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A mathematical formulation for processing time computing in disassembly lines and its optimization

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Disassembly is the first practice in maintenance and recycling of industrial products. For productivity and efficiency, it is necessary to optimize its operative manners by reducing: change of tools and directions, process variation, wastes, etc. The simulation of Disassembly Plan (DP) allows the detection and identification of difficulties from the design stage in order to avoid them.

This paper proposes a mathematical formulation which combines two principal indicators: the index of Quality (Qi) and the index of processing Time (Ti) in order to choose the best and feasible disassembly plan. The Failure Mode, Effects and Criticality Analysis method is implemented to compute Qi. Ti is obtained according to real manufacturing constraints (workspace, layout, tools, machines, etc.). Based on 5S method, the workspace can be optimized which directly impacts the timing index and contribute to the selection of the best DP. A gear box is used to show up the efficiency of the proposed approach.

1. Introduction and literature review

Recycling as well as remanufacturing are significant from an economic perspective, protecting environment and conserving resources. In this field, when starting-up a new project, processing time (disassembly preparation and operation) is a main indicator that managers take in consideration to correctly assess the revenue. In all organization, industrial engineering team precisely evaluates disassembly operations and preparations time (manual or machinery operation) aiming to decrease it and avoid wastes in order to accomplish the efficiency goal. This assessment can be efficient if it is obtained using feasible disassembly plans generation (APG/DPG) and considered during the design phase. This paper proposes a mathematical formulation which combines two principal indicators: the index of Quality (Qi) and the index of processing Time (Ti), as criteria whereas choosing best and feasible disassembly plan. The Failure Mode, Effects and Criticality Analysis method (FMECA) is implemented to compute Qi. Ti is obtained according to real manufacturing constraints (workspace, layout, tools, machines, etc.). Based on 5S method, the workspace can be optimized which directly impacts the timing index and contribute to the selection of the best DP. The next section details a review on APG/DPG and its automation.

1.1. Review on APG / DPG and its automation

The first researches regarding APG/DPG problems are just theoretical and wholly disconnected to Computer Aided Design (CAD) systems. The integration of APG/DPG approaches in CAD tools begins by the earliest development on informatics technologies. A matrix representation of liaisons by using binary codes is used to generate APG/DPG. The proposed square matrix is manually created, (Dini & Santochi, 1991). Computer-aided techniques and methods were proposed to extract liaison matrix throughout Application Programming Interfaces (APIs) from CAD tools to perform APG/DPG (Gandouzi, Belhadj, Aifaoui & Hammadi, 2021; Aicha et al. 2021; Vigano & Gomez, 2012; Li et al., 2012). An AND/OR graph is developed to represent (Assembly Plans) APs. For complex mechanisms, the proposed method which is limited to traduce the AP only as a graph representation becomes complex and difficult to manipulate. For a mechanical product, a subset recognition method is developed using a set of matrices such as: the relationship matrix, the contact matrices and the anteriority matrices according to the three directions of the assembly. With this approach, the planner intervention is needed to generate feasible subsets (Dini & Santochi, 1992).

For the automobile field, a mathematical model to generate feasible

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APs is proposed (Zang, Ni, Lin & Lai, 2002). Since remanufactured parts should be already dismounted, disassembly is a significant step in the recovery of End of Life machines (EoL). DPG is a crucial step of the disassembly process focused on determining an optimal meticulous disassembly plan for eliminating specific parts or subsets from a mechanism (Lambert, 2002; Gungor & Gupta, 2001). Moreover, based on the total disassembly process, partial disassembly becomes an increasing focus of attention compared to previous research investigations (Rickli & Camelio, 2013; Smith, Hsu, & Smith, 2016). In the same context, based on a standard format which is the STEP format (STandard for the Exchange of Product model data), To produce feasible APs, a new integrated CAD method is developed based on the investigation of relationship matrices. The proposed approach needs the aid of the planner in some needed data (Su, 2007; Mathew & Rao, 2010). Design for disassembly (DFD) is a main methodology to create mechanisms easy for maintenance and reuse practices. The choice of connecting parts (screw, pin, rivet, etc.) used in a mechanism is one of the significant questions in DFD. Gungor, (2006) proposed a substitute connection elements based the high ability of the Analytic Network Process (ANP). The proposed method produces a whole ANP representation that integrates panoply of propositions for the selection of connector parts. The proposed ANP model assesses alternative connectors based on three major features: create a friendly product disassembly; create an efficient product assembly and rising the performance when the mechanism is exploited.

Afterward, researches in robotic disassembly began. Elsayed, Kongar, and Gupta (2010) proposed a methodology which uses a Genetic Algorithm (GA) for DPG of EoL mechanisms in disassembly processes based on robots. However, collaboration between robots and humans remains the main issue. ElSayed, Kongar, Gupta, and Sobh (2011), Elsayed et al. (2012) developed a smart automated disassembly unit for online selective disassembly. More recent researches done by Vongbunyong, Kara, and Pagnucco (2012, 2013, 2015) propose other accomplishments in robotic dismounting, mostly in the use of cognitive robotics and vision-based systems. The proposed smart method pays attention on the reduction of the fuzzy and the variation that exist in the dismounting procedure. According to the authors, the proposed approaches eliminate the necessity for human intervention to produce required information. According to Habibi, Battaia, Cung & Dolgui, (2017), concluding the round in the production lines is one of the obligatory constraints for best permanent development. The disassembly planning comes in the reversal level of the production lines. The main objective is to collect the tasks of EoL of machines. The disassembly process is necessary for powerful reuse and recovering of retained parts or subsets. The developed approach is based on iterative two steps using heuristic method to efficiently associate huge size occurrences. The numerical investigations demonstrate that the heuristic aspect gives high-quality results with satisfactory calculation time.

Parallel mounting and dismounting methods based on robot and human cooperation can raise the design quality by selecting the lower solution to wholly dismount the mechanism or to dismount wear parts (bearing, sealing gasket, etc.). The programming of these techniques in CAD systems can improve the today's industry efficiency by several aspects as: decrease product cost, reduce time to market and enhance the product quality. In this context Belhadj, Hammadi & Aifaoui, (2020, 2021) proposed an original method to dismount totally a complex mechanism with a parallel process. Collision matrices according to the three directions of the assembly are used to produce feasible Disassembly Plan (DP). Additionally, a set of evaluation indexes (design efficiency, recyclability, disassembly time and dismounting parallelism) are considered to enhance the design quality of the proposed solution. In a preventive maintenance context, a wear part priority criterion is added in an extended method to propose a new feasible and optimal DP. The part and subset's disassembly time considered in the proposed approach is inspired by industrial practices (Belhadj, Khemili, Trigui & Aifaoui, (2019). Wang, Mitrouchev, Li, & Lu, (2014) proposed a virtual environment for the disassembly operations evaluation through the

development cycle of products by predicting manufacture, maintenance and EoL. In the assessment procedure, various criteria are considered such as: parts and subsets stability, disassembly orientation, tool and direction change. Based on the stability of components during the assembly operations of heavy machines, Bedeoui BenHadj, Hammadi & Aifaoui, (2021) proposed an original method to produce feasible Assembly Plans (APs) using relationships between parts and subsets. Furthermore, to increase the value of the generated APs the number of the retained criteria is augmented. An extend approach based on three sub-routines is developed. The first sub-routine creates a list of APs. Based on an assembly tools (ATs) workspace criterion, the second sub-routine treats the obtained APs and retains the valid ones. The third sub-routine is used to minimize the change of ATs through.

The improvement of human and robot contribution in maintenance and product disassembly, that are important in EOL preparation and sustainability is necessary in today's industry. However, most maintenance and disassembly tasks are still carried out manually. Consequently, a concurrent architecture that integrates appropriate human issue and ergonomic environment is proposed by Siew, Chang, Ong & Nee, (2020). In the same context, Ramirez, Aledo, Gamez & Pham, (2020) developed a new method to implement a disassembly process based on robotic intervention for EoL of mechanisms. Moreover, the proposed algorithm helps the robotic unit to carry out the disassembly operations. Including two collaborative robots and a human worker Huang et al., (2021) proposed a disassembly unit based on collaborative robots. Human and robot can work securely in a common environment to execute disassembly operations which can be sequential or simultaneous.

1.2. Review on APG / DPG evaluation techniques

APG/DPG evaluation techniques are commonly used to validate the obtained results. Several modeling tools are used (Petri net, stochastic and probability approaches, etc.). Furthermore, quality tools are introduced to evaluate APG/DPG by anticipating production and workspace conditions at the early design stages.

Kuo, (2013) proposed a disassembly tree based on a Petri net which includes only one non-leaf output. It includes four main steps: identify the disassembly tree; determine the assembly rate, construct and evaluation the final disassembly tree. In this approach the planner intervention still significant, moreover, the feasibility of the generated DP is not guarantee. Tian et al., (2012, 2012) developed an assessment method for complete disassembly procedure of mechanisms with stochastic approach. According to the authors, the input data are manual and the disassembly operations are sequential.

To produce best and feasible DP, Belhaj, Hammadi, Trigui & Aifaoui, (2020) developed a methodology which evaluates the feature of the generated DPs. the Failure Mode, Effects and Criticality Analysis (FMECA) and Ishikawa method are implemented in the proposed model. This quality assessment has optimized the decision of the DP generation but still exist other enhancement parameters such as the processing time indicator. Later, Lean tools have been slightly introduced in the APG/DPG. Lean can be referred by many names: lean manufacturing, lean enterprise, lean production and lean office (Chiarini, Baccarani & Mascherpa, 2018).

2. Literature synthesis and positioning of the main novelties

The above-mentioned literatures can highlight the following points:

- The developed works on APG/DPG are based on mathematical foundations but not fully automated and integrated to CAD systems. A lot of research works remain to be done.
- For the APG/DPG, numerous parameters are considered as: gravity center, mass of part, execution tool, mounting/dismounting

trajectory, precedence constraints, time of disassembly/assembly time, etc.

- Quality assessment of APG/DPG not yet elaborated. Nevertheless, these tools are commonly used in multiple industries. The integration of Quality tools in the APG/DPG can engender indisputable benefits.
- MUDA (motion, transport...) associated to practical process execution, non-ergonomic workplace, bad equipment and non-optimal material distribution are not yet considered to evaluate APG/DPG. The integration of the real operating time, according to industrial practices, in the assessment of APG/DPG can produce optimal ones.

This paper develops the mathematical formulation of the practical operating time of DPG of mechatronic systems. The question that arises at this level is: "Why do the authors conduct the research around the operating time computing in production lines?". In fact, the above-mentioned literatures introduced theoretical disassembly time which does not include real conditions of the workspace. This paper breaks down disassembly time in depth according to industrial practices. The proposed model should put a focus on waste identification and additional motions that can be caused by bad working area and setting-up. These aspects can induce ergonomic problems, bad equipment's and material dispatching. Based on a real workspace, this approach evaluates the necessary operating time for every DP and generates the optimal one. Consequently, the proposed model can evaluate the list of generated DPs and contribute to the choosing of the optimal one.

The main novelty that this approach shows is focused on the evaluation of the previously generated DPs. This evaluation refers to the coupling of two parameters: T_i and Q_i . The Q_i is precisely presented in (Belhadj, Hammadi, Trigui & Aifaoui, 2020). On the other side, T_i is defined with reference to the computation of the real disassembly time which is done based on industrial practices and real working environment such as: layout, process setting-up, disassembly tools, pressure machine, etc. Based on the proposed approach, for every disassembly plan two metrics are assigned: T_i and Q_i . The disassembly plan that

corresponds to the lowest execution time (T_i) and to the highest quality index (Q_i) is selected as the best DP in terms of: real operating time, change of directions, use of tools, ergonomics. Additionally, and in order to have visual information which is more representative than numbers, a difference parameter (gap), mathematically represented by Δi , is introduced. The gap parameter represents the difference between T_i and Q_i . In target of optimal DP condition satisfactory aiming at minimizing T_i and maximizing Q_i , the Δi rate must be at its minimum value.

3. Proposed approach

The process flow of the main approach in this paper is represented in Fig. 1. The proposed approach follows four phases in sequence:

- (1) DPG phase: it defines the generated disassembly plans.
- (2) Real disassembly processing time calculation step: It consists on the estimation of the real disassembly time for each DP based on industrial practices. With a lean background, this step aims at evaluating the disassembly processing time by detecting wastes then eliminates them.
- (3) Quality evaluation step: it consists on the quality assessment of every disassembly plan with calculation of a quality index called Q_i (extracted from FMECA tool).
- (4) A gap parameter estimation step: It is calculated by the difference between T_i and Q_i and characterizes the main parameter in the proposed approach.

In target of highlighting the main steps of the proposed approach and proving the added value, an industrial case study is introduced in the following section.

3.1. Industrial case study and associated DPG

The industrial mechanism founded from the literature (Belhadj et al.,

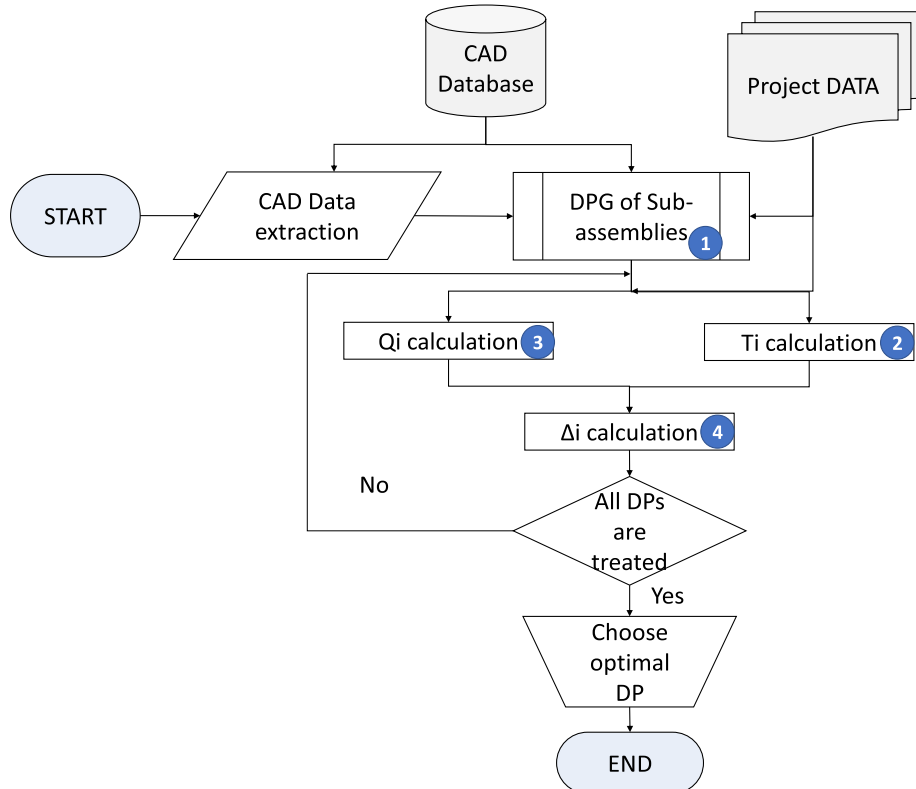


Fig. 1. Architecture of the proposed approach.

2019) is a 17 parts' gear box. Fig. 2 illustrates its exploded view and its decomposition into six subsets.

The DPG process (its flowchart is represented in Fig. 3) starts with the instant delete of all parts of connection (CPs). This approach is based on two principal steps. First of all, the subsets (a subset is a previously defined as part/group of parts) disassembly plans generation. Secondly, the DPs are regenerated in details by recalling connecting parts which were previously eliminated. The DP procedure begins by uploading the interferences matrices following k axis which can be x, y or z axis [IMsubk]. From [IMsubk] each line or column null allows to initiate a DP by dismounting the corresponding subset (SUB). Once a SUBi is disassembled, the corresponding column and line are deleted from [IMsubk] and a new matrix (size n-1) is generated. This loop process keeps, continuously, running until all SUBs are disassembled. Concerning the treated mechanism, Fig. 2 shows a summary of the 32 feasible disassembly plans generated from the DPG procedure.

3.2. Real disassembly processing time calculation of DPG

In industrial organizations, management team puts their main focus on balancing between cost, quality and time while treating business. This way of thinking is particularly extracted from iron triangle, called also project management triangle. In order to evaluate the disassembly processing time, a deep analysis and anticipation of the workplace elements is elaborated, such as: layout, process setting-up, accessibility,

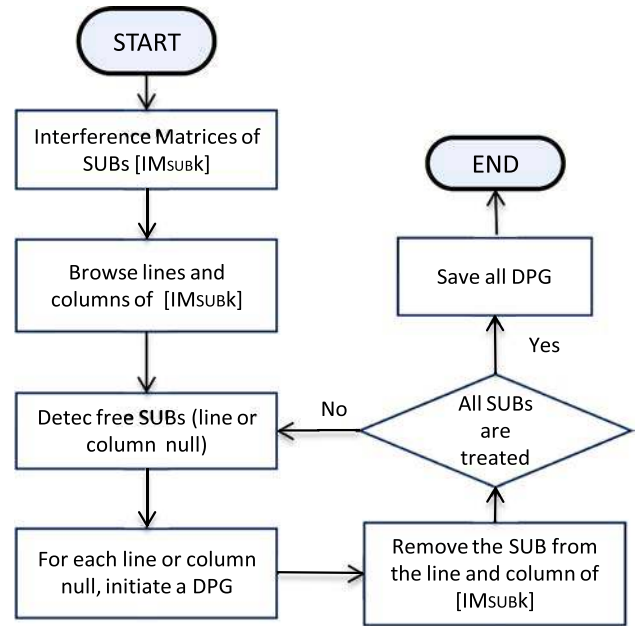


Fig. 3. Architecture of the DPG process.

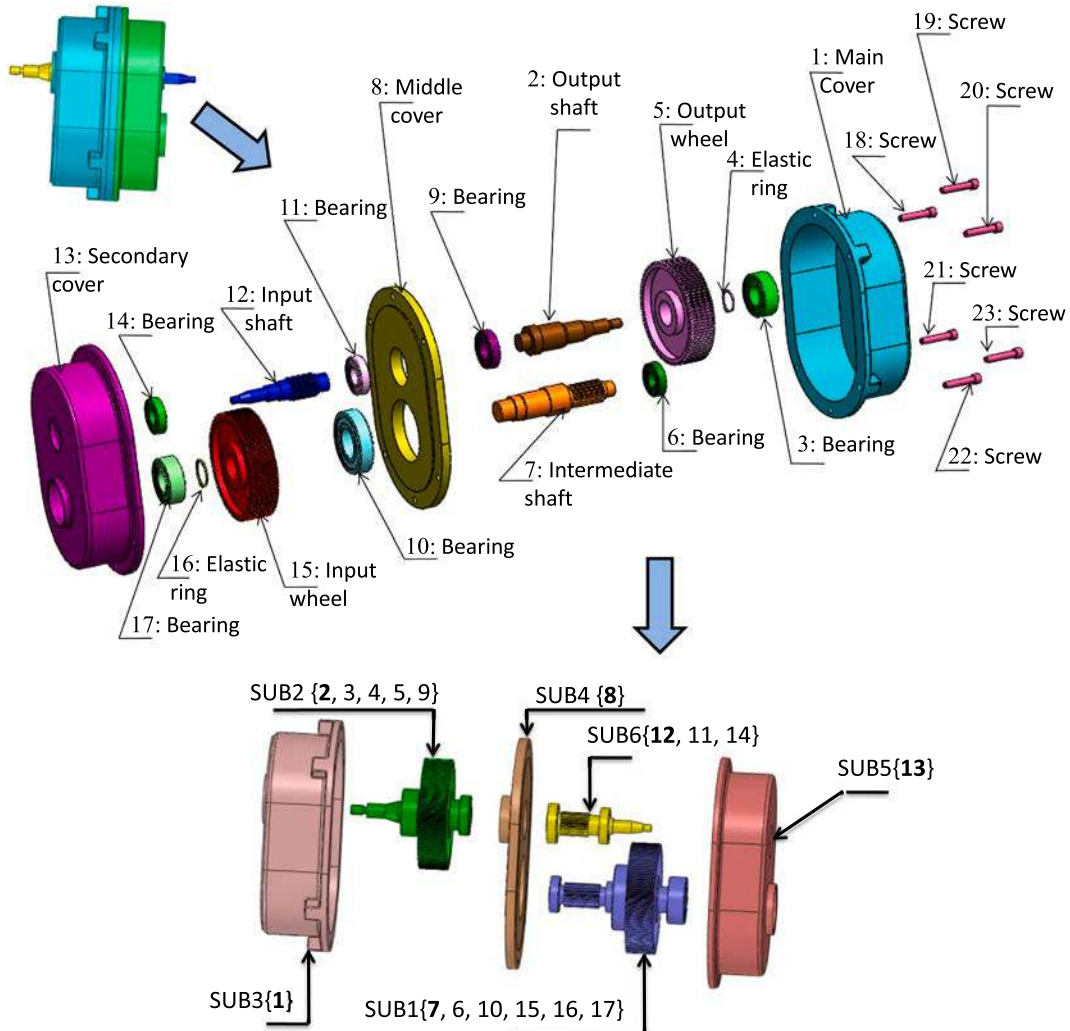


Fig. 2. Exploded view and subsets decomposition of the case study.

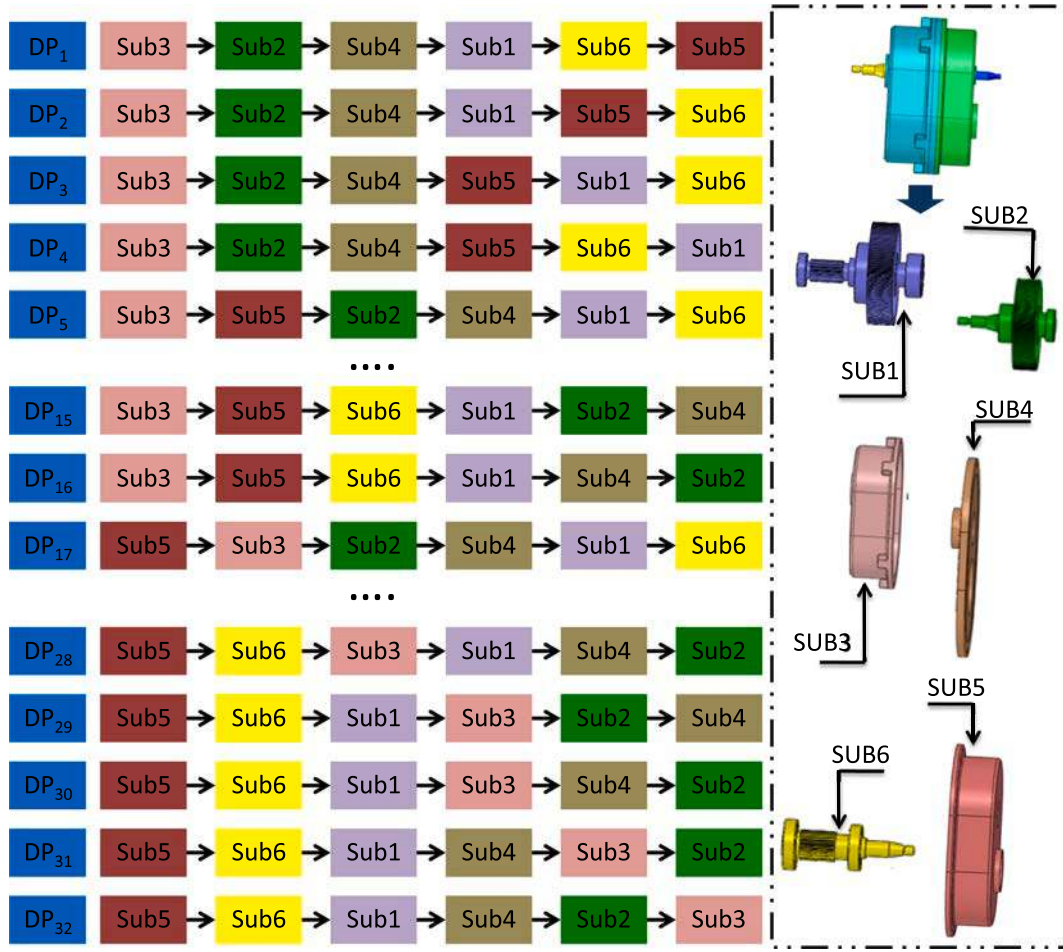


Fig. 4. List of DPs of the case study.

ergonomics, etc.

Operations inside production site can be classified into three categories:

- Tasks with essential added value: necessary for product manufacturing.
- Non-added value tasks but necessary: these tasks are inefficient, but cannot be removed.
- MUDA (waste): operations without added value and must be eliminated.

Wastes reduction or totally driving them out (by integration of lean tools) if possible, is one of the main objectives that organization aims to reach. This is in order to ameliorate efficiency and improve quality of output. In order to evaluate the disassembly time of the treated mechanism, it is necessary to define the elementary operational time that composes the process. In this approach, the DP is composed of multiple subsets' or component's disassembly operations. The real operating time of DPi (the treated example has generated 32 DPs) is given by formula (1):

$$T_{DP(i)}^{Real} = \sum_{j=1}^n [T_{prep(j)} + T_{D-sub(j)}] \quad (1)$$

where

$T_{DP(i)}^{Real}$: The global real time of disassembly plan "i".

$T_{prep(j)}$: The total preparation time of the subset "j".

$T_{D-sub(j)}$: The disassembly time of subset "j".

n : Number of Subsets in the assembly.

a. **Disassembly time of subset** : $T_{D-sub(j)}$

The disassembly time of the subset "j" $T_{D-sub(j)}$ is expressed by equation (2):

$$T_{D-sub(j)} = \sum_{k=1}^p T_{D-part(k)} \quad (2)$$

where

$T_{D-part(k)}$: Disassembly time of part "k".

p: Amount of parts per Subset.

Table 1 summarizes the disassembly time of each subset for the treated mechanism. It is noticed that these elementary disassembly times are obtained by timing in a gearbox overhaul manufacturing company which is based in Tunisia.

b. **Preparation time definition**: $T_{prep(j)}$

It is indisputable that simulating a process (assembly, disassembly, manual, machinery, etc) in the real production site shows some unexpected parameters and difficulties. Based on these anomalies, starts the process improvement and optimization until it becomes stable and efficient. The operator's workspace and its workflow is one of the most critical parameters that can influence tasks execution. It can be in multiple cases the root cause behind the existence of some preparations before exercising principal operations. The layout of the workplace of the treated mechanism disassembly process is shown in Fig. 5. The

Table 1

Detailed disassembly time of each subset.

	Dismounting and removing operation	Tool (M: manual; Pm: Press-machine; Er: Elastic-ring tool; Sd: Screwdriver	Elementary dismounting time (s)	Total dismounting time (s)		
Sub1	(7)	M	15	200		
	(6)	Pm	45			
	(10)	Pm	45			
	(15)	M	35			
	(16)	Er	15			
	(17)	Pm	45			
Sub2	(2)	M	15	155		
	(3)	Pm	45			
	(4)	Er	15			
	(5)	M	35			
	(9)	Pm	45			
Sub3	(18)	Sd	16.5	0	(3)→	(5)→
	(19)	Sd	16.5	0	(5)	(3)
	(20)	Sd	16.5	0		
	(21)	Sd	16.5	0	109	10
	(22)	Sd	16.5	0		
	(23)	Sd	16.5	0		
—	(1)	M	10	10		
Sub4	(8)	M	20		20	
Sub5	(18)	Sd	0	16.5	(5)→	(3)→
	(19)	Sd	0	16.5	(3)	(5)
	(20)	Sd	0	16.5		
	(21)	Sd	0	16.5	109	10
	(22)	Sd	0	16.5		
	(23)	Sd	0	16.5		
	(13)	M	10	10		
Sub6	(12)	M	15		105	
	(11)	Pm	45			
	(14)	Pm	45			

Ishikawa plan exposed in Fig. 6 is employed to detail the impact of the layout on the disassembly execution. During simulations, and according to the working area layout presented in Fig. 5, machinist is required to do various operations (handling, transportation, motion, etc.) in order to be ready for the effective disassembly tasks. Spaghetti diagram is an efficient tool which allows the visualization of physical and informational flows in a workplace. In order to observe the workflow execution, Fig. 5 shows the Spaghetti diagram for the disassembly plan number 1

(Fig. 4).

Operations (preparations) that precede effective disassembly tasks depend on many parameters such as: selection of right tool, transport, motion, manipulation, etc. the needed preparation operations for the disassembly of the treated gear box are shortlisted in Table 2.

Consequently, the total preparation time of a subset (j) is given by formula (3):

$$T_{\text{prep}(j)} = \sum_{k=1}^m T_{e(k)} \quad (3)$$

where

$T_{e(k)}$: The timing of the execution task (k) for the subset (j).

m: The number of execution tasks associated to the subset (j).

c. **Application of the real processing timing calculation on each DP of the case study**

According to the disassembly time of each subset provided by Table 1 and all standard preparations given by Table 2, the real processing time can be calculated according to formula (1). Fig. 7 shows the real processing time calculation process for the DP₁ of the treated case study.

To observe the discrepancy of the real processing time between DPs, an indicator Ti was introduced for $T_{\text{DP}(i)}^{\text{Real}}$ of each DPi and listed in Table 3. Without dimension, Ti index is defined by formula (4). It is noticed that the coefficient 5 in the formula (4) is a scale coefficient allowing the different values of Ti to be in the interval [0,5].

For the treated gear box, Fig. 8 presents the (Ti) of each DP of the 32 generated ones. It is noticed that DP₁ has the lowest T_i (T₁ = 4.26) and DP₁₆ comes in the second position with a T₁₆ = 4.38. Using the Ti criterion, DP₁ and DP₁₆ belong to the customer satisfaction zone.

$$T_i = \frac{T_{\text{DP}(i)}^{\text{Real}} \times 5}{\max_{i:1 \rightarrow 32} (T_{\text{DP}(i)}^{\text{Real}})} \quad (4)$$

3.3. **Optimization of disassembly processing time: Reduction of preparation time**

In order to reduce the preparation time before the disassembly process, Lean tools have been used to optimize to workplace setting-up. 5S method is used to organize tools and standardize workplace. Spaghetti

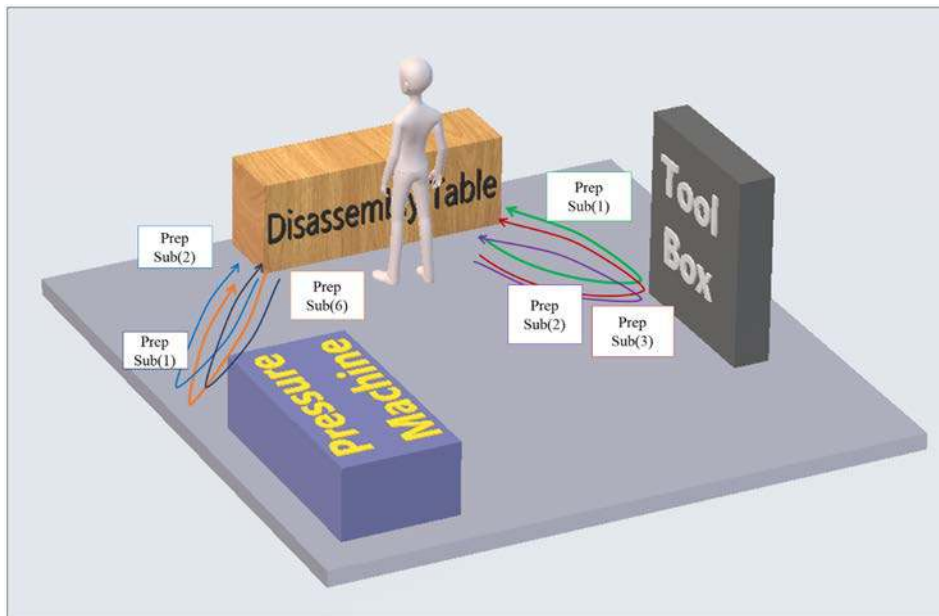


Fig. 5. Workplace with the associated Spaghetti diagram applied to DP₁ of the case study.

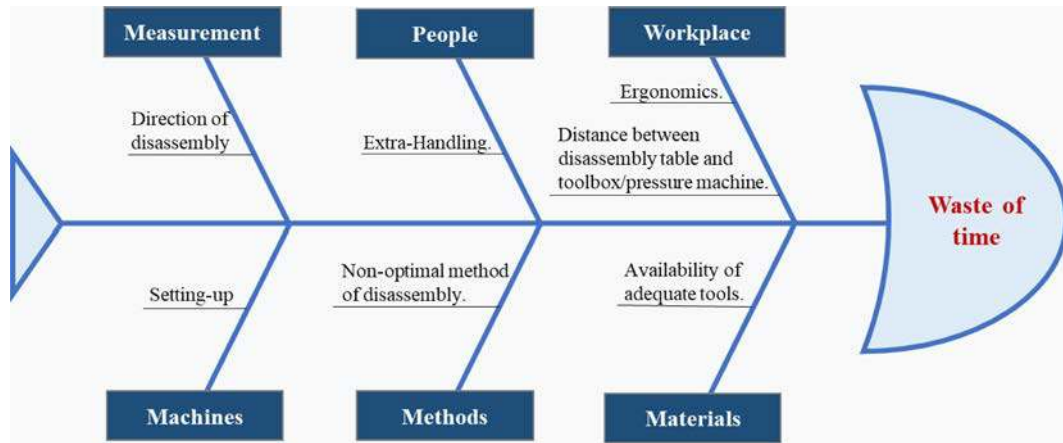


Fig. 6. Ishikawa diagram.

Table 2
Standard operations and preparation types.

Operation	Acronym			Preparation Type	Processing time (seconds)		
rotate the mechanism to the required direction	0°	90°	180°	Direction	0° → 0	90° → 15	180° → 30
identify the screw type	S			Tool	4		
identify the elastic-ring type	E			Tool	5		
transport the subset to the pressure machine	P			Motion	27		
transport the required tool from the tool box	T			Motion	13		
Handle and manipulate	H-L	H-M	H-H	Handle	low (H-L) → 4	medium (H-M) → 7	high (H-H) → 11

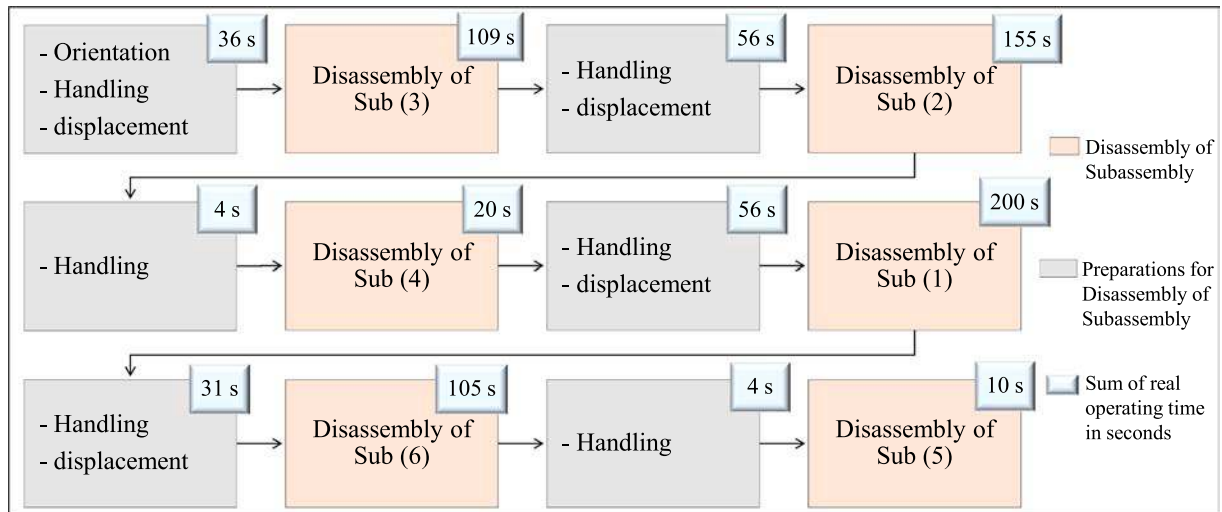


Fig. 7. Real processing time calculation for DP₁ of treated case study.

Diagram and MUDA chasing are used to transform lay-out and reduce wastes. The optimized workplace layout and its spaghetti diagram are represented in Fig. 9.

The optimized workspace is elaborated using the KAIZEN card which is a Japanese word. KAIZEN means “change to the better”, it represents one of the powerful lean manufacturing tools and refers to continuous improvement in performance cost and quality. For the treated case, the KAIZEN card is represented in Fig. 10.

After optimization of the workplace, preparation time is reduced. The real processing time and the timing index Ti are recalculated for each DP. For the gear box, Fig. 11 represents the evolution of Ti for the 32 DP before and after the optimization of the working area.

3.4. Quality index formulation

The quality assessment procedure is based on the generated DPs. The principle of this procedure is to estimate the dismounting complexity of each DP by calculating the index of quality (Qi) for each DPi. The Qi is computed after evaluating the Qik of every Disassembly Operation (DOK) which composes the DPi. Given by formula (5), DOK is a list of connecting parts (CP), a disassembly tool (T) and a disassembly direction (D).

$$DOK = \{CP, T, D\} \quad (5)$$

The produced DPs should be classified using the Qi metric and, for the real execution, the planner can select the best DP which has the highest Qi. To calculate the Qi, the FMECA method is used and executed

Table 3
DPs timing index for the gear box.

DP _i	$T_{DP(i)}^{Real}$	Ti	DP _i	$T_{DP(i)}^{Real}$	Ti
DP ₁	786	4.26	DP ₁₇	849	4.60
DP ₂	823	4.46	DP ₁₈	845	4.58
DP ₃	835	4.52	DP ₁₉	917	4.97
DP ₄	812	4.40	DP ₂₀	890	4.82
DP ₅	842	4.56	DP ₂₁	869	4.71
DP ₆	838	4.54	DP ₂₂	890	4.82
DP ₇	849	4.60	DP ₂₃	905	4.90
DP ₈	845	4.58	DP ₂₄	875	4.74
DP ₉	849	4.60	DP ₂₅	890	4.82
DP ₁₀	849	4.60	DP ₂₆	863	4.67
DP ₁₁	865	4.69	DP ₂₇	923	5.00
DP ₁₂	902	4.89	DP ₂₈	893	4.84
DP ₁₃	834	4.52	DP ₂₉	852	4.62
DP ₁₄	861	4.66	DP ₃₀	878	4.76
DP ₁₅	849	4.60	DP ₃₁	860	4.66
DP ₁₆	809	4.38	DP ₃₂	826	4.47

by a working team. In the following section the FMECA method is briefly detailed.

a. FMECA formulation applied to DPG

The FMECA is a methodology to determine all plausible failure modes of a system, as well as the effects obtained by failures and adequate solutions (Belhadj et al., 2020). Performed by a working team, the FMECA procedure is based on three parameters. The Gravity (G): represents the complexity level to carry out a DOK; the Frequency (F): traduces the incidence of direction and tool change when accomplishing a DOK compared to a previous disassembly operation; the Detection (D): involves wear components in the DOK and measures the complexity level of its access.

Each parameter G, F and D is associated to a value (the minimum is 1 and the maximum is 4). This interval is proposed by the FMECA working team and can be change depending on the treated case. Formula (6) gives the Criticality Failure Mode value (CFM) of each DOK. The minimum value of CFM which is 1 (1x1x1) corresponds to a good design and reliability of the mechanism. However, the maximum value which is 64 (4x4x4) corresponds to a worst design and reliability of the mechanism. In this case, design modifications are needed.

$$CFM = G.F.D$$

(6)

b. Qi computation

To evaluate the quality of a DP, Qi is calculated using formula (7), where k is the total number of subsets, Qij is given by the addition of qi as shown in formula (8). The qi values depended on the CFM limits. The working team selects the qi values according to the treated mechanism, using formula (9). The qi values can be change from a system to another. However, qi must be inversely proportional to CFM is the main rule for defining qi values.

$$Q_i = \frac{1}{\sum_{j=1}^k Q_{ij}} \quad (7)$$

$$Q_{ij} = \sum_{i=1}^s q_i \quad (8)$$

$$\left[\begin{array}{l} 1 \leq CFM \leq 8 \rightarrow q_i = \frac{1}{5} \\ 8 < CFM \leq 14 \rightarrow q_i = \frac{1}{4} \\ 14 < CFM \leq 24 \rightarrow q_i = \frac{1}{3} \\ 24 < CFM \leq 64 \rightarrow q_i = \frac{1}{2} \end{array} \right] \quad (9)$$

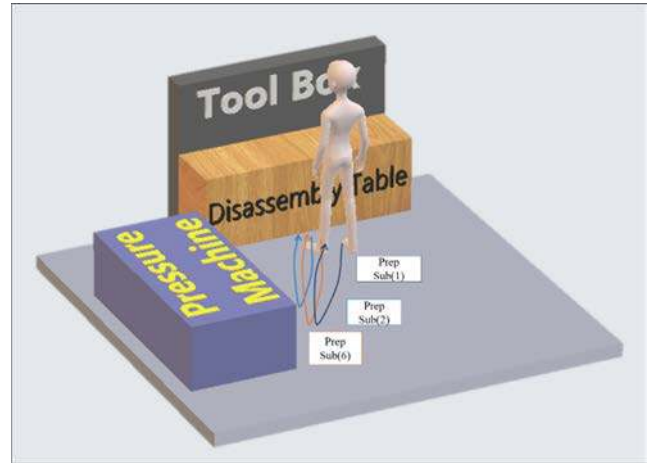


Fig. 9. Optimized workplace and the new Spaghetti diagram of DP₁ of the treated mechanism.

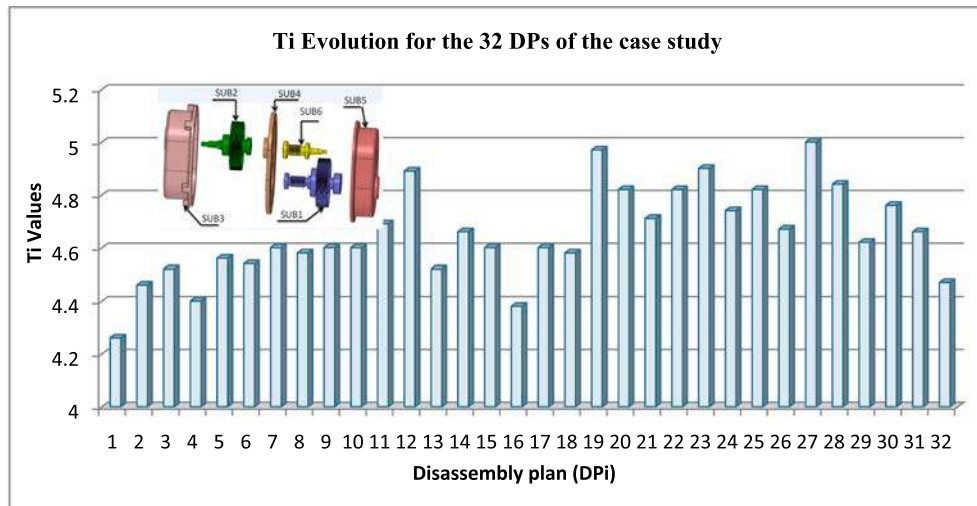


Fig. 8. Timing index evolution for the 32 DPs for the treated case study.

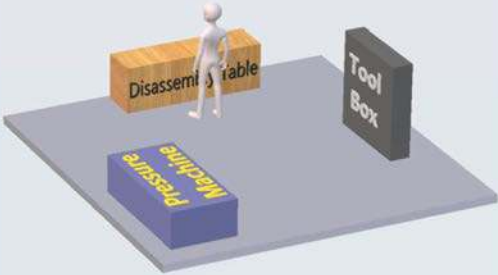
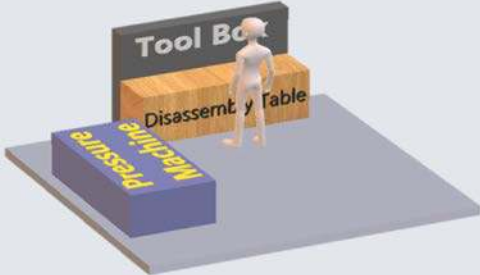
KAIZEN CASE										
Description: Optimize the workplace setting-up in order to reduce wastes (motion, transport...)										
X	Efficiency		Quality		Motivation		Logistics	X	Ergonomics	
									Cost	X
									Health & Security	X
										55
Before						After				
Problem Description						Solution				
* The Tool box is far from disassembly table. * The pressure machine is far from the workplace. * The operator is doing motions and transport.						* The Tool box is integrated in the disassembly table. * The pressure machine is next to the workplace.				
										

Fig. 10. Optimization of the workspace based on the KAIZEN card.

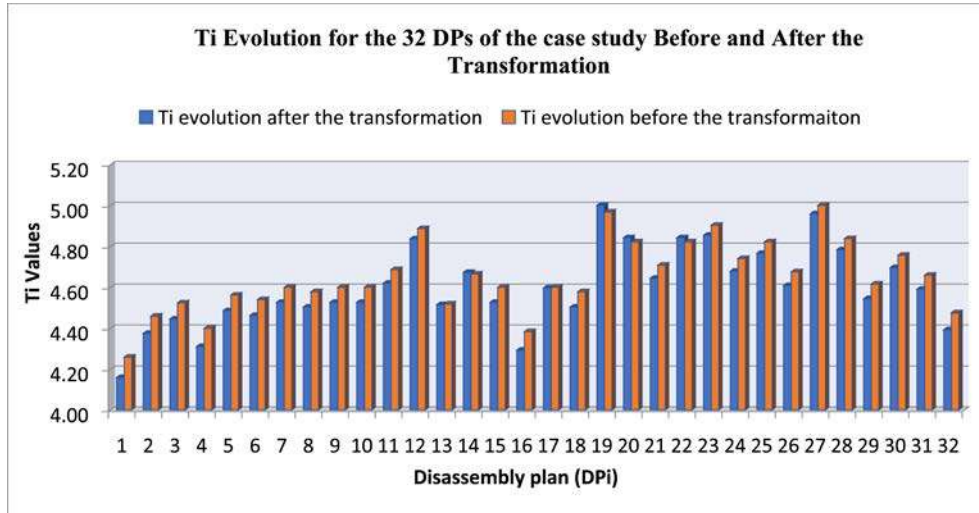


Fig. 11. Ti evolution before and after the optimization.

For the treated case study, Fig. 12 presents the Qi progress of the 32 DPs of the gear box. It is noticed that DP₁₅ has the highest Qi (Q₁₅ = 2.9). DP₅ and DP₁₆ come in the second position with Q₅ = Q₁₆ = 2.8. Using the Qi criterion, DP₁₅, DP₅ and DP₁₆ belong to the customer satisfaction zone.

Based on the previous study on Ti and Qi indexes, it is noticed that DP₁ and DP₁₆ belong to the customer satisfaction zone according to the Ti index. However, according to Qi index DP₁₅, DP₅ and DP₁₆ belong to the customer satisfaction zone. In order to choose the best DP according to the two indicators (Qi and Ti), a deep analysis is performed.

3.5. Difference (Ti - Qi) gap evolution

After calculation of Ti and Qi indexes, the selection of the best DP solution is now elaborated based on both of them simultaneously. Thus, the optimal disassembly plan should correspond to the highest index of quality (Qi) and lowest index of processing time (Ti) in the same time. Formula (10) gives the condition that allows this duality.

$$DP_{\text{optimal}} = [\max(Q_i); \min(T_i)] \quad (10)$$

To satisfy the optimal DP condition given by formula (10) and

defines the best DP, a gap index (Δ) traduces the disparity between Ti and Qi and given by formula (11). Table 4 shows values of Ti, Qi, and Δ of every disassembly plan for the gear box.

$$\Delta_i(DP_i) = T_i - Q_i \quad (11)$$

At this advanced phase, Ti, Qi and Δ i are plotted simultaneously in a composed diagram exposed in Fig. 13. To accomplish constraints of optimal DP that minimizes Ti and maximizes Qi, Δ i has to be minimal as shown by formula (12).

$$\{\min \Delta_i(DP_i)\} \Rightarrow \{DP_{\text{best}} = [\max(Q_i); \min(T_i)]\} \quad (12)$$

From Fig. 13 it can be noticed that the smallest rate of Δ i corresponds to Δ_{16} , associated to DP₁₆, which is equal to 1.58. Consequently, DP₁₆ represents the best DP following to Qi and Ti indicators.

At second level, Δ i is recalculated but this time with taking Ti values after the transformation and optimization of the workplace. In order to visualize the difference between Δ i before and after the transformation, all the Δ i for the 32 treated DP are represented in Fig. 14.

From Fig. 14 it can be concluded that there is multiple transformation in values of Δ i. Some of them have increased and some other has decreased. But, the smallest value of Δ i still corresponds to Δ_{16} ,

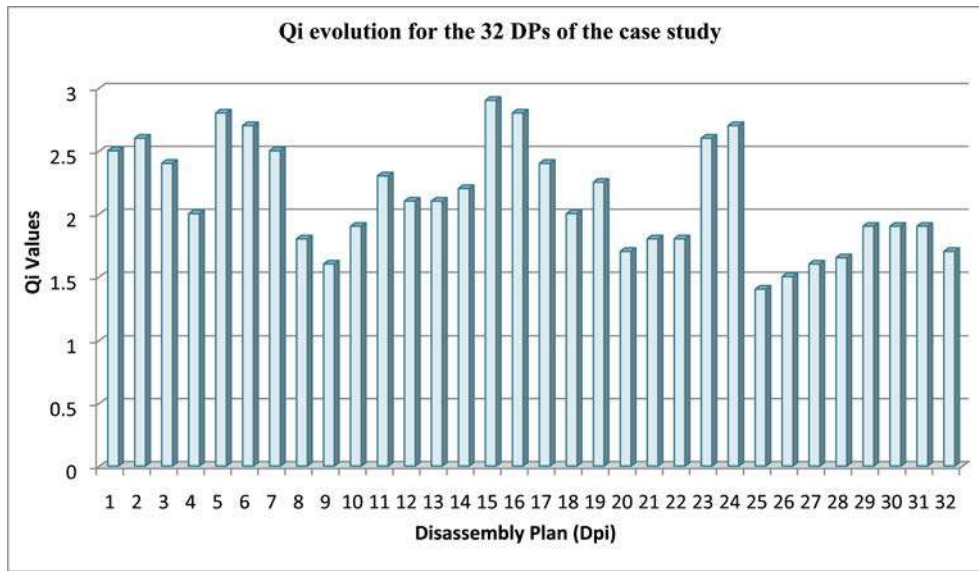


Fig. 12. Evolution of the Qi for the 32 DPs for the case study.

Table 4

Δ computation for the gear box.

DP _i	Qi	Ti	Gap Δ	DP _i	Qi	Ti	Gap Δ
DP ₁	2.50	4.26	1.76	DP ₁₇	2.4	4.60	2.20
DP ₂	2.60	4.46	1.86	DP ₁₈	2	4.58	2.58
DP ₃	2.40	4.52	2.12	DP ₁₉	2.25	4.97	2.72
DP ₄	2.00	4.40	2.40	DP ₂₀	1.7	4.82	3.12
DP ₅	2.80	4.56	1.76	DP ₂₁	1.8	4.71	2.91
DP ₆	2.70	4.54	1.84	DP ₂₂	1.8	4.82	3.02
DP ₇	2.50	4.60	2.10	DP ₂₃	2.6	4.90	2.30
DP ₈	1.80	4.58	2.78	DP ₂₄	2.7	4.74	2.04
DP ₉	1.60	4.60	3.00	DP ₂₅	1.5	4.82	3.32
DP ₁₀	1.90	4.60	2.70	DP ₂₆	1.4	4.67	3.27
DP ₁₁	2.30	4.69	2.39	DP ₂₇	1.6	5.00	3.40
DP ₁₂	2.10	4.89	2.79	DP ₂₈	1.65	4.84	3.19
DP ₁₃	2.10	4.52	2.42	DP ₂₉	1.9	4.62	2.72
DP ₁₄	2.2	4.66	2.46	DP ₃₀	1.9	4.76	2.86
DP ₁₅	2.9	4.60	1.70	DP ₃₁	1.9	4.66	2.76
DP ₁₆	2.8	4.38	1.58	DP ₃₂	1.7	4.47	2.77

associated to DP16, which is equal to 1.49. Consistently, DP16 represents the best DP according to Qi and optimized Ti indicators.

4. Discussion and synthesis

Belhadj et al. (2019) developed a method to select the best DP based on a quality index. The proposed method was accomplished that the best DP is DP₁₅ with a $Q_{15} = 2.90$. In the current method, judgment was based on coupled indicators which are Ti and Qi. Based on the new approach, it was concluded that DP₁₆ having the couple ($T_{16} = 4.29$; $Q_{16} = 2.80$) is chosen as the best one. In fact, based on Qi index, $Q_{15} = 2.90$ is higher than $Q_{16} = 2.80$, consequently DP₁₅ is the best one. However, based on Ti index, $T_{15} = 4.53$ is higher than $T_{16} = 4.29$, which leads to choose DP₁₆ as the best one. According to the gap index Δ which combine Qi and Ti a couple formula, $\Delta_{16} = 1.49$ is lower than $\Delta_{15} = 1.63$. Accordingly, in relationship with the Quality-Time-Cost balancing concept, efficiency and productivity, it was concluded that DP₁₆ is better than DP₁₅. Moreover, for various reasons as delivery date, cost, production capacity, etc. flexibility can be considered to the DP selection procedure. A set of five zones classified, according to Δ_i . The satisfaction zones can be divided as below:

- Satisfaction zone which includes D₁₆, D₁₅, D₁ and D₅.

- Moderately satisfaction zone which includes D₆, D₂, D₂₄, D₇, D₃.
- Minor modification needed to reach the satisfaction zone which includes D₁₇, D₂₃, D₁₁, D₄, D₁₃, D₁₄.
- Major modification needed to reach the satisfaction zone which includes D₁₈, D₁₀, D₂₉, D₃₁, D₃₂, D₈.
- Rejection of DP for inability to reach the satisfaction zone which includes D₁₂, D₁₉, D₃₀, D₂₁, D₉, D₂₂, D₂₈, D₂₀, D₂₆, D₂₅, D₂₇.

Fig. 15 shows the satisfaction zones as a set of interconnected spheres. The boundary spheres can be defined by the working group.

5. Conclusion and future work

This research develops a mathematical formulation for processing time computing in disassembly lines and its optimization. The input of the proposed approach is a set disassembly plans (DPs). The generated DPs are, firstly, classified using a real processing time index (Ti) which is obtained by a depth study of disassembly preparations and operations. A quality index (Qi) is also used to evaluate DPs according to an FMECA methodology. A coupling model between Ti and Qi given by a gap index Δ is then developed in answer to the Quality-Time-Cost efficiency and productivity concepts. Using Δ the best DP having the lowest Ti and the highest Qi which correspond to the lowest Δ is chosen. In order to optimize the results a 5S method in proposed in order to reorganize the workspace for reducing the spaghetti diagram of DPs. The best DP which has the minimal Δ and the optimal workspace can be selected. The major advantages of the proposed approach are:

- The use of a mathematical formulation to generate a real processing time model and a timing index. The selected DP must have the lowest value of Ti.
- The use of the FMECA method to select the best DP having minimum direction and tool change in the disassembly operation and facility access of wear parts.
- The classification of DPs using a gap index Δ which combine the two indexes Qi and Ti.
- Lean tools and industrial practices are considered to develop the proposed model.

The proposed approach can be enhanced by taking into account further aspects. As a future work, the cost and the consumed energy criteria for disassembly preparations and operations can be integrated.

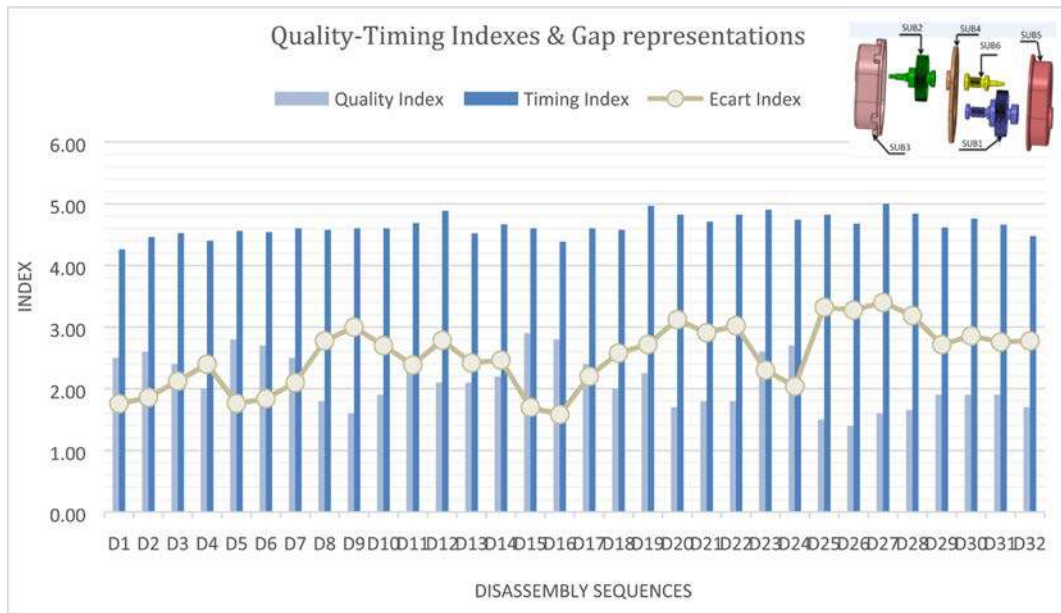


Fig. 13. Qi, Ti and Δ indexes for the 32 DPs for the case study.

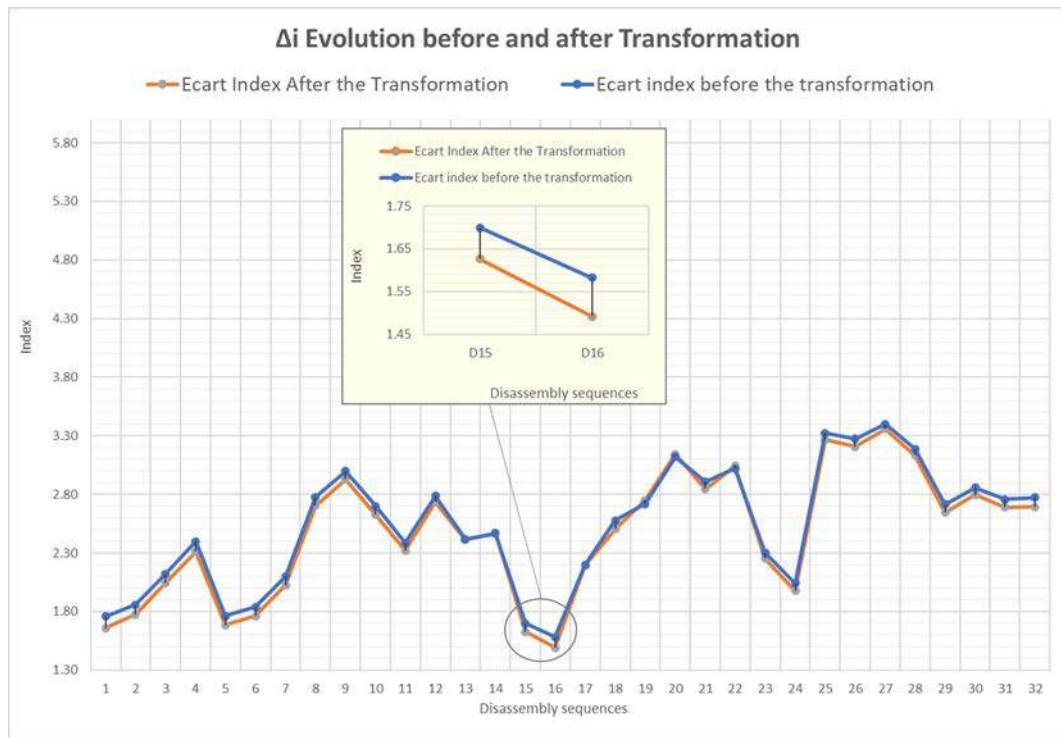


Fig. 14. Δ_i evolution before and after the optimization.

Furthermore, formula (11) which calculates the gap Δ_i uses the same weight of Ti and Qi. A parametric study on the weights of Ti and Qi can be elaborated in order to study the Δ_i evolution.

Ethical Approval

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors Contributions

In this paper, a mathematical formulation for operating time computing in disassembly lines and its optimization is proposed.

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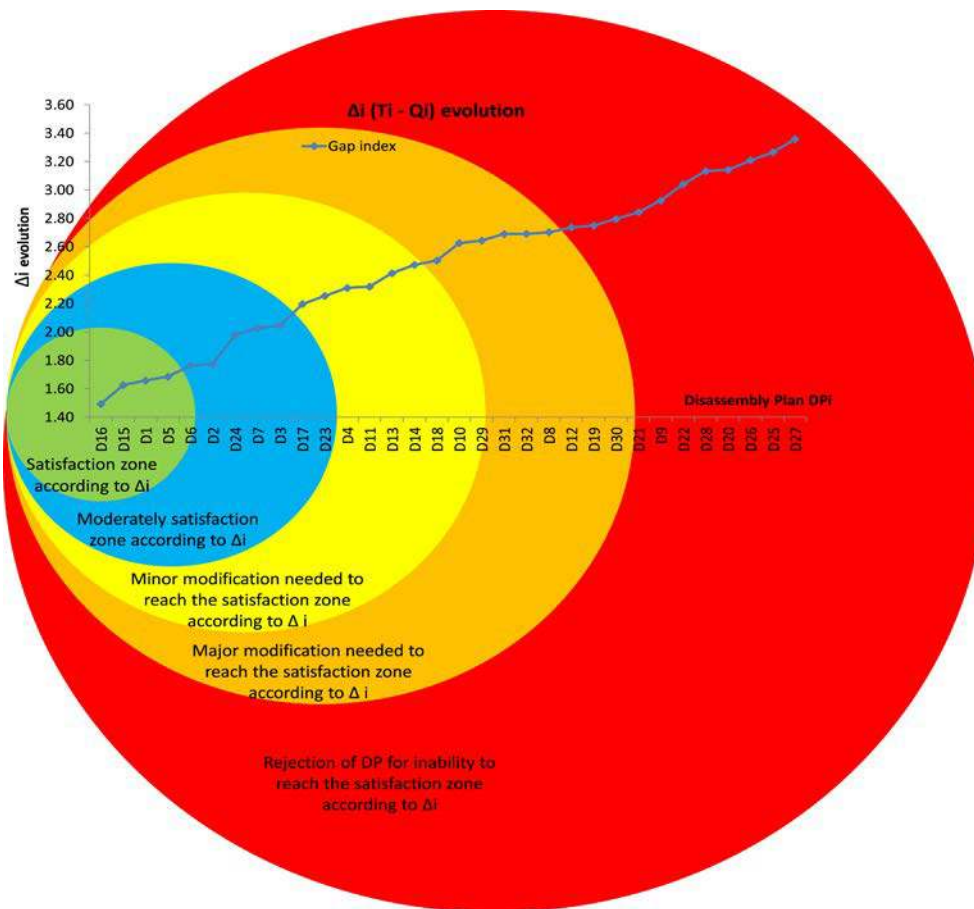


Fig. 15. Gap index representation with recommended satisfaction zones.

CRedit authorship contribution statement

Mahdi Aicha: Investigation, Conceptualization, Methodology, Writing – original draft. **Imen Belhadj:** Software, Validation, Writing – original draft. **Moncef Hammadi:** Visualization, Supervision, Project administration. **Nizar Aifaoui:** Visualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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