovery aims to minimise the amount of waste sent to landfills by recovering materials by means of recycling, disassembling, sorting and refurbishing in order to bring the product to a desired level of quality. In all product recovery operations, disassembly has proven its role in material and product recovery by allowing selective separation of desired parts and materials (Koç, Sabuncuoğlu, and Erel 2009).

Disassembly may be defined as a systematic method for separating a product into its constituent parts, components, subassemblies or other groupings. While disassembly operations can be performed at a single workstation, in a disassembly cell, or on a disassembly line, the highest throughput and productivity is provided by the disassembly line (Güngör and Gupta 2002). There are a number of sub-problems arising within disassembly operations and lines in literature such as disassembly planning, disassembly scheduling, disassembly sequencing and disassembly line balancing (DLB) (Lee, Kang, and Xirouchakis 2001).

The disassembly planning includes product representation with disassembly level and end-of-life options, and related product design/redesign issues (Lee, Kang, and Xirouchakis 2001), while the disassembly scheduling is the problem of determining the order quantity of the used product to full the demand of disassembled parts and subassemblies (Kim, Lee, and Xirouchakis 2007). On the other hand, disassembly sequencing seeks a feasible/optimal order in which the disassembly tasks are processed (Lambert 2003). The DLB problem is at the forefront (Wan and Gonnuru 2013) among the sub-problems mentioned above and can be generally stated as the assignment of disassembly tasks to workstations such that all precedence relations between the tasks are satisfied and some measure of effectiveness is optimised (Ding et al. 2010b).

The DLB problem is somewhat related to assembly line balancing (ALB) and has been attracting interest from the field of reverse logistics in recent years (Boysen, Fliedner, and Scholl 2007). Even though considering disassembly as the reverse of assembly may sound reasonable, for complex products, the operational characteristics of disassembly and assembly are quite different (Güngör and Gupta 1999a). Unlike in an assembly environment, in a disassembly environment, a product may be broken down into many parts and subassemblies whose qualities, quantities and reliabilities

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*Corresponding author. Email: S.Gupta@northeastern.edu cannot be controlled. The assembly process has to be complete while the disassembly process does not have to be carried out completely due to technical and economic restrictions. For a detailed comparison of operational and technical considerations of assembly and disassembly lines, the reader is referred to the book by Lambert and Gupta (2005c).

These characteristics of disassembly make disassembly lines more challenging. Therefore, particular attention should be dedicated to their balancing phase and efficient tools are needed in order to optimise their performances and effectiveness (Bentaha et al. 2014d). With this motivation, it is also necessary to provide a comprehensive review to help researchers focus on future directions. According to the authors' best of knowledge, no review paper is available in this field that presents a systematic classified analysis of recent papers to spot future avenues. This paper tries to cover this gap by reviewing, categorising and analysing 116 papers published between 1999 and 2018.

The remainder of the paper is structured as follows: Section 2 discusses some earlier review/partial-review papers. Research methodologies are clarified in Section 3. Detailed analysis and classification of reviewed papers are discussed in Section 4. The current gaps analysis results and future research opportunities are presented and discussed in Section 5.

2. Previous review articles

Before presenting the comprehensive review of papers related to DLB problems, some earlier review articles related to environmental conscious manufacturing and product recovery are briefly discussed to clarify the value of this study. In order to manage a structured review, the characteristics of the earlier review/partial-review papers are depicted in Table 1.

As is clear from Table 1, no comprehensive review exists in the literature on the DLB problem. Güngör and Gupta (1999c) and Ilgin and Gupta (2010a) provided excellent and comprehensive literature reviews of the entire 'environmentally conscious manufacturing and product recovery' area. Although their comprehensive reviews cover hundreds of papers spanning more than two decades, their reviews do not focus on the DLB issues.

Gagnon and Morgan (2013) do cover a small portion of the DLB papers in their review but they limit the scope of their review by considering only 31 publications in the area of remanufacturing line balancing that were published through the year 2012. Finally, Bentaha, Dolgui, and Battaïa (2015c) review the solution methods developed for the designing and balancing of assembly and disassembly lines with uncertain assembly/disassembly task time.

Thus, this is the first paper to focus on the DLB problems and provides a thorough review and analysis of the characteristics of DLB problems such as the objective functions, complications, models and solution approaches and other parameters found in the literature.

Table 1. Characteristics of earlier review/partial-review studies.

Study	Area	Scope	Year Range	Number of Papers Reviewed
Güngör and Gupta (1999c)	Environmentally conscious manufacturing and product recovery	Environmentally conscious design and production, material recovery or recycling, product recovery or remanufacturing, disassembly levelling, and disassembly process planning.	1967–1998	331
Ilgin and Gupta (2010a)	Environmentally conscious manufacturing and product recovery	Environmentally conscious product design, reverse and closed-loop supply chains, remanufacturing, and disassembly.	1967–2010	540
Gagnon and Morgan (2013)	Remanufacturing line balancing	Complications, objectives, task allocations, and solution methodologies for DLB problem.	1999–2012	31
Bentaha, Dolgui, and Battaïa (2015c)	Production line design and balancing under uncertainty	Deterministic disassembly line design and balancing, non-deterministic production line design and balancing, uncertain assembly / disassembly task processing times, modelling with closed intervals and fuzzy sets.	1976–2015	90
Proposed study	Disassembly line balancing	Disassembly line types, objectives, product types, parameter types, disassembly levels, product structural conditions, complications, solution approaches and disassembled product.	1999–2018	116

3. Review methodology

According to Govindan, Soleimani, and Kannan (2015), content analysis and description of research methodology should include four steps: material collection, descriptive analysis, category selection and material evaluation. This paper utilises the steps mentioned in Govindan, Soleimani, and Kannan (2015) to discuss and clarify the research methodology of the paper.

3.1 *Material collection*

The material for the literature review and the unit of analysis are detailed in this part. The study was conducted by covering the accepted journal papers (available online) and proceedings in scientific English language from 1999 (introduction of DLB problem) to 2018. The search terms were identified through several trial and error attempts, replying on the prior experience of the authors and the keywords utilised in other aforementioned review papers. Through this process, a sophisticated keyword structure was designed combining a four-level search structure (see Table 2).

We design a four-level keyword assembly structure that aims to accommodate a broad range of search terms for capturing published DLB problem papers. Table 2 shows the assembly structure where level 1 defines the search context (disassembly); level 2 outlines disassembly problem keywords such as 'line', 'system', 'sequencing' and 'scheduling'; level 3 contains the related performance keywords and the last level includes needless keyword as 'assembly'. The keywords in levels 2 and 3 are kept at a general level to cover a broader range of studies. For example, although some of the studies (Igarashi, Yamada, and Inoue 2014; McGovern and Gupta 2015; Igarashi et al. 2016) use 'design', 'system', 'planning' and 'modelling' keywords instead of 'balancing' in their titles, they consider DLB problem in their studies.

Using the "title, abstract, keywords" search in Google-scholar database, proceedings and articles are stored in English language, and sorted by relevance. It is known that the Google-scholar database is more comprehensive than the Web of Science and Scopus databases (Fahimnia et al. 2015). It should be mentioned that the search engine is updated periodically due to the acquisition of new publications, relevance, citations, and so forth, so the process of collecting papers is undertaken over a period of time. In the initial search from Google-scholar, 574 papers including book series, commercial publications and magazine papers from various publishers were obtained. To refine of the initial results, papers are cross-checked with results of the same keywords in Web of Science and Scopus. The refinement resulted in 116 journal articles and proceedings by eliminating duplications, non-refereed articles, commercial magazine papers and papers with unknown author names.

Finally, 116 papers are reviewed and classified in the review study. They are evaluated and their differentiating characteristics are defined and recorded in a spread sheet to analyse holistically.

3.2 *Descriptive analysis*

Figure 1 shows the publishing trend using the number of publications in a given year. Although the number of journal articles seems low in the earlier stages, it surpassed the number of proceedings papers in total. This significant growth in the number of papers is more noticeable after 2013.

The publications and distribution of the journals and conferences are presented in Figures 2 and 3. While 70 of 116 papers are published in journals, the rest of them appeared in conference proceedings. Figure 2 shows that 36 journals have contributed to the publication of 70 articles. It was found that the first 8 journals have published 39 of these identified articles, representing approximately 56% of all the published articles. Among the journals, *International Journal of Production Research* seems dominant, representing 21% of all published articles.

Table 2. The proposed four-level keyword search items.

Search keywords
Disassembly
AND
Line OR System OR Sequencing OR Scheduling
AND
Balancing OR Planning OR Modelling OR Design
AND NOT
Assembly

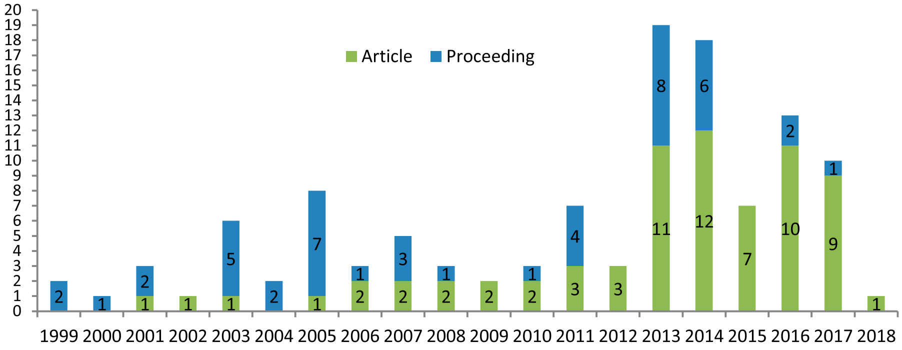

Figure 1. Distribution of publications per year.

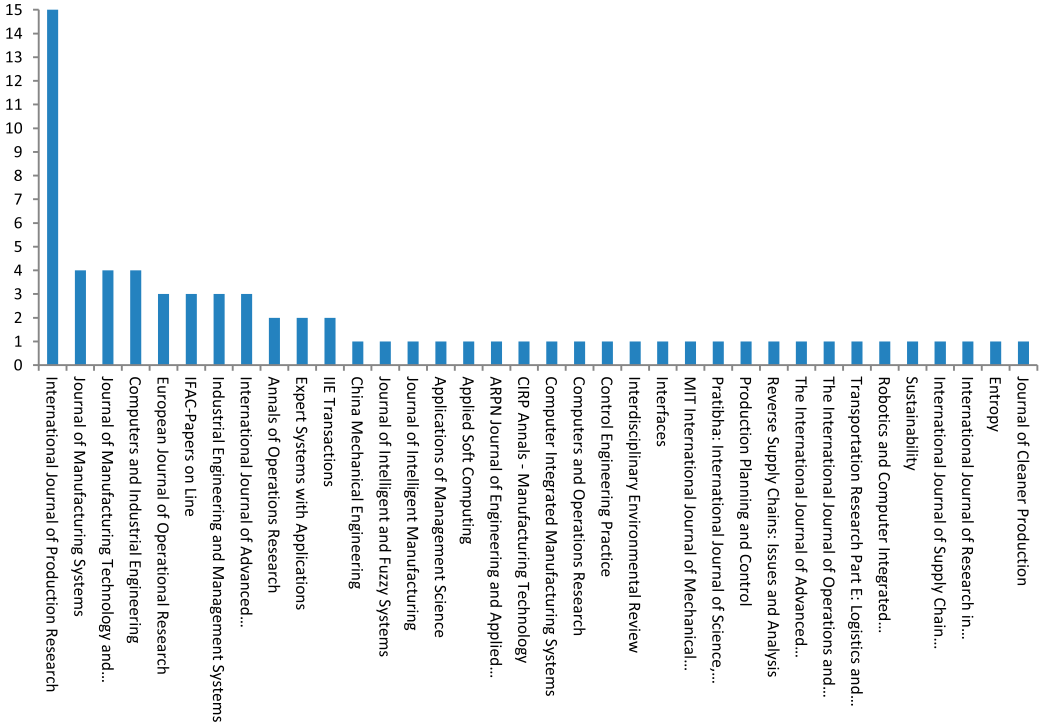

Figure 2. Distribution of publications based on different journals (70 papers: 1999–2018).

According to Figure 3, 16 conferences have contributed to the publication of all proceedings papers. It was found that three conferences, viz., SPIE International, IEEE International and IFAC have played host to 21 of these identified proceedings papers, representing approximately 47% of all the published conference papers.

3.3 *Category selection*

The classification applied in this review is formed based on different features and properties of DLB problem models. The classifications used in Boysen, Fliedner, and Scholl (2007) (due to similarity with ALB problem), Gagnon and Morgan (2013) and Bentaha, Dolgui, and Battaïa (2015c) are used as benchmark to check the comprehensiveness of the proposed classification framework. We have expanded the categories proposed by aforementioned researchers by adding six additional criteria: product types, parameter types, disassembly levels, product structural conditions, complications and disassembled products. The main topics and categories used to classify the papers are shown in Figure 4 and are briefly described below:

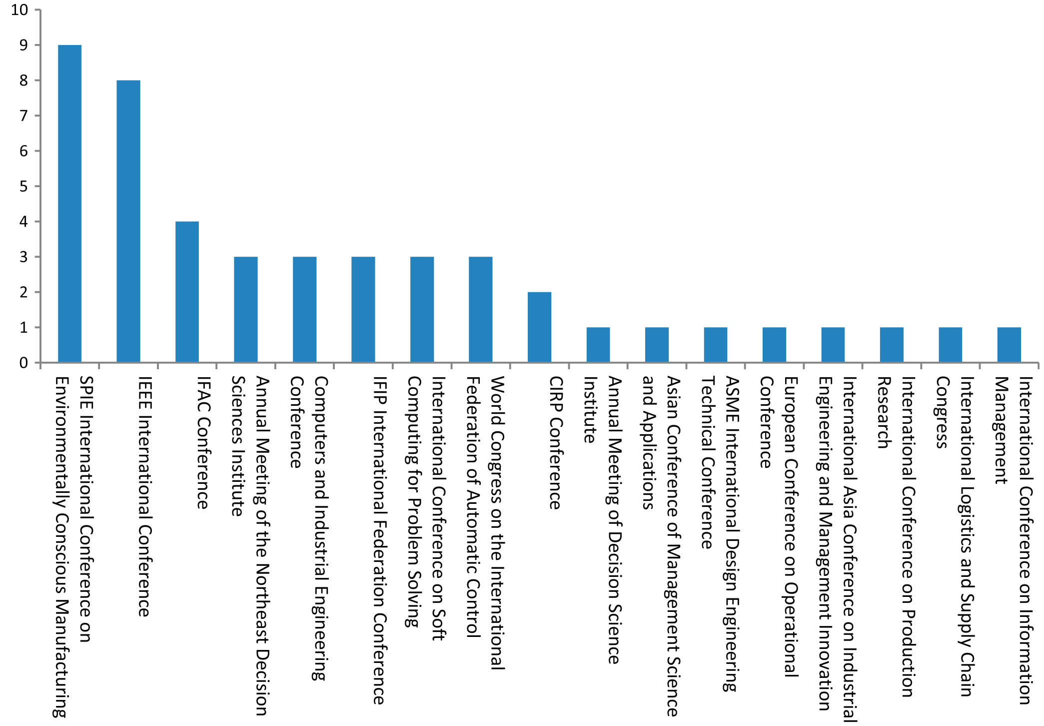

Figure 3. Distribution of proceedings (46 proceedings: 1999–2018).

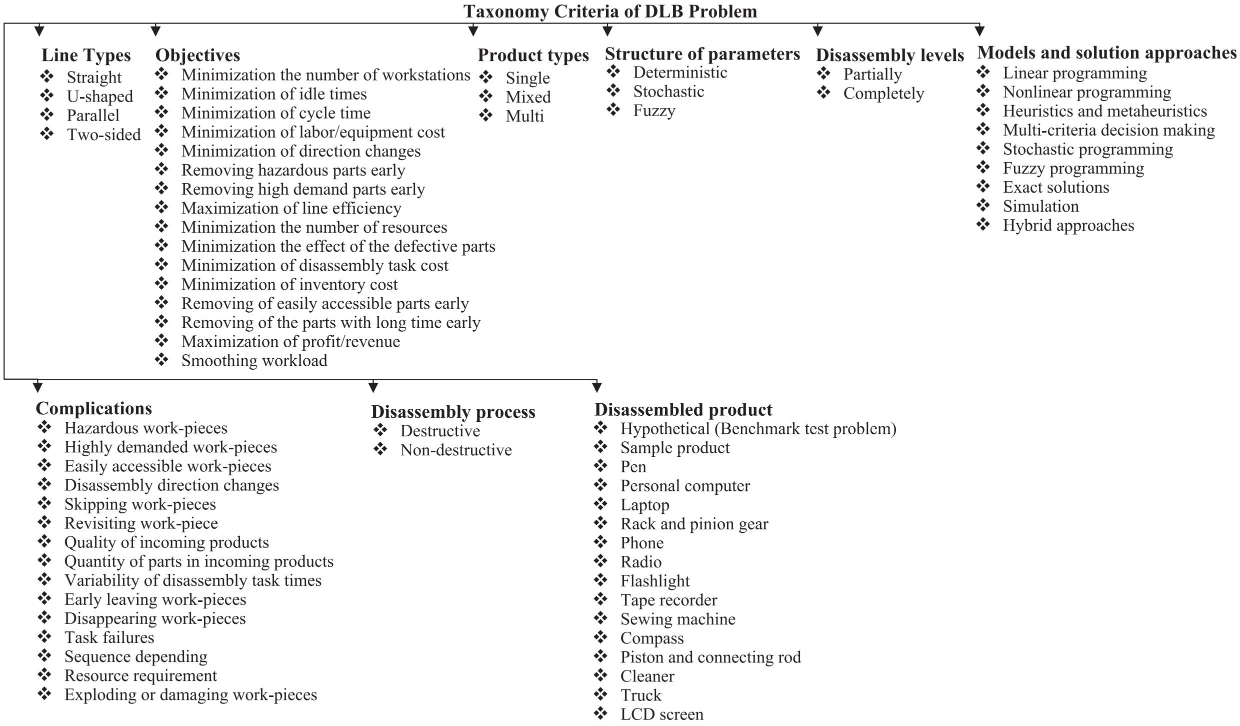

Figure 4. Classification of the DLB problem.

Line types: It refers to the type of layout, i.e. straight, U-shaped, parallel and two-sided layouts, used to disassemble products.

Objectives: This/these is/are the objective/s defined in the DLB problem model, e.g. minimisation of the number of workstations, idle times and cycle time.

Product types: The disassembled product on the disassembly line may be single, mixed or multi product.

Structure of parameters: This category refers to the use of deterministic, stochastic or fuzzy parameters.

Disassembly levels: It refers to the identification of how far to disassemble a product. The products may be disassembled partially or completely.

Disassembly process: According to a desired target, two types of disassembly processes can be considered; namely, the non-destructive disassembly and the destructive disassembly. Non-destructive disassembly allows the separation of components, which may be reused in remanufactured products or sold thus optimising the use of resources. On the other hand, destructive disassembly is used if the component separation requires the destruction of some part(s); therefore, it does not allow direct reuse of retrieved components in new products (Mircheski, Kandikjan, and Prangoski 2012). According to Duta, Filip, and Caciula (2008), disassembly operations may use a methodology that is destructive (focusing on materials rather than parts recovery) or non-destructive (focusing on parts rather than materials recovery).

Complications: Unlike assembly, in disassembly environment, there are serious complications such as a high degree of uncertainty in the structure, the quality of the products, and uncertainty factors associated with the reliability of the workstations (Güngör et al. 2000).

Models and solution approaches: This category consists of models and solution approaches developed for the DLB problem such as mathematical models, heuristics and meta-heuristics approaches.

Disassembled product: This category is to present application aspects of papers investigated in this study.

3.4 *Material evaluation*

The use of deductive/inductive methods in the validation stage enhances the credibility of the research. Also, the application of spread sheet software such as Microsoft Excel and Access in the evaluation and analysis phase reduces errors (Ghaderi, Pishvaee, and Moini 2016). The materials are cross-checked with other databases to ensure enrichment of the study as mentioned before, and those papers not found in the first search are added to the list. Besides, researchers of this study worked independently to investigate the sufficiency of papers to be reviewed through a series of search and cross-check activities.

4. Detailed analyses of the literature

In this section, the selected papers are discussed and analysed based on the classification criteria given in Figure 4 to construct a holistic view of the state-of-the-art studies in DLB problem. The results may help clarify the current gaps and future directions for research in the field.

4.1 *Considering line types*

Disassembly lines can be classified as straight, U-type, parallel and two-sided disassembly lines. In straight disassembly line, products are disassembled in an ordered sequence of workstations operating under a defined cycle time constraint (Hezer and Kara 2015). In some cases, the capacity of a straight disassembly line is insufficient due to high demand for recovered parts. Therefore, it is highly desirable to increase the capacity in order to meet the demand. One of the ways to do this is to design parallel disassembly lines (Ketzenberg, Souza, and Guide 2003). Reduction in the redundant movement of operators and higher flexibility in workforce planning may be achieved using U-type disassembly lines. In U-type disassembly lines, product flow and hence operator movement may be clockwise or counter clockwise (Agrawal and Tiwari 2008). To overcome the capacity problem, disassembly lines can also be placed two-sided in which products flow along a production line with workstations on both sides of the line (Bartholdı 1993).

The majority of the previously published studies (approximately 96%) consider the straight line type. Only three references consider a U-type layout (Agrawal and Tiwari 2008; Avikal and Mishra 2012; Avikal, Jain, and Mishra 2013a). Additionally, parallel layout is only used in two references (Karadağ and Türkbey 2013; Hezer and Kara 2015). There is no published paper considering two-sided layout for DLB problem.

4.2 *Analysis of performance measures*

The objective of the DLB problem is to utilise the resources of the disassembly line as efficiently as possible while meeting the demand. Efficient utilisation of resources consists of finding the minimum number of disassembly workstations required, optimally assigning the disassembly tasks to the workstations, and improving the layout and material handling features of the disassembly line (Güngör et al. 2000). There are same performance measures used for both DLB and ALB problems. For example, the frequently used objectives include minimising the number of workstations or equivalently minimising the total idle time or maximising the line efficiency and balancing the work load among the workstations. However, there are some special objectives for DLB such as removing hazardous parts early, removing highly demanded parts early, removing easily accessible parts early, minimising the effect of the defective parts and removal of the parts with longer disassembly task times early. Table 3 indicates the number of papers employing each type of objective. The studies that consider a single objective are shown in bold fonts in Table 3.

Distribution of objective functions is given in Figure 5 which indicates that minimising the number of workstations has been the most chosen performance measure. 52.53% of papers prefer the use minimising idle times as a performance measures. Approximately, 40% of the papers aim to remove hazardous and high demand parts as early as possible which are unique to DLB problem. It is noticed that papers usually consider early removal of hazardous and valuable parts simultaneously. There are studies aiming for maximisation such as maximisation of the profit/revenue (18.8%) and maximisation of the line efficiency (5.05%). In addition to the aforementioned popular performance measures, removing easily accessible parts and removing the parts with longer task times as early as possible are considered by Güngör and Gupta (1999b, 2001, 2002) and Avikal et al. (2014c), respectively.

In addition to the types of performance measures considered, there have been single- and multi- objective models to take into account various and conflicting objectives in DLB literature (Figure 6). The figure indicates that 26.3% papers present single-objective models vs. 73.7% for multi-objective ones. In multi-objective DLB models, the objectives are usually either the combination of (*i*) minimising the number of workstations, minimising the idles times, removing hazardous parts early and removing highly demanded parts early (Ding et al. 2010b; Kalayci and Gupta 2013b) or the combination of (*ii*) minimisation of the idles times, minimisation of the number of direction changes, removing hazardous parts early and removing highly demanded parts early (Zhu, Zhang, and Hu 2014).

4.3 *Considering product types*

In DLB problem area, the disassembled product can be categorised into three types including (*i*) single, (*ii*) mixed and (*iii*) multi-product. Due to natural complexity of DLB problem, the vast majority (approximately 96%) of the studies consider the single-product case. There are only three studies dealing with mixed-product type (Agrawal and Tiwari 2008; Paksoy et al. 2013 and Riggs, Battaïa, and Hu 2015); and also three studies (Ilgin and Gupta 2010b; Ilgin, Akçay, and Araz 2017 and Kannan et al. 2017) dealing with the multi-product case for disassembly. A cost effective reverse logistics network which integrates the DLB in the planning recovery network is considered by Kannan et al. (2017). Amplified public consciousness in environmental issues has led to rising concern on environmental implications of product design, manufacturing process and reutilisation of used and outdated products (Avikal 2016). Thus, the researchers are expected to concentrate more on the consideration of mixed and multi products to be disassembled in the future studies.

4.4 *Structure of parameters*

It was mentioned in the beginning that the disassembly process is more complex than assembly. Indeed, in a disassembly environment, a product is broken down into many parts and subassemblies whose qualities, quantities and reliabilities cannot be controlled which creates an uncertain environment (Bentaha et al. 2014d).

Uncertainty in a DLB problem may be included in task times, demand, cycle times and objective functions and other unforeseen events that may occur in disassembly operations. Therefore, taking into account the uncertain nature of parameters and developing appropriate non-deterministic models are the requirements to increase the practical implications of DLB. Stochastic and fuzzy approaches are used to handle uncertainty in DLB models. The distribution of deterministic and non-deterministic approaches is depicted in Figure 7. Despite the fact that there is a high level of uncertainty in DLB problems, only 28.9% studies consider non-deterministic models, indicating that there is a huge future research potential here.

The following uncertainty factors have been addressed among the DLB studies:

Task failures: Only two studies consider uncertainty within the task failures. While a heuristic method was proposed to probabilistically minimise the cost of defective parts in the presence of task failures by Güngör and Gupta (2001); Altekin and Akkan (2012) maximised the profit generated by a disassembly line considering the probability of the reassignment of the remaining tasks in the case of a task failure.

Table 3. Purpose of the reviewed studies.

Performance measures	Studies
Minimisation of the number of workstations	**Güngör and Gupta (1999a, 2001)**; Altekin, Kandiller, and Özdemirel (2003); Altekin, Kandiller, and Ozdemirel (2008); McGovern and Gupta (2003a, 2003b, 2004, 2005a, 2005b, 2005c, 2006a, 2006b, 2007a, 2007b, 2007c, 2015); McGovern, Gupta, and Kamarthi (2003); Ranky et al. (2003); Turowski, Morgan, and Tang (2005); Prakash and Tiwari (2005); Lambert (2007); Agrawal and Tiwari (2008); Ding et al. (2009, 2010b); **Koç, Sabuncuoğlu, and Erel (2009)**; Kalayci and Gupta (2011a, 2011b, 2013c, 2013d, 2013e, 2013f, 2014, 2015a, 2015b); Kalayci et al. (2011, 2016); Wang et al. (2011); Altekin and Akkan (2012); Avikal and Mishra (2012); Avikal et al. (2013b, 2013c, 2013a, 2014c, 2014a, 2016); Karadağ and Türkbey (2013); **Özceylan and Paksoy (2013, 2014a, 2014b, 2014c)**; Paksoy et al. (2013); Bentaha et al. (2013a, 2013b, 2013c, 2013d, 2013e, 2014c, 2014a, 2015a, 2015b); Liu, Chen, and Huang (2013); **Pehlivan, Özceylan, and Paksoy (2013)**; **Özceylan, Paksoy, and Bektaş (2014)**; Tuncel, Zeid, and Kamarthi (2014); Zhu, Zhang, and Hu (2014); **Habibi et al. (2014)**; **Igarashi, Yamada, and Inoue (2014); Igarashi et al. (2016)**; McGovern and Gupta (2015); **Hezer and Kara (2015)**; **Mete et al. (2016b)**; **Altekin (2016)**; Hao and Hasan (2016); Avikal (2016); Liu and Wang (2017); **Altekin (2017)**; **Habibi et al. (2017)**; Jia and Shuwei (2017); Ren et al. (2017, 2018); Xiao and Nie (2017); Xiao et al. (2017)
Minimisation of idle times	Güngör and Gupta (1999b, 2002); Güngör et al. (2000); Gupta and Güngör (2001); Tang, Zhou, and Caudill (2001); McGovern and Gupta (2003a, 2003b, 2004, 2005a, 2005b, 2005c, 2006a, 2006b, 2007a, 2007b, 2007c, 2015); McGovern, Gupta, and Kamarthi (2003); Prakash and Tiwari (2005); Tang and Zhou (2006); **Duta, Filip, and Henrioud (2007)**; Duta, Filip, and Caciula (2008); Lambert (2007); Agrawal and Tiwari (2008); Ding et al. (2009, 2010a, 2010b), Kalayci and Gupta (2011a, 2011b, 2013a, 2013b, 2013c, 2013d, 2013e, 2013f, 2014); Wang et al. (2011); Avikal and Mishra (2012); Karadağ and Türkbey (2013); Avikal et al. (2013c, 2013a, 2016); Liu, Chen, and Huang (2013); Tuncel, Zeid, and Kamarthi (2014); Zhu, Zhang, and Hu (2014); Kalayci et al. (2015b); Kalayci, Polat, and Gupta (2016); **Riggs, Battaïa, and Hu (2015)**; Hao and Hasan (2016); Avikal (2016); **Kannan et al. (2017);** Liu and Wang (2017); Jia and Shuwei (2017); Xiao and Nie (2017); Xiao et al. (2017); Ren et al. (2018)
Removing hazardous parts early	Güngör and Gupta (1999b, 2002); Güngör et al. (2000); Gupta and Güngör (2001); McGovern and Gupta (2003b, 2005a, 2005b, 2005c, 2006a, 2006b, 2007a, 2007b, 2007c, 2015); Kalayci and Gupta (2011a, 2011b, 2013d, 2013e, 2013f, 2013c, 2013b, 2013a, 2014); Kalayci et al. (2011, 2015a, 2015b, 2016); Avikal and Mishra (2012); Avikal, Jain, and Mishra (2013a); Avikal, Mishra, and Jain (2013b); Avikal et al. (2013c); Avikal, Mishra, and Jain (2014a); Avikal, Jain, and Mishra (2014b); Avikal et al. (2014c); Bentaha et al. (2013b, 2015a, 2015b); Tuncel, Zeid, and Kamarthi (2014); Zhu, Zhang, and Hu (2014); Liu and Wang (2017); Jia and Shuwei (2017); Xiao and Nie (2017); Xiao et al. (2017); Ren et al. (2018)
Removing highly demanded parts early	Güngör and Gupta (1999b, 2002); Güngör et al. (2000); Gupta and Güngör (2001); McGovern and Gupta (2003b, 2005a, 2005b, 2005c, 2006a, 2006b, 2007a, 2007b, 2007c, 2015); Ding et al. (2010b); Kalayci and Gupta (2011a, 2011b, 2013d, 2013e, 2013f, 2013c, 2013b, 2013a, 2014); Kalayci et al. (2011, 2015b, 2015a, 2016); Avikal and Mishra (2012); Avikal, Jain, and Mishra (2013a); Avikal, Mishra, and Jain (2013b); Avikal et al. (2013c); Avikal, Mishra, and Jain (2014a); Avikal, Jain, and Mishra (2014b); Avikal et al. (2014c); Tuncel, Zeid, and Kamarthi (2014); Zhu, Zhang, and Hu (2014); Liu and Wang (2017); Jia and Shuwei (2017); Xiao and Nie (2017); Ren et al. (2018)
Maximisation of the profit/revenue	**Altekin, Kandiller, and Özdemirel (2003);** Altekin, Kandiller, and Ozdemirel (2008); Altekin, Bayındır, and Gümüşkaya (**2016**); **Lambert and Gupta (2005a)**; Turowski, Morgan, and Tang (2005); Altekin and Akkan (2012); Avikal, Mishra, and Jain (2013b); Bentaha et al. (2013c, 2013b, 2013a, 2014a, 2014b, 2014e, 2015b); Liu, Chen, and Huang (2013); **Minca, Filipescu, and Voda (2014)**; **Kalaycılar, Azizoğlu, and Yeralan (2016)**; **Duta, Caciula, and Patic (2016)**; Ren et al. (2017)
Minimisation of the number of direction changes	Güngör and Gupta (1999b, 2002); Güngör et al. (2000); Gupta and Güngör (2001); McGovern and Gupta (2005b, 2005c, 2006a, 2006b, 2007a, 2007b, 2007c, 2015); Zhu, Zhang, and Hu (2014)
Minimisation of the labour/equipment cost	Ding et al. (2009, 2010a); Bentaha et al. (2013a, 2013c, 2013e, 2013d, 2014a, 2014b, 2014c, 2014e); Ren et al. (2017)

(*Continued*)

Table 3. (*Continued*)

Performance measures	Studies
Smoothing workload	McGovern and Gupta (2004, 2015); Ding et al. (2010a); Wang et al. (2011); Karadağ and Türkbey (2013); Paksoy et al. (2013); **Bentaha et al. (2014d)**; Kalayci et al. (2015b); Seidi and Saghari (2016); Zhang et al. (2017)
Maximisation of the line efficiency	Tang, Zhou, and Caudill (2001); Tang and Zhou (2006); Agrawal and Tiwari (2008); McGovern and Gupta (2015); Avikal et al. (2016); Avikal (2016)
Minimisation of the disassembly task cost	Altekin, Kandiller, and Özdemirel (2003); Altekin, Kandiller, and Ozdemirel (2008); Ding et al. (2010a); Altekin and Akkan (2012); Avikal et al. (2014c)
Minimisation of the cycle time	**Kekre et al. (2003)**; **Lambert and Gupta (2005b)**; Duta, Filip, and Caciula (2008); Paksoy et al. (2013)
Removing easily accessible parts early	Güngör and Gupta (1999b, 2001, 2002); Güngör et al. (2000)
Minimisation of inventory cost	Altekin, Kandiller, and Özdemirel (2003); **Kizilkaya and Gupta (2004, 2005)**
Minimisation of the number of resources	**Mete et al. (2016a)**
Minimisation of the effect of the defective parts	Güngör and Gupta (2001)
Removal of the parts with longer disassembly task times	Avikal et al. (2014c)

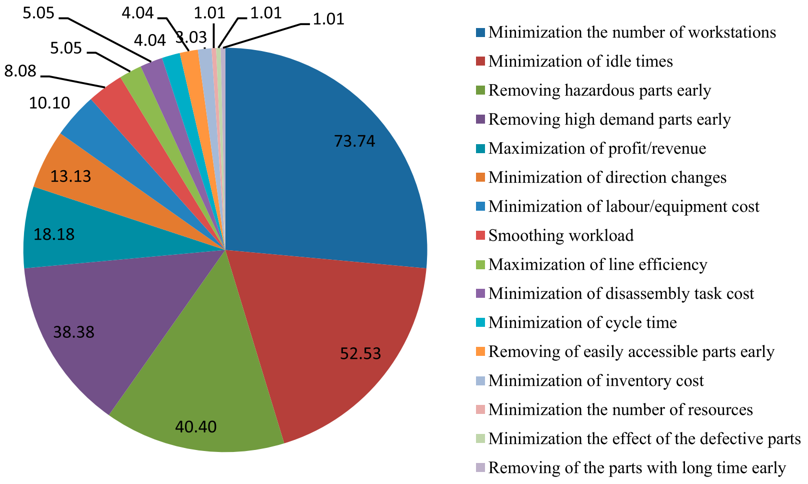

Figure 5. Distribution of objective functions of papers reviewed (%).

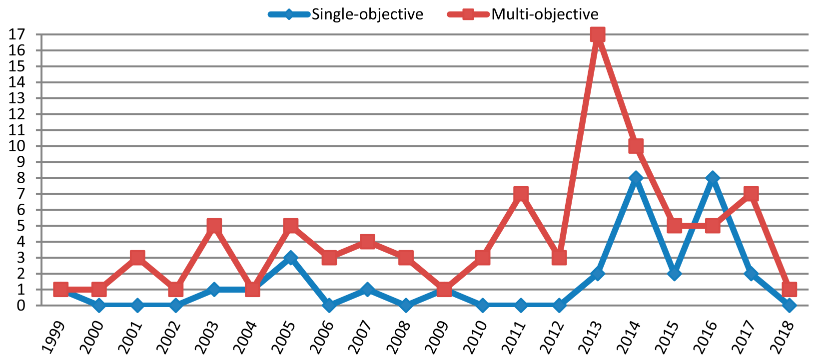

Figure 6. Spread of studies with single-objective and multi-objective models over the years.

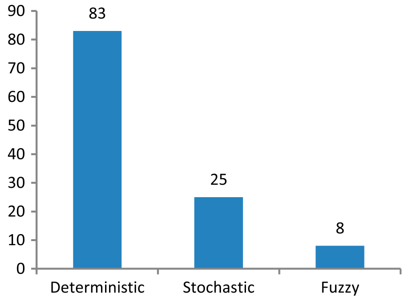

Figure 7. Number of studies presenting deterministic and non-deterministic approaches.

Workload in workstations: Uncertainty within the workload in workstations is considered by only Paksoy et al. (2013). They proposed a binary fuzzy goal programming approach for the DLB problem in order to take into account the vague aspirations of decision-makers on workload in workstations.

Number of workstations: As in the previous factor, Paksoy et al. (2013) and Özceylan and Paksoy (2014a) handled number of workstations as fuzzy in their objective functions.

End-of-life product condition: There is only one study proposed by Turowski, Morgan, and Tang (2005) that developed a fuzzy coloured Petri net model and a heuristic solution method to deal with end-of-life product condition.

Demand: In literature, demand is considered both fuzzy and stochastic. While Özceylan and Paksoy (2014a) took into account the demand as a triangular fuzzy membership function, Tuncel, Zeid, and Kamarthi (2014) used a Monte Carlo-based reinforcement learning technique to solve the DLB problem under demand variations of retrieved parts.

Task processing times: The disassembly task processing times are the most common uncertain parameter considered in DLB models. While Turowski, Morgan, and Tang (2005), Özceylan and Paksoy (2014c), Kalayci et al. (2015b), Seidi and Saghari (2016) and Zhang et al. (2017) assumed fuzzy task processing time; the disassembly task times are assumed to be independent random variables with known and normal probability distributions by Kekre et al. (2003), Ranky et al. (2003), Kizilkaya and Gupta (2004, 2005), Agrawal and Tiwari (2008), Karadağ and Türkbey (2013), Bentaha et al. (2013a, 2013b, 2013c, 2013d, 2013e, 2014a, 2014b, 2014c, 2014d, 2014e, 2015a, 2015b), Riggs, Battaïa, and Hu (2015), Altekin (2016), Altekin, Bayındır, and Gümüşkaya (2016) and Altekin (2017).

Cycle time: Only few studies dealing with the uncertainty of cycle times have appeared in the literature. Paksoy et al. (2013), Liu, Chen, and Huang (2013), Kalayci et al. (2015b), Seidi and Saghari (2016) and Zhang et al. (2017) tried to balance of disassembly lines with multi conflicting objectives under fuzzy cycle times.

A general summary of uncertainty issues in existing DLB studies is given in Table 4. As can be seen from Table 4, all factors except *task failures* are considered fuzzy, and the task processing time is the most frequently studied uncertain factor handled as stochastic.

4.5 *Disassembly levels and processes*

Unlike assembly, in disassembly, several parts and subassemblies can be demanded in different quantities, implying various disassembly depths or rates (Altekin, Kandiller, and Özdemirel 2003). Depending on the product recovery option executed and the technical and economic constraints of the product under consideration, disassembly may be complete

Table 4. Considered uncertain factors with their approaches.

Uncertainty within	Considered as fuzzy	Frequency	Considered as stochastic	Frequency	Total
Task processing time	✓	5	✓	22	27
Demand	✓	1	✓	1	2
End-of-life product conditions	✓	1	×	0	1
Cycle time	✓	5	×	0	5
Number of workstations	✓	2	×	0	2
Workload in workstations	✓	1	×	0	1
Task failures	×	0	✓	2	2

so as to fully disassemble the product or partial so as hindering full disassembly of the product (Altekin, Kandiller, and Ozdemirel 2008; Altekin and Akkan 2012).

Increasing the complexity of the problem with the addition of part and task selection under partial disassembly leads to more studies which consider complete disassembly. Out of 116 papers reviewed, 16 papers (14%) are related to partial disassembly. Partial disassembly in DLB is considered by Altekin, Kandiller, and Özdemirel (2003) for the first time. Then Altekin, Kandiller, and Ozdemirel (2008) formulate and solve the profit-oriented DLB problem under partial disassembly. They allow partial disassembly and simultaneously determine the disassembly level (which parts to release through which tasks), the number of stations and the cycle time along with the assignment of the tasks to the stations. Later on, partial disassembly is handled by Altekin and Akkan (2012), Bentaha et al. (2013b, 2013c, 2013a, 2014a, 2014b, 2014e, 2014d, 2015b), Habibi et al. (2014); Kalaycılar, Azizoğlu, and Yeralan (2016), Altekin, Bayındır, and Gümüşkaya (2016), Altekin (2017) and Ren et al. (2017). However, considering partial and complete disassembly simultaneously in DLB is still lacking.

Besides disassembly levels, there is another factor relating with disassembly processes namely non-destructive and destructive disassembly. Only two papers (Duta, Filip, and Caciula 2008; Igarashi, Yamada, and Inoue 2014) consider destructive disassembly. Non-destructive disassembly allows the separation of components from each other by keeping their original shape and integrity since they may be reused in remanufactured products or sold as refurbished parts. On the other hand, in the destructive disassembly, components lose their original identities and mostly aimed at the efficient material recovery.

4.6 *Considering complications*

Since a disassembly line is fraught with many complications, various considerations in a disassembly line setting are investigated in detail by Güngör, Gupta, Pochampally, and Kamarthi 2000, Güngör and Gupta (2001, 2002). According to Güngör and Gupta (2001), complications in DLB may be classified into six different categories: early leaving work-pieces, self-skipping work-pieces, skipping work-pieces, disappearing work-pieces, revisiting work-pieces and exploding work-pieces. Detailed list of considered complications is given in Table 5. As stated, considering hazardous work-pieces is the most popular complication in reviewed studies. Highly demanded work-piece is another frequently used complication, which forces to disassemble the highly demanded parts at the earliest workstations possible. As Table 5 demonstrates, 53.5% of papers include the issue of hazardous work-pieces and less than 36% deals with highly demanded work-pieces. Studies with stochastic task times also involve variability in disassembly task times. 13.1% of papers consider the direction changes required for disassembly. The complications of revisiting work-piece, quality of incoming products, early leaving work-pieces and resource requirement are considered only once. In other words, 28 papers (24.6%) consider the product flow on the disassembly line without any complications.

4.7 *Models and solution approaches*

In this section, different models and solution approaches used in DLB problem are evaluated and analysed in an integrated framework. Modelling approaches are classified in nine main categories including linear programming, non-linear programming, heuristics and metaheuristics, multi-criteria decision-making, stochastic programming, fuzzy programming, exact solutions, simulation and hybrid approaches. It is worth noting that these classes may have overlaps; for instance, a paper with mathematical programming approach can also be classified as a multi-criteria decision-making model. Figure 8 shows the distribution of different modelling approaches used in DLB problem. The heuristics and metaheuristics are the most applied approaches in DLB models. In spite of the fact that the real-world problems are often complicated and cannot be modelled by linear methods, 11.84% of papers propose linear models and only 5.92% of the published papers offer non-linear models for DLB problems. 9.21 and 2.63% of the total papers apply stochastic and fuzzy programming approaches, respectively. Figure 8 shows that only a few papers consider multi-criteria decision-making, exact solutions approaches, simulation and hybrid approaches.

The DLB problem seeks to find a feasible assignment of disassembly tasks to stations of a paced disassembly line under precedence relations, while optimising some measure of effectiveness. Güngör and Gupta (1999a) were the first researchers to define DLB problem and present a systematic approach-oriented heuristic solution procedure. Later on, Güngör and Gupta (2001) proposed a solution procedure using the shortest-path formulation adopted from the ALB problem such that the effect of the defective parts on the disassembly line is minimised.

Combinatorial optimisation techniques were first applied by McGovern and Gupta (2003a) on the DLB problem. They presented a greedy/2-opt hybrid algorithm for the multi-objective DLB problem to minimise the number of workstations while addressing hazardous and high demand parts. Although there have been several applications of heuristic

Table 5. Considered complications related with DLB.

Considered complications	Frequency	Studies
Hazardous work-pieces	55	Güngör and Gupta (1999a, 1999b, 2002); Güngör et al. (2000); Gupta and Güngör (2001); McGovern and Gupta (2003a, 2003b, 2005a, 2005b, 2005c, 2006a, 2006b, 2007a, 2007b, 2007c, 2015); McGovern, Gupta, and Kamarthi (2003); Kizilkaya and Gupta (2004, 2005); Lambert and Gupta (2005b); Wang et al. (2011); Avikal and Mishra (2012); Karadağ and Türkbey (2013); Avikal et al. (2013c, 2013b, 2013a, 2014b, 2014a, 2014c, 2016); Kalayci and Gupta (2011a, 2011b, 2013a, 2013b, 2013c, 2013d, 2013e, 2013f, 2014); Bentaha et al. (2013b, 2013a, 2014e, 2014b, 2014d, 2015a, 2015b); Tuncel, Zeid, and Kamarthi (2014); Zhu, Zhang, and Hu (2014); Kalayci et al. (2011, 2015a, 2015b, 2016); Hao and Hasan (2016); Avikal (2016); Liu and Wang (2017); Xiao and Nie (2017); Jia and Shuwei (2017); Xiao et al. (2017); Ren et al. (2018)
Highly demanded work-pieces	37	McGovern and Gupta (2003a, 2003b, 2005a, 2006a, 2006b, 2007b, 2015); Lambert and Gupta (2005b); Ding et al. (2009, 2010b); Wang et al. (2011); Avikal and Mishra (2012); Avikal et al. (2013c, 2013b, 2013a, 2014c, 2014b, 2014a, 2016); Kalayci and Gupta (2011a, 2011b, 2013a, 2013b, 2013c, 2013d, 2013e, 2013f, 2014); Zhu, Zhang, and Hu (2014); Tuncel, Zeid, and Kamarthi (2014); Kalayci et al. (2011, 2015b, 2015a, 2016); Avikal (2016); Liu and Wang (2017); Xiao and Nie (2017); Jia and Shuwei (2017); Ren et al. (2018)
Normal flow (No complication)	28	Tang, Zhou, and Caudill (2001);Ranky et al. (2003); McGovern and Gupta (2004); Lambert and Gupta (2005a); Tang and Zhou (2006); Duta, Filip, and Henrioud (2007); Lambert (2007); Altekin, Kandiller, and Ozdemirel (2008); Koç, Sabuncuoğlu, and Erel (2009); Ding et al. (2010a); Özceylan and Paksoy (2013, 2014a, 2014b, 2014c); Paksoy et al. (2013); Bentaha et al. (2013c); Liu, Chen, and Huang (2013); Pehlivan, Özceylan, and Paksoy (2013); Minca, Filipescu, and Voda (2014); Özceylan, Paksoy, and Bektaş (2014); Habibi et al. (2014); Hezer and Kara (2015); Kalaycılar, Azizoğlu, and Yeralan (2016); Mete et al. (2016a, 2016b); Igarashi et al. (2016); Kannan et al. (2017); Ilgin, Akçay, and Araz (2017); Habibi et al. (2017)
Variability of disassembly task times	19	Kekre et al. (2003); Kizilkaya and Gupta (2004); Turowski, Morgan, and Tang (2005); Agrawal and Tiwari (2008); Karadağ and Türkbey (2013); Bentaha et al. (2013e, 2013d, 2013b, 2013a, 2014b, 2014d, 2014e, 2014c, 2014a, 2015b); Riggs, Battaïa, and Hu (2015); Altekin (2016); Altekin, Bayındır, and Gümüşkaya (2016); Altekin (2017)
Disassembly direction changes	13	Güngör and Gupta (1999b, 2002); Güngör et al. (2000); Gupta and Güngör (2001); Kizilkaya and Gupta (2004); McGovern and Gupta (2005c, 2005b, 2006b, 2006a, 2007c, 2007b, 2007a); Zhu, Zhang, and Hu (2014)
Sequence depending	9	Kalayci and Gupta (2013a, 2013b, 2013c, 2013d, 2013e, 2013f); Kalayci, Polat, and Gupta (2015a, 2016); Jia and Shuwei (2017)
Skipping work-pieces	8	Güngör and Gupta (2001); Altekin, Kandiller, and Özdemirel (2003); McGovern, Gupta, and Kamarthi (2003); Kizilkaya and Gupta (2004); Bentaha et al. (2014d, 2014b, 2014a, 2014e)
Easily accessible work-pieces	3	Güngör and Gupta (1999b); Güngör et al. (2000); Gupta and Güngör (2001)
Quantity of parts in incoming products	3	Güngör and Gupta (2001); Kizilkaya and Gupta (2004); Tuncel, Zeid, and Kamarthi (2014)
Task failures	3	Güngör and Gupta (2001); Prakash and Tiwari (2005); Altekin and Akkan (2012)
Disappearing work-pieces	2	Kizilkaya and Gupta (2004); Igarashi, Yamada, and Inoue (2014)
Exploding or damaging work-pieces	2	Kizilkaya and Gupta (2004); Duta, Filip, and Caciula (2008)
Revisiting work-piece	1	Kizilkaya and Gupta (2004)
Quality of incoming products	1	Kizilkaya and Gupta (2004)
Early leaving work-pieces	1	Kizilkaya and Gupta (2004)
Resource requirement	1	Mete et al. (2016a)

approaches (Tang, Zhou, and Caudill 2001; Güngör and Gupta 2002; Lambert and Gupta 2005a; Tang and Zhou (2006); McGovern and Gupta 2007b) on DLB, the NP-completeness proof of the decision version of DLB was provided by McGovern and Gupta (2007a) and unary NP-completeness (i.e. NP-completeness in the strong sense) is shown by McGovern and Gupta (2007c). For this reason, there is still an increasing need to use metaheuristic techniques such as genetic algorithms (McGovern and Gupta 2007a; Kalayci and Gupta 2011a; Kalayci, Polat, and Gupta 2016; Seidi and

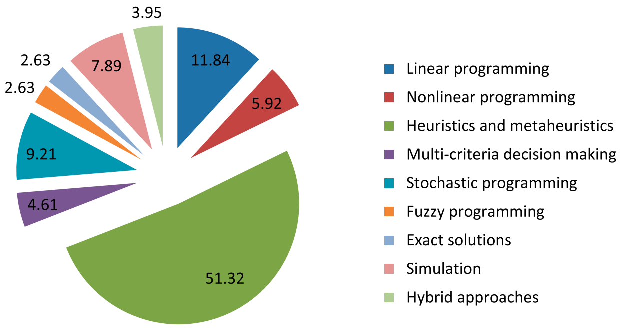

Figure 8. Distribution of models and solution approaches proposed in reviewed studies (%).

Saghari 2016), ant colony optimisation (Agrawal and Tiwari 2008; Ding et al. 2009; Zhu, Zhang, and Hu 2014), simulated annealing (Kalayci and Gupta 2013d, 2013f), tabu search (Kalayci and Gupta 2011b, 2014), particle swarm optimisation (Kalayci and Gupta 2013a; Xiao and Nie 2017; Xiao et al. 2017), immune algorithm (Wang et al. 2011), beam search (Mete et al. 2016b), gravitational search algorithm (Ren et al. 2017), river formation dynamics (Kalayci and Gupta 2013e), artificial bee colony (Kalayci and Gupta 2013c; Kalayci et al. 2015b; Liu and Wang 2017) and artificial fish swarm algorithm (Zhang et al. 2017). McGovern and Gupta (2006c) compare stochastic and deterministic methods using a recent electronic product disassembly case study. A recent book by McGovern and Gupta (2011a) describes and mathematically defines DLB by providing in-depth information illustrated by case studies with a focus on efficient combinatorial optimisation methodologies required to solve this complex problem.

In addition to aforementioned heuristic and metaheuristic algorithms, there have been some attempts to optimally solve DLB problem using mathematical programming techniques (Altekin, Kandiller, and Özdemirel 2003; Altekin, Kandiller, and Ozdemirel 2008; Koç, Sabuncuoğlu, and Erel 2009; Altekin and Akkan 2012; Paksoy et al. 2013; Igarashi, Yamada, and Inoue 2014; Mete et al. 2016a). However, they quickly become unsolvable for a practical-sized problem due to combinatorial nature of DLB problem.

The inclusion of uncertainty in the various models is achieved by fuzzy programming with stochastic programming. The stochastic version of DLB problem has been recently formulated using stochastic programming (Bentaha et al. 2013c, 2013d, 2014a, 2014b, 2014c, 2014e, 2015a, 2015b, Altekin 2017). On the other hand, fuzzy goal programming (Paksoy et al. 2013), interactive fuzzy programming (Özceylan and Paksoy 2014a, 2014b) and fuzzy-coloured Petri net (Turowski, Morgan, and Tang 2005) approaches are applied to DLB problem to characterise the impact of uncertain factors on disassembly. Simulation techniques (Kekre et al. 2003; Ranky et al. 2003; Kizilkaya and Gupta 2004, 2005) and Monte Carlo methods (Bentaha et al. 2013c, 2013d, 2014a, 2014b, 2014c, 2014e) are also very powerful methodologies to handle uncertainties in real situations. By means of rapid development in sensor technology, the condition monitoring of products has been significantly improved. In product disassembly, the sensors embedded in products enable the estimation of the conditions and remaining lives of components without the necessity of a testing operation after disassembling the components. Thus, maintenance and repair activities may be performed in a timely manner (Ilgin and Gupta (2010b)). Comparison of economic benefits of sensor-embedded products and conventional products in a multi-product disassembly line are provided by Ilgin and Gupta (2010b). Ilgin and Gupta (2011a) evaluates the impact of sensor-embedded products on the performance of an air conditioner disassembly line while recovery of sensor embedded washing machines using a multi-kanban-controlled disassembly line is discussed by Ilgin and Gupta (2011b) and Nakashima, Kojima, and Gupta (2012) demonstrates the effectiveness of utilising the multi-kanban mechanism in a disassembly line.

The DLB problem is considered as a multi-criteria decision-making problem (McGovern and Gupta 2011b) by some researches. PROMETHEE (Avikal et al. 2013c), AHP (Avikal, Mishra, and Jain 2013b) and TOPSIS (Avikal, Jain, and Mishra 2014b) are used for prioritising the tasks to be assigned. Exact solution approaches are used as complementary techniques to solve mathematical programming models, mainly dynamic programming (Koç, Sabuncuoğlu, and Erel 2009), integer programming (Koç, Sabuncuoğlu, and Erel 2009; Bentaha et al. 2014b, 2014d) and column generation (Duta, Caciula, and Patic 2016). Finally, the hybrid combinations of greedy algorithm with hill-climbing algorithm (McGovern and Gupta, 2004, 2005b, 2007c), greedy algorithm with 2-Opt algorithm (McGovern and Gupta 2005a, 2007c), local search procedure with genetic algorithm (Kalayci and Gupta 2011a), artificial bee colony with variable neighbourhood search (Kalayci et al. 2015b) and genetic algorithm with variable neighbourhood search (Kalayci, Polat, and Gupta 2016) are also considered as complementary modelling approaches for DLB problems. Detailed list of generated models and applied solution approaches is given in Table 6.

Table 6. Models and solution approaches to DLB problem.

Models and solution approaches	Studies
Linear Programming	Altekin, Kandiller, and Özdemirel (2003); Altekin, Kandiller, and Ozdemirel (2008); Altekin, Bayındır, and Gümüşkaya (2016); Lambert and Gupta (2005b); Koç, Sabuncuoğlu, and Erel (2009); Altekin and Akkan (2012); Paksoy et al. (2013); Bentaha et al. (2013b, 2015b); Habibi et al. (2014); Igarashi, Yamada, and Inoue (2014); Igarashi et al. (2016); Hezer and Kara (2015); Kalaycılar, Azizoğlu, and Yeralan (2016); Mete et al. (2016a, 2016b); Duta, Caciula, and Patic (2016); Altekin (2016); Ilgin, Akçay, and Araz (2017)
Non-linear programming	McGovern and Gupta (2003a); Duta, Filip, and Caciula (2008); Özceylan and Paksoy (2013, 2014a, 2014b, 2014c); Pehlivan, Özceylan, and Paksoy (2013); Özceylan, Paksoy, and Bektaş (2014); Bentaha et al. (2014d, 2015a, 2015b); Kannan et al. (2017)
Heuristic	Güngör and Gupta (1999a, 1999b, 2001, 2002); Güngör et al. (2000); Gupta and Güngör (2001); Tang, Zhou, and Caudill (2001); Lambert and Gupta (2005a, 2005b); Tang and Zhou (2006); McGovern and Gupta (2007b); Avikal and Mishra (2012); Avikal, Jain, and Mishra (2013a); Avikal, Mishra, and Jain (2013b); Avikal et al. (2013c); Avikal, Mishra, and Jain (2014a); Avikal et al. (2014c); Igarashi, Yamada, and Inoue (2014); Hao and Hasan (2016)
Genetic algorithm	McGovern, Gupta, and Kamarthi (2003); McGovern and Gupta (2004, 2005b, 2006b, 2007a, 2007c); Kalayci, Gupta, and Nakashima (2011); Karadağ and Türkbey (2013); Liu, Chen, and Huang (2013); Kalayci, Polat, and Gupta (2016); Seidi and Saghari (2016)
Greedy algorithm	McGovern and Gupta (2003a, 2003b, 2004, 2005a, 2005b, 2007c); Kizilkaya and Gupta (2005); Lambert (2007)
Ant colony optimisation	McGovern and Gupta (2004, 2005c, 2006a, 2006b, 2007c); Agrawal and Tiwari (2008); Ding et al. (2009); Kalayci and Gupta (2013b); Zhu, Zhang, and Hu (2014)
Hill climbing	McGovern and Gupta (2003a, 2003b, 2004, 2005b, 2005a, 2007c, 2015); Kizilkaya and Gupta (2005)
Simulated annealing	Kalayci and Gupta (2013d, 2013f)
Particle swarm optimisation	Kalayci and Gupta (2013a); Xiao et al. (2017)
Artificial bee colony	Kalayci et al. (2011, 2015b); Kalayci and Gupta (2013c); Liu and Wang (2017)
Artificial fish swarm algorithm	Zhang et al. (2017)
Reinforcement learning technique	Tuncel, Zeid, and Kamarthi (2014)
Tabu search	Kalayci and Gupta (2011b, 2014)
Immune algorithm	Wang et al. (2011)
Beam search	Mete et al. (2016b)
Psycho-clonal algorithm	Prakash and Tiwari (2005)
Gravitational search algorithm	Ren et al. (2017)
Variable neighbourhood search	Kalayci, Polat, and Gupta (2015a); Kalayci et al. (2015b); Kalayci, Polat, and Gupta (2016)
Network-based shortest route model	Hezer and Kara (2015)
Hunter-Killer heuristic	McGovern and Gupta (2005c)
River formation dynamics	Kalayci and Gupta (2013e)
2-opt algorithm	McGovern and Gupta (2003a, 2005a, 2007c); Kizilkaya and Gupta (2004, 2005); Ren et al. (2018)
Equal piles approach	Duta, Filip, and Henrioud (2007)
Computer Method of Sequencing Operations for Assembly Lines	Ranky et al. (2003)
Multi-criteria decision-making	Pehlivan, Özceylan, and Paksoy (2013); Avikal et al. (2013b, 2013c, 2014a, 2014b, 2016); Avikal (2016)
Stochastic programming	Bentaha et al. (2013a, 2013c, 2013b, 2013d, 2013e, 2014b, 2014e, 2014d, 2014a, 2014c, 2015a, 2015b); Riggs, Battaïa, and Hu (2015); Altekin (2016, 2017)
Linear physical programming	Ilgin, Akçay, and Araz (2017)
Fuzzy programming	Turowski, Morgan, and Tang (2005); Paksoy et al. (2013); Özceylan and Paksoy (2014b, 2014c); Kalayci et al. (2015b); Seidi and Saghari (2016); Zhang et al. (2017)
Exact Solution approaches	(Koç, Sabuncuoğlu, and Erel 2009); Bentaha et al. (2014b, 2014d); Duta, Caciula, and Patic (2016)
Simulation Approaches	Kekre et al. (2003); Ranky et al. (2003); Kizilkaya and Gupta (2004, 2005); Bentaha et al. (2013e, 2013d, 2014d, 2014b, 2014e, 2014c, 2014a); Minca, Filipescu, and Voda (2014); Tuncel, Zeid, and Kamarthi (2014)
Hybrid approaches	McGovern and Gupta (2004, 2005a, 2005b, 2007c); Kalayci and Gupta (2011a); Kalayci et al. (2015b, 2015a, 2016)

4.8 *Disassembled products*

Verification, validation, sensitivity analysis and the applicability proof of the proposed approaches need data that have the highest compatibility with the subject. In the literature, these data are gathered either from case studies or randomly generated by the aid of software in reasonable bounds. This section aims to investigate and evaluate the considered products to be disassembled existed in the literature. As shown in Figure 9, 65.79% of the reviewed papers include real products. Rest of them are based on benchmark test problems. Detailed analyses of disassembled products are illustrated in Figure 10.

Figure 10 shows that a majority of papers have focused on real cases rather than the benchmark test problems to evaluate proposed models. In the case study framework, phones and personal computers have taken the most attention in DLB studies. Sample products (e.g. proposed by Koç, Sabuncuoğlu, and Erel 2009) which do not exactly reflect the real products are also considered. While some researchers use electronic devices such as radio, flashlight, laptop, tape recorder and cleaner, some others consider automotive parts such as piston and connecting rod, gear and truck to evaluate their models. Table 7 presents the considered real products with their components, tasks and available data in literature.

In addition to real products, components and tasks details of sample products considered in studies under review are also given in Table 8. As can be seen from Table 8, while the number of components of sample products varies between 4 and 10 and the range of the number of tasks is between 7 and 23. It should be noted that although the number of components/tasks are the same in Hezer and Kara (2015), Minca, Filipescu, and Voda (2014), McGovern and Gupta (2003a), and Kizilkaya and Gupta (2004), sample products considered are different.

The majority of papers have focused on real products rather than the benchmark test problems to evaluate their approaches. The ones used for DLB problems are presented in Table 9. Each problem is represented by a code. The first two letters of the code comes from the first author's last name who defined the problem. Then the number of actual tasks and the number of demanded parts (or subassemblies) are written in the code. As can be seen from Table 9, the maximum number of total tasks and the maximum number parts/components are 49 and 33, respectively. To make these test problems more accessible, a website (library) can be developed.

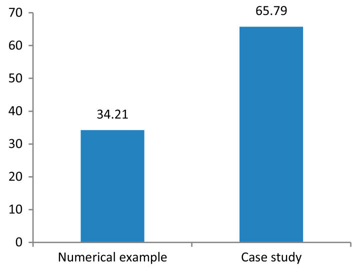

Figure 9. Distribution based on the use of case study and numerical example (%).

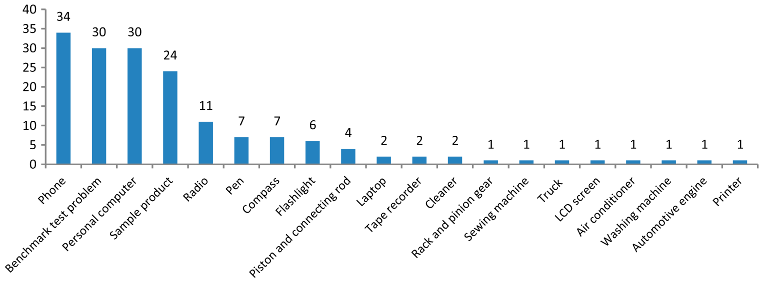

Figure 10. Number of product occurrences in the DLB literature.

Table 7. Considered real products in DLB problem literature.

Disassembled product	Number of components/tasks	Available data	Studies
Personal computer	8/8	Time, hazardous, demand, direction, revenue	Güngör and Gupta (1999b, 2002); Güngör et al. (2000); Gupta and Güngör (2001); McGovern and Gupta (2003a, 2003b, 2005a, 2006a, 2007a); Ranky et al. (2003); Prakash and Tiwari (2005); Wang et al. (2011); Avikal, Mishra, and Jain (2013b); Kalayci and Gupta (2013a, 2013b, 2013c, 2013d, 2013e, 2013f, 2014); Tuncel, Zeid, and Kamarthi (2014); Kalayci, Polat, and Gupta (2015a, 2016); Altekin, Bayındır, and Gümüşkaya (2016); Altekin (2017)
	11/11	Time, revenue, demand,	Tang, Zhou, and Caudill (2001); Tang and Zhou (2006)
	10/10	Time, hazardous, demand	Avikal, Mishra, and Jain (2014a); Avikal, Jain, and Mishra (2014b); Avikal et al. (2014c)
	14/14	Time, recycling rate, cost	Igarashi, Yamada, and Inoue (2014)
Phone	25/25	Time, hazardous, demand, direction	McGovern and Gupta (2005b, 2005c); Lambert and Gupta (2005a, 2005b); Turowski, Morgan, and Tang (2005); Lambert (2007); Duta, Filip, and Henrioud (2007); Duta, Filip, and Caciula (2008); Duta, Caciula, and Patic (2016); Ding et al. (2009, 2010b); Kalayci, Gupta, and Nakashima (2011); Kalayci and Gupta (2011a, 2013c, 2013d, 2013a, 2013e, 2013b, 2014, 2015a, 2015b, 2016); Bentaha et al. (2014c), Tuncel, Zeid, and Kamarthi (2014); Altekin (2016); Altekin, Bayındır, and Gümüşkaya (2016); Jia and Shuwei (2017); Liu and Wang (2017); Ren et al. (2017); Xiao and Nie (2017); Xiao et al. (2017)
	14/14	Time, demand	Liu, Chen, and Huang (2013)
	12/12	Material type, weight, recycling rate, CO_2 rate, cost, time	Igarashi, Yamada, and Inoue (2014); Ilgin, Akçay, and Araz (2017)
Radio	10/30	Time, revenue, cost	Duta, Filip, and Henrioud (2007); Altekin and Akkan (2012); Paksoy et al. (2013); Bentaha et al. (2013b, 2014e, 2014a, 2015b); Kalaycılar, Azizoğlu, and Yeralan (2016); Mete et al. (2016a, 2016b); Altekin, Bayındır, and Gümüşkaya (2016)
Pen	10/20	Time, revenue, cost	Bentaha et al. (2013b, 2014e, 2015b); Kalaycılar, Azizoğlu, and Yeralan (2016); Altekin, Bayındır, and Gümüşkaya (2016)
	6/6	Time	Riggs, Battaïa, and Hu (2015)
Compass	7/10	Time, demand	Bentaha et al. (2013e, 2013d, 2013b, 2014e, 2014c, 2015b); Habibi et al. (2014)
Flashlight	7/10	Time	Paksoy et al. (2013); Özceylan and Paksoy (2014b, 2014c); Özceylan, Paksoy, and Bektaş (2014); Bentaha, Battaïa, and Dolgui (2015a); Mete et al. (2016b)
Piston and connecting rod	16/25	Time, revenue, hazardous	Bentaha et al. (2013a, 2013b, 2014e, 2015b)
Laptop	47/47	Time, demand, hazardous	Kalayci et al. (2015b)
	13/13	Time	Riggs, Battaïa, and Hu (2015)
Tape recorder	18/18	Time	Duta, Filip, and Caciula (2008); Duta, Caciula, and Patic (2016)
Cleaner	23/23	Material type, weight, recycling rate, CO_2 rate, cost, time	Igarashi, Yamada, and Inoue (2014); Igarashi et al. (2016)
Rack and pinion gear	4/4	–	Kekre et al. (2003)
Sewing machine	52/52	Time, cost	Ding et al. (2010a)
Truck	37/37	Time	Hao and Hasan (2016)
LCD screen	16/16	Time, revenue, cost, recycling rate	Kannan et al. (2017)
Air conditioner	9/9	Time, volume, weight	Ilgin and Gupta (2011a)
Washing machine	3/3	Time, volume	Ilgin and Gupta (2011b)
Automotive engine	34/34	Time, demand	Seidi and Saghari (2016)
Printer	55/55	Time, cost, direction	Zhang et al. (2017)

Table 8. Sample products considered in the DLB problem literature.

Number of components/tasks	Studies
4/22	Altekin, Bayındır, and Gümüşkaya (2016)
5/22	Hezer and Kara (2015)
5/22	Minca, Filipescu, and Voda (2014)
7/7	Güngör and Gupta (1999a)
7/10	Bentaha et al. (2013c)
7/23	Koç, Sabuncuoğlu, and Erel (2009); Özceylan and Paksoy (2013); Bentaha et al. (2013b, 2014e, 2015b); Pehlivan, Özceylan, and Paksoy (2013); Özceylan and Paksoy (2014a); Mete et al. (2016a)
9/9	Güngör and Gupta (2001); Altekin, Kandiller, and Özdemirel (2003)
10/10	McGovern and Gupta (2003a, 2005c); Kizilkaya and Gupta (2005); Kalayci and Gupta (2011b); Avikal and Mishra (2012); Avikal, Jain, and Mishra (2013a); Avikal et al. (2013c); Ren et al. (2018)
10/10	Kizilkaya and Gupta (2004)

Table 9. Benchmark test problems for DLB.

Studies	Problem code	Actual tasks	Total tasks[a]	Total parts	AND Prec.	OR Prec.	OR Succ.
Güngör and Gupta (2002)	GU8T8P	8	10	8	10	2	0
Lambert (1999); Lambert and Gupta (2005b)	LA20T10P	20	25	10	5	8	5
	LA20T24P	20	25	24	5	8	5
	LA25T25P	25	27	25	45	0	0
	LA30T10P	30	49	10	16	11	10
	LA30T29P	30	49	29	16	11	10
Altekin, Kandiller, and Ozdemirel (2008)	AL8T6P	8	11	6	9	3	0
Altekin, Bayındır, and Gümüşkaya (2016)	AL20T4P-A	20	22	4	15	6	1
	AL20T4P-B	20	22	4	15	5	1
	AL20T4P-C	20	22	4	15	5	1
	AL30T12P	30	39	12	22	9	5
Koç, Sabuncuoğlu, and Erel (2009)	KO23T7P	23	36	7	4	14	5
Ma et al. (2011)	MA37T33P	37	22	33	4	27	6
Bentaha, Battaia, and Dolgui (2013a)	BE25T27P	25	11	27	4	18	3
Bentaha, Battaïa, and Dolgui (2013d)	BE10T12P	10	5	12	3	6	1

[a]Values in this column include dummy tasks.

5. Conclusions and directions for future research

This work presented a literature review on the disassembly line balancing (DLB) problem. Papers reviewed were classified based on nine aspects: line types, objectives, product types, structure of parameters, disassembly levels, disassembly process, complications, models and solution approaches and disassembled product. In order to analyse the current gaps in the literature regarding the DLB problem, this section discusses results of the review and provides some research directions for researchers.

The conclusions drawn from this work affirm that: (i) the vast majority of the studies have been targeted to balance the workstations on a straight line; (ii) the purpose of the vast majority of the models proposed is the minimisation of the total number of workstations and idle times and, to a lesser extent, the removal of hazardous parts early; (iii) the product type commonly preferred is the single product; (iv) deterministic models dominates the studies which use stochastic and fuzzy parameters and the task processing time is the most frequently used uncertain factor among others; (v) the most widely used disassembly level is complete disassembly, (vi) where the use of non-destructive disassembly processes stands out; (vii) considering hazardous work-pieces is the most popular complication, to a lesser extent, the removal of highly demanded parts are given priority; (viii) the most widely used modelling approaches are heuristics and metaheuristics, where the use of linear and stochastic programming to solve the approach stands out; and (ix) more proposed models validated by case studies than numerical examples. Most of the products which are disassembled are personal computers and cell phones.

According to findings above, the following research potentials are available in the literature: (i) There is a lack of two-sided DLB problems and combination of different layout types; (ii) absence of models that include sustainability issues (such as social responsibility/equity, green technology, labour rights, energy usage, lean philosophy and machine-to-machine systems) is strongly felt in DLB models; (iii) the researchers are expected to concentrate more on the consideration of mixed and multi products to be disassembled in the future; (iv) although there have been quite a few DLB models which include fuzziness and stochasticity, uncertainty in objective values, product conditions/complications, cycle time and task failures should be considered for future studies; (v) we have not identified any proposal that can simultaneously consider partial and complete disassembly in one model unless all components are demanded; (vi) since almost all existing DLB models assume that the disassembly tasks are non-destructive, DLB problem that includes destructive disassembly tasks should be studied; (vii) resource constraints, set-up times or feeding lines should be embedded in next DLB models; (viii) some solution techniques which are not applied to DLB problem previously, such as bacterial foraging, artificial neural network, branch-and-price-and-cut, multi-agent system, robust optimisation, matheuristic and simheuristic, may be used in future studies; (ix) real products with more than 50 parts or tasks such as white appliances may be valuable to increase the practical implications of the DLB research; (x) more opportunities and actual experiences with more automated/robotic disassembly processes need to be investigated and reported; (xi) integration and/or the hierarchical structure of the tactical (e.g. DLB problem) and operative planning levels (e.g. routing, truck loading, scheduling) in the production planning context; (xii) proposal of a collaborative planning structure which manages the information shared through the cloud computing (see the study by Papakostas et al. (2016) for assembly lines) and finally (xiii) simultaneous balancing of ALB and DLB problems should be discussed for future studies.

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