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Integrated workstation design and buffer allocation in disassembly systems for remanufacturing

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Abstract

Remanufacturing is recognized as one of the most profitable and environmentally conscious options of the circular economy. A remanufacturing process chain includes disassembly, cleaning, inspection, reconditioning and reassembly stages to recover the functionality and value of post-use products. However, the efficiency and profitability of remanufacturing are significantly affected by the variability of post-use product conditions. Consequently, the disassembly tasks times are highly uncertain, and this leads to a lack of robustness in disassembly lines designed without considering these challenges. This paper aims at finding the optimal disassembly line design under uncertainty of tasks times to support remanufacturing. A mathematical optimization model with the objective of profit maximization is proposed which jointly optimizes and determines (1) the sequence of components to be disassembled and the assignment of disassembly tasks to workstations and (2) the allocation of buffers in order to provide a disassembly line design which has the maximum profit and satisfies the desired cycle time. The benefits of the proposed model are validated within a real case study dedicated to the remanufacturing of mechatronic components in the automotive industry.

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Keywords: Remanufacturing under uncertainty; Workstation design; Buffer allocation; Automotive industry.

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1. Introduction, motivation and objectives

The concept of circular economy has been configured as a new economic paradigm, leading to the growth and wealth separated from the consumption of natural resources [1]. The backbone of this paradigm is the involvement of sustainability and social responsibility. Nevertheless, incorporating the concept of sustainability inside the circular economy requires some effective technological advancements. Remanufacturing is one of the main pillars of technology for the circular economy, especially in automotive industries. The remanufacturing process chain of a post-use product consists of disassembly, cleaning, inspection, reconditioning, reassembly and testing. The remanufacturing process contains high complexity, which is mainly due to the variability of post-use product conditions. This leads to the highly uncertain disassembly tasks times. Consequently, this uncertainty can significantly disturb performance and feasibility of remanufacturing, since disassembly is the prerequisite of other steps [3]. The second effect is the partial potential use of post-use products, which indicates all the components to be disassembled do not have an acceptable final value. Therefore, it is important to define the optimal sequence and level of disassembly. Disassembly process is mostly performed in a line configuration consisting of several manual workstations. The manual nature of disassembly process imposes higher cost and uncertainty on remanufacturing. The high level of uncertainty leads to interruptions inside the line. Hence, the disassembly line is required to be well designed to work efficiently. In the scientific literature, most of the works are related to the disassembly planning, which is defined as finding the best sequence of disassembly tasks and defining the depth of disassembly sequence. Several studies focused on finding the optimal disassembly sequence which leads to the maximum revenue by the consideration of uncertainty in End-of-Life (EOL) products [4,5]. Besides, some works are dedicated to the disassembly line balancing which defines the disassembly sequence and the assignment of tasks to workstations in order to achieve the desired cycle time and a balanced line under consideration of some sources of uncertainties [2,6,7]. In these methods, the desired cycle time of the line is investigated in each workstation by limiting the operation time of each workstation to be less than the desired cycle time. However, the inter-departure

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tain operation times of workstations. The uncertainty makes the efficiency of workstations variable. This variability imposes interruptions to workstations, such as blockage and starvation phenomena which affect the achievement of desired cycle time. Consequently, the achievement of the desired cycle time depends on the line configuration rather than on each workstation separately. Therefore, proper assignment of tasks to workstations and appropriate allocation of buffer capacities between workstations are the most probable solutions to compensate the line interruptions and in turn achieve the desired cycle time.

This paper develops a mathematical optimization model with the objective of profit maximization which jointly optimizes and determines (1) the sequence of components to be disassembled, and the assignment of disassembly tasks to workstations and (2) the allocation of buffers between workstations in order to provide a disassembly line design which has the maximum profit and satisfies the desired cycle time. Moreover, this paper provides a new method in order to properly evaluate the achievement of the desired cycle time by analyzing the inter-departure time of finished components from the line. The proposed method is applied to a real case study in the automotive remanufacturing sector to demonstrate its industrial application and the provided benefits.

2. Disassembly problem formulation

In this paper, we consider an asynchronous and serial disassembly line contains several manual workstations. It is assumed that uncertainties of workstations are due to variations of post-use products and the inherent nature of manual operations. Accordingly, disassembly task times are considered to be random variables. Uncertain task time has an independent normal distribution. Besides, uncertainties can impose amount of time to complete the tasks for workstations. These irregularities for a workstation can interrupt the operations of other workstations and impose blocking and starvation phenomena. In order to mitigate the effects of interruptions, the workstations are decoupled by buffers. Figure 1 shows the structure of the considered disassembly line. The joint disassembly tasks sequencing, depth of disassembly, the assignment of tasks to workstations and buffer capacities under uncertainty of tasks times, is formulated as follows. The objective is to design a disassembly line consisting of a sequence of workstations 'W', which are decoupled by 'B' buffers. The number of workstations cannot exceeds from 'WS'. The set of possible disassembled components 'N' is given, but it is possible to disassemble a set of components if complete disassembly is not profitable. The objective is to maximize the profit of the disassembly line, which is defined as the difference between the net revenue of recovered components ,'RC_i', from the post-use products and the line cost. The latter includes five categories of costs described as follows:

- DC_i: The cost of recycling or disposing un-reusable non-target component or subassembly 'i',
- FC: Fixed cost per operation time unit,
- FW: Fixed cost per opening a workstation,
- FB: Fixed unit cost of buffer 'b',
- FI: The cost of stocking a component in buffer 'b'.

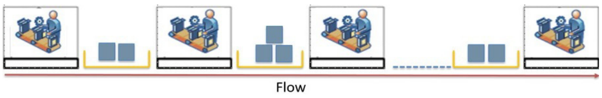

Fig. 1. Representation of workstations and buffers

The precedence relations among the components to be disassembled, 'P_{im}', are defined by precedence graph. If it is equal to 1, component 'm' is the predecessor of component 'i' in the sequence. Besides by this information a set of successors ,'S_i', for each component will be defined. Each sequence has 'K' positions for disassembled components.

Disassembly task time of a component, '$T_i(\zeta)$', has known mean and variance (μ_i, σ_i^2). The disassembly task of a component can be done with any, but just one workstation. In addition, we consider the sequence dependent repositioning time between the disassembly tasks of components (STT_{im}).

The workstation is blocked when it does not have space to pass the work and the workstation is starved when it does not have a work to process. It is considered that only limited number of buffers ,'N_b', can be allocated between each pair of workstations, and the first workstation is never starved and the last workstation is never blocked.

The disassembly line design guarantees the desired cycle time (CT). The cycle time is defined as the time between the successive finished works of the line.

3. Description of the disassembly line design procedure

In this section, the mathematical optimization model of the monolithic problem (integrated sequencing, assignment of tasks to workstations and buffer allocation) is presented.

3.1. Decision variables

To model the disassembly line design problem, the following decision variables are considered.

- x_{ikw}: Binary variable. It takes the value '1' if the component 'i' is disassembled in position 'k' of a sequence and assigned to station 'w', and '0' otherwise,
- z_i: Positive Integer variable. Position of component 'i' in a sequence,
- y_{im}: Binary variables. It takes the value '1' if the component 'i' is disassembled before component 'm' of a sequence, and '0' otherwise,
- q_{im}: Binary variable. It takes the value '1' if the component 'i' is just disassembled before component 'm' of a sequence, and '0' otherwise,
- a_w: Binary variable. It takes the value '1' if the workstation 'w' is occupied, and '0' otherwise,
- n_b: Positive Integer variable. It is the capacity of buffer 'b',
- $\bar{n}_b$: Positive real variables. It is the average inventory level of buffer 'b',
- IT: Positive real variables. Inter-departure time of the line, which is defined as the time between two successive components from the last workstation.

3.2. Objective function

The objective function (1) is the maximization of the total profit of the disassembly line by summing up the total revenue and minimizing the total cost.

$$\begin{aligned}&Maximize \quad R = \sum_{i=1}^{N}(RC_i - \mu_i * FC)\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w} - \sum_{i=1}^{N}(1- \\ &\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w}) * DC_i - FC * \sum_{i=1}^{N}\sum_{\substack{m=1 \\ i\neq m}}^{N} q_{i,m} * STT_{i,m} \\ &-FW * \sum_{w=1}^{W} a_w - \sum_{b=1}^{B}(FB * n_b + FI * \bar{n_b})\end{aligned} \tag{1}$$

3.3. Constraints

Constraint (2) ensures that component 'i' holds as a maximum one position in a sequence:

$$\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w} \leq 1 \qquad (\forall i = 1, ..., N) \tag{2}$$

Constraint (3) ensures that each position in a sequence only contains as a maximum one component:

$$\sum_{i=1}^{N}\sum_{w=1}^{W} x_{i,k,w} \leq 1 \qquad (\forall k = 1, ..., K) \tag{3}$$

Constraint (4) defines the position of component 'i' in a sequence path:

$$\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w} * k = z_i \qquad (\forall i = 1, ..., N) \tag{4}$$

Constraints (5) and (6) ensure the precedence constraints:

$$\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i',k,w} \leq \sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w} \qquad (\forall i', i = 1, ..., N, i' \in S_i) \tag{5}$$

$$\sum_{w=1}^{W} x_{i',u,w} \leq \sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w} \qquad (\forall i', i = 1, ..., N, i' \in S_i, \forall u = 1, ..., k) \tag{6}$$

Constraints (7) and (8) express the Miller-Tucker-Zemlin subtour elimination condition. These two constraints link the sequence of components with the variable which expresses the components connections:

$$z_i - z_m \leq N * (1 - y_{im}) \qquad (\forall i, m = 1, ..., N, i \neq m) \tag{7}$$

$$z_m - z_i \leq N * y_{im} \qquad (\forall i, m = 1, ..., N, i \neq m) \tag{8}$$

Constraint (9) represents that if component 'm' be disassembled after component 'i' in a sequence, it can be disassembled after it immediately:

$$q_{im} \leq y_{im} \qquad (\forall i, m = 1, ..., N, i = m) \tag{9}$$

Constraint (10) ensures that only the component 'i' which is disassembled immediately before the component 'm' is considered:

$$\sum_{i=1}^{N}\sum_{m=1}^{N} q_{im} - (\sum_{i=1}^{N}\sum_{k=1}^{K}\sum_{w=1}^{W} x_{ikw} - 1) = 0 \tag{10}$$

Constraint (11) assures that positions are assigned in an increasing order:

$$\sum_{i=1}^{N}\sum_{w=1}^{W} x_{i,k',w} \leq \sum_{i=1}^{N}\sum_{w=1}^{W} x_{i,k,w} \qquad (\forall k', k = 1, ..., K, k' \leq k) \tag{11}$$

Constraint (12) assures that stations are assigned in an increasing order:

$$\sum_{i=1}^{N}\sum_{k=1}^{K} x_{i,k,w'} \leq \sum_{i=1}^{N}\sum_{k=1}^{K} x_{i,k,w} \qquad (\forall w', w = 1, ..., W, w \leq w') \tag{12}$$

Constraint (13) defines that if workstation 'w' is occupied or not:

$$a_w \geq \sum_{i=1}^{N}\sum_{k=1}^{K} x_{i,k,w}/W \qquad (\forall w = 1, ..., W) \tag{13}$$

Constraint (14) defines the repositioning time calculation (TR_{imw}) between the components to be disassembled inside each workstation and between the last component to be disassembled in workstation 'w' and the first component to be disassembled in workstation 'w + 1':

$$\begin{aligned}&TR_{imw} = STT_{im} * (x_{ikw} + x_{mk'w'} - 1) \\ &(\forall i, m = 1, ..., N, i \neq m, \forall k = 1, ..., K, k' = k + 1, \\ &\forall w = 1, ..., W, w' = w \quad or \quad w' = w + 1)\end{aligned} \tag{14}$$

Constraint (15) assures that cycle time is respected in each workstation:

$$\sum_{i=1}^{N}\sum_{k=1}^{K} x_{ikw} * \mu_i + \sum_{i=1}^{N}\sum_{\substack{m=1 \\ m\neq i}}^{N} TR_{imw} \leq CT \qquad (\forall w = 1, ..., W) \tag{15}$$

Constraint (16) defines the maximum number of workstations:

$$\sum_{w=1}^{W} a_w \leq WS \tag{16}$$

Constraint (17) satisfies maximum buffer capacity:

$$n_b \leq N_b \tag{17}$$

The constraint (18) satisfies that the expected value of the inter-departure time between the successive finished works meets the cycle time:

$$E(IT) \leq CT \tag{18}$$

Since the disassembly times of components are considered to be random variables, the inter-departure time of finished works is a random variable.So, the expected value of the inter-departure time is considered.

3.4. Non-linear quantities of the model

The proposed model has two non-linear quantities. Equations (19) and (20) explain that the average inter-departure of the line and the average inventory level in each buffer are functions of disassembly sequencing, task assignments to workstations and allocation of buffer capacities.

$$E(IT) = f(x_{ikw}, T_i(\zeta), a_w, n_b) \tag{19}$$

$$\bar{n_b} = g(x_{ikw}, T_i(\zeta), a_w, n_b) \tag{20}$$

As a consequence, the monolithic problem cannot be solved by an MIP(Mixed Integer Programming) model.

4. Solution Methodology

The methodology entails a decomposition of the monolithic problem ((1)-(18)) into two sub-problems that can be iteratively solved in order to provide a good estimation of the optimal solution. The problem is decomposed into two sub-problems: 1) disassembly sequence of components and assignment of the disassembly tasks to several workstations, and 2) buffer allocation problem. Table 2 presents the mathematical optimization modeling of the two sub-problems. First sub-problem is optimized by an MIP model. For the second sub-problem, an analytic decomposition method based on Markovian chain models is used to evaluate the expected inter-departure time and average inventory level of the line. This method was developed for estimating the performance of generally unreliable transfer lines with finite capacity buffers where machines have predetermined failure modes [8]. In order to apply this method for our problem which contains reliable workstations, the completion time approach is utilized [9]. This approach incorporates failures and repairs into processing time of workstations. Accordingly, the distribution of disassembly time duration at each work station is approximated by ADPH(2) (Acyclic Discrete Phase Type distribution of second order), which perfectly describes the behavior of normal distribution with coefficient of variation higher than 0.5. From this assumption, a reliable work station can be modeled by an unreliable machine which has two down states and the repair processes of down states have discrete acyclic phase-type distribution. Therefore, the disassembly line with manual workstations is converted to a disassembly line with several unreliable machines. We use the decomposition method proposed in [10], which is appropriate for a line consists of machines with discrete acyclic phase-type distribution for repair processes of failure modes. By application of this method, expected value of the inter-departure time and average inventory level are achievable under consideration of various buffer capacities. Moreover, the optimization model of the second sub-problem is solved by the algorithm proposed in [11] to find the minimum buffer capacities between workstations that will guarantee the desired cycle time.

The two sub-problems should be solved in an integrated way, since the configuration of disassembly workstations from the first sub-problem may not meet the desired cycle time by the allocation of the available buffer capacities. This mismatching is derived from the fact that in the first sub-problem the average operation time of a workstation, 'μ_w'(sum of the mean time values of the assigned tasks and the repositioning time in workstation w), is constrained by the desired cycle time. Nevertheless, this constraint cannot guarantee the desired cycle time of the line for the following two reasons: 1) the disassembly task times are random variables, so the operation time of a workstation may exceed its mean time value; 2) the workstations are working jointly, so if the operation time of a workstation exceeds from its mean value, the other workstations will be affected in terms of being blocked or starved.

Moreover, the optimal solution from the first sub-problem can be feasible for the monolithic problem but it may not have the minimum buffer and inventory costs in comparison to the other feasible solutions. Therefore, an algorithm which iteratively solves the two sub-problems is required to achieve the solution that has minimum disassembly costs, meets the desired cycle time and leads to the minimum buffer and inventory costs.

Table 1. Mathematical optimization model of sub-problems

Sub-problem1	Sub-problem2
$Maximize\ Z1 =$ $\sum_{i=1}^{N}(RC_i - \mu_i * FC)\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w}$ $-\sum_{i=1}^{N}(1 - \sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w}) * DC_i$ $-FC * \sum_{i=1}^{N}\sum_{i\neq m\ m=1}^{N} q_{i,m} * STT_{i,m}$ $-FW * \sum_{w=1}^{W} a_w$	$Mainimize\ Z2 = \sum_{b=1}^{B}(FB * n_b + FI * \bar{n_b})$
subject to Constraints (2) to (16)	subject to Constraints (17) and (18)

4.1. Iterative algorithm

An iterative algorithm is developed to provide an optimal/near-optimal solution which proposes a disassembly line with higher profit. The proposed algorithm starts with solving the first sub-problem. In order to generate the feasible solutions, constraint (15) is substituted with constraint (21).

$$\sum_{i=1}^{N}\sum_{k=1}^{K} x_{ikw} * \mu_i + \sum_{i=1}^{N}\sum_{m=1}^{N}\sum_{m\neq i} TR_{imw} \leq (1-\alpha) * CT \qquad (21)$$
$$(\forall w = 1, ..., W, 0 \leq \alpha \leq 1)$$

By applying this constraint, the maximum allowed operation time in each workstation ($(1-\alpha) * CT$) can be reduced, which in turn limits the mean operation time of each workstation (μ_w) to be strictly less than 'CT'. Therefore, the probability to reach the desired cycle time will increase as 'μ_w' is reduced for each workstation. Figure 2 shows the iterative algorithm for joint optimization of the two sub-problems. The algorithm begins with solving the first sub-problem by considering '$\alpha = 0$'. Then, the value of 'α' increases until the optimal solution from the first sub-problem becomes a feasible configuration of workstations that can reach the desired cycle time in the second sub-problem. Afterwards, it is possible to reduce the buffer and inventory costs by modifying mean operation time of each workstation (μ_w). In other words, the sequence of components which are disassembled can be changed that leads to the different mean operation time of each workstation (μ_w). However, the change in the disassembly sequence of components should not impose the high disassembly repositioning cost. Also, by increasing the value of 'α', the number of workstations increases as well. Therefore, the increase in the value of 'α' is limited by the maximum number of workstations.

A sensitivity analysis is proposed to provide the value of 'μ_w' for each workstation, that will reduce significantly buffer and inventory costs under the consideration of not imposing high repositioning cost. It is started with the primal solution (W, α_1, $\mu_W(1)$, $Z2(1)$). The primal solution is obtained by the value of 'α'(α_1) that leads to a feasible configuration with 'W' workstations and with a set of mean operations times,'$\mu_W(1)$', in which the desired cycle time is achievable with the cost amount of '$Z2(1)$' in the second sub-problem. Then, starting from the first workstation, an iteration which increases the value of 'α_1' is performed ($\alpha_t \rightarrow \alpha_{t-1}+\epsilon$). In each iteration, the 'ϵ' value is added until the total number of workstations does not exceed from 'W'. To evaluate the value of objective function '$Z2$' un-

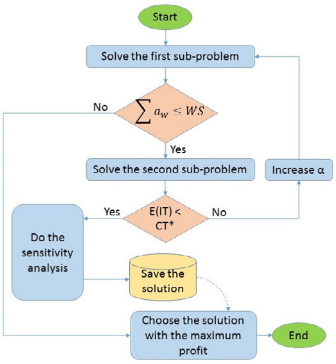

Fig. 2. Iterative algorithm

der various levels of 'α_t', $(\Delta Z2)/(\Delta\mu_w)$, is defined. This property describes the change in the objective function$(Z2_t - Z2(1))$ over the change in the mean operation time of a workstation $(\mu_w(t) - \mu_w(1))$. Among various values of 'α_t', the one which significantly reduces the value of '$Z2$' in comparison to the change in the value of 'μ_w' is the optimal value (α_{opt}). Then, the value of 'α' in constraint (21) is substituted with 'α_{opt}' for workstation 'w'. This procedure is implemented for several iterations with values of 'α_{opt}' instead of α_1 from the first step until the decrease in the '(1-α) $*$ CT' is not possible for any of workstations. Also, to evaluate other disassembly configurations with more number of workstations, the proposed algorithm will increase the first accepted 'α' in the primal solution to increase the number of workstations from 'W' to '$W+1$' and the sensitivity analysis is implemented again for new configurations. Finally, the best solution is chosen on the basis of maximum profit. The sensitivity analysis steps are as follows:
1) Accepted $\alpha \rightarrow \alpha_1$, $w \rightarrow 1$, $t \rightarrow 1$
2) $t \rightarrow t+1$
3) $\alpha_t \rightarrow \alpha_{t-1}+\epsilon$, $0 \leq \epsilon \leq 1$;
4) Solve the two sub-problems;
5) Calculate $(\Delta Z2)/(\Delta\mu_w)$, and return to step 2 until the increase in the value of α is not possible;
6) Choose the value of α_t that generates the largest value of $(\Delta Z2)/(\Delta\mu_w)$, and put this '$\alpha_t$ as α_{opt}. Then, update the value of α in constraint (21) with α_{opt} for workstation w;
7) $w \rightarrow w+1$, and return to step 2. if w is the last workstation, go to step 9;
8) Solve the two sub-problems with the updated values of α and save the solution. The updated $\alpha \rightarrow$ Accepted α;
9) Steps 1 to 8 are done for several iterations until the increase in α is not possible.

5. Validation of the solution methodology

In this section we evaluate the performance of the proposed solution methodology. Due to the division of the monolithic problem into sub-problems, some feasible solutions are neglected. Therefore, for validation of the obtained solution, Extensive Search Method (ESM) is developed. ESM generates all the feasible solutions and provides the optimal solution on the basis of the maximum profit value. It provides all the possible solutions by generating all the feasible sets of binary values for '$x_{i,k,w}$'. Consequently, all the possible disassembly workstation configurations will be achieved. Then, by applying all the combinations of buffer capacities for each configuration that leads to a accepted solution, the whole set of feasible disassembly lines are generated. We used ModeFrontier software to generate all the feasible disassembly lines that have the desired cycle time by the minimum allocation of buffer capacities. In order to show the accuracy and efficiency of our solution methodology, an experiment has been performed. This experiment is dedicated to the disassembly line design of a post-use product with 6 components. The desired cycle time is equal to 18 Time Unit (TU) and the buffer capacities are considered to be maximum 4 units. The disassembly task times (mean, variance) for each components are reported in (TU) as following: Task1 (6,36), Task2 (8,64), Task3 (9,81), Task4 (10,100), Task5 (12,144), Task6 (7,49). Table 2 provides solution of disassembly line designs from the proposed method in this paper (1) and the extensive search method (2). As it is presented, the number of iterations in terms of the number of evaluated disassembly lines to achieve the optimal solution is reduced significantly by the proposed method in this paper. On the other hand, the accuracy of the solution depends on the value of 'ϵ'. By choosing the small value of 'ϵ', the solution is more accurate but the number of iterations will increase.

Table 2. Solution validation by extensive search method

Method		Tasks assignment	Buffer allocation	Iteration
1	ϵ=0.1	ws1(T1,T6), ws2(T4) ,ws3(T3),ws4(T2) ,ws5(T5)	3-3-3-3	74
	ϵ=0.2	ws1(T1,T6), ws2(T3) ,ws3(T2),ws4(T4) ,ws5(T5)	3-3-4-3	41
2		ws1(T1,T6),ws2(T4) ,ws3(T3),ws4(T2) ,ws5(T5)	3-3-3-3	108

6. Application to a real remanufacturing industrial case

The proposed methodology has been implemented in the remanufacturing sector of automotive mechatronic products at Knorr-Bremse, the worlds leading manufacturer of braking systems for rail and commercial vehicles. In this research, the disassembly line design analysis is dedicated to the complex and critical mechatronic product, Electro-Pneumatic Module (EPM-2). A picture of the EPM-2 and its exploded view are shown in figure 3. To design a profitable disassembly line for this product, the case study was implemented by the two main phases. *Providing disassembly information*. A sample of 60 post-use EPMs has been analyzed through complete disassembly in the Mechatronics Demanufacturing Pilot Plant at ITIA-CNR, Milan. Then, a list of components with their estimated disassembly task times are reported in Table 3. In this table, the time unit (TU) duration is excluded for confidentiality reasons.

Disassembly line design. In the second phase, the method proposed in this paper has been utilized to jointly optimize the disassembly level, assignment of disassembly tasks to workstations and allocation of buffer capacities with the information provided from product analysis and company data base. The cost and revenue parameters are excluded due to confidentiality reasons. The maximum allowed number of workstations is equal to 5. The disposition times between tasks are between 0.5 and 1 TU. Buffer capacities could be allocated between any workstations under the respect of maximum available buffer capacities (4 units). Particularly, three disassembly line designs are compared. Design 1 is obtained by traditional disassembly line balancing method that are described in the introduction. Design 2 is acquired by solving the disassembly line design

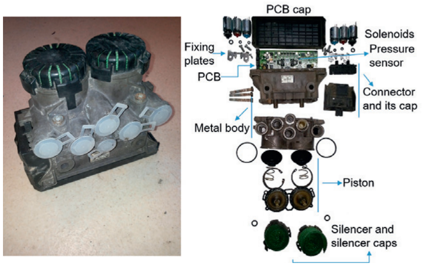

Fig. 3. EBS-5, EPM-2 (left) and its exploded view (right)

Table 3. Task description for the study case

ID	Disassembled component	Mean task time	Variance
1	PCB Cap	16.04	162.07
2	PCB	22.18	285.33
3	Pressure sensor	2.12	3.14
4	Fixing plate	10.96	84.08
5	Solenoid	9.84	77.45
6	Cap connector	2.5	5.62
7	Connector	1.64	1.61
8	Air filter	1	1
9	Connector cap	7.28	31.79
10	Silencer cap	2.13	2.72
11	Silencer	4.2	10.58
12	Upper part	32	921.60
13	Lower part	12	86.39
14	First stage piston	2.06	2.54
15	Sealing ring	2.07	2.78
16	Second stage piston	2.06	2.80

Table 4. Optimal line designs

Design	Workstation and Task assignment	Buffer allocation	Average inventory level	Profit
1	ws1(T1,T10,T6), ws2(T2), ws3(T4,T3,T5,T7)	/	/	Infeasible solution
2	ws1(T1),ws2(T2), ws3(T4,T3,T5), ws4(T10,T6,T7)	4-4-4	5.25	10.05
3	ws1(T1,T10),ws2(T2), ws3(T4,T3,T6,T7),ws4(T5)	3-3-3	2.94	12.75

problem in which the tasks are assigned to workstations and then the required buffer is allocated to achieve the desired cycle time. Design 3 is achieved by adopting the method proposed in this paper. The disassembly line designs, by consideration of the desired cycle time equal to 30 TU are reported in Table 4. Table 4 shows that the disassembly line achieved by the traditional method cannot provide the desired cycle time, so it is an infeasible solution. This infeasibility is due to neglecting the evaluation of the line configuration in order to achieve the desired cycle time. The disassembly line design 2 shows that if the iterative way of solving tasks assignment to workstations and buffer allocation is neglected (Design 2), 8 tasks are assigned to the 4 workstations with buffer and inventory levels equal to 12 and 5.25, respectively. On the other hand, if the proposed method in this paper is applied (Design 3), the optimal solution is a disassembly line with the assignment of 8 tasks to 4 workstations with buffer and inventory levels equal to 9 and 2.94, respectively. Besides, in Design 3 the disposition time is only 0.9 TU more than Design 2. The profit difference between Design 3 and Design 2 is 21.2 which is a significant amount. Knorr-Bremse has stated the following outcomes by the implementation of the proposed method for designing the disassembly line:

- The profit margin obtained by the disassembly process makes the remanufacturing alternative an economically attractive option for product recovery.
- The optimized disassembly sequence provides 30 % increase in the regeneration rate of disassembled components;

7. Discussion

The results in Table 4 shows that the achieved disassembly line by the proposed method provides a more efficient and a more profitable solution in comparison to the two other line designs. The priority of the proposed method in comparison to the two other methods is due to two main reasons. First, it evaluates properly the achievement of desired cycle time by introducing and analyzing the inter-departure time of the finished components. Second, it provides a mathematical optimization model in which the disassembly sequencing, workstation assignments, and buffer allocation are jointly optimized. In traditional line balancing methods, the achievement of the desired cycle time is evaluated by limiting the operation time of each workstation to be less than the desired cycle time. Nevertheless, due to the uncertainty of tasks times, limiting the operation times of the workstations by the desired cycle time will not necessarily lead to the achievement of the desired cycle time. As it is shown by Design 1, the obtained disassembly line design in infeasible. On the other hand, the disassembly line design 2 is a feasible solution but the provided profit is lower than the profit of design 3. This signifies the importance of the joint optimization of workstation assignments and buffers allocation. In other words, the line design 2 has the lower costs of disassembly sequencing but it requires a higher number of buffers to achieve the desired cycle time and due to the cost and revenue parameters, it arrives at the lower profit in comparison to design 3.

8. Conclusions and future research

In this paper, a new method to support a profitable disassembly line design of the post-use products has been proposed. The method has been successfully implemented on a real case study in the remanufacturing sector of Knorr-Bremse. Numerical results show that the proposed method can improve the profitability and efficiency of disassembly processes, which in turn supports remanufacturing. Future research will concern the consideration of various uncertainty resources inside the model for validation of the systems service level in order to increase resilience in remanufacturing systems. Moreover, the method can be extended to disassembly lines consist of manual, and semi-automatic tasks.

References

[1] McKinsey Center for Business and Environment (2015). Ellen Macarthur Foundation Growth Within: A Circular Economy Vision for a Competitive Europe.

[2] Colledani M, Battaïa O (2016). A decision support system to manage the quality of End-of-Life products in disassembly systems. CIRP Annals; 65: 41-4.

[3] Junior ML, Filho MG (2012).Production planning and control for remanufacturing: literature review and analysis. Production Planning and Control; 23: 419-35.

[4] Erdos G, Kis T, Xirouchakis P. Modelling and evaluating product end-of-life options (2001). International Journal of Production Research; 39: 1203-20.

[5] Tripathi M, Agrawal S, Pandey MK, Shankar R, Tiwaric MK (2009). Real world disassembly modeling and sequencing problem: Optimization by Algorithm of Self-Guided Ants (ASGA). Robotics and Computer-Integrated Manufacturing; 23: 483-96.

[6] Bentaha ML, Battaa O, Dolgui A (2014). Disassembly Line Balancing and Sequencing under Uncertainty. Procedia CIRP; 15: 239-44.

[7] McGovern SM, Gupta SM (2007). A balancing method and genetic algorithm for disassembly line balancing. European Journal of Operational Research; 179: 692708.

[8] Gershwin SB (1994). Manufacturing systems engineering. Englewood Cliffs: Prentice-Hall.

[9] Altiok T (1997). Performance Analysis of Manufacturing Systems. New York: Springer.

[10] Colledani M, Tolio T (2011). Performance evaluation of transfer lines with general repair times and multiple failure modes. Annals of Operations Research; 182: 31-65.

[11] Gershwin SB, Schor JE (2000). Efficient algorithms for buffer space allocation. Annals of Operations Research; 93: 111-144.