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# A Coupled Method for Disassembly Plans Evaluation Based on Operating Time and Quality Indexes Computing

Mahdi Aicha<sup>1</sup>, Imen Belhadj<sup>1</sup>, Moncef Hammadi<sup>2</sup>, Nizar Aifaoui<sup>1</sup>

Every industrial organization, whether it deals with an assembly or a disassembly process, is definitely putting a huge focus on how to optimize its operative mode by reducing: process variation, frequent changes of production tools, quality issues, wastes. That's why, disassembly plan generation (DP) is a very supportive tool that detects and identifies difficulties and probable blocking assembly/disassembly situations from the early design steps and avoid them. This anticipation is quite beneficial to manufactories point of view cost, time and quality of products as it returns with a remarkable reduction in production stopping time and products' defects, as a result reduction in cost of production. In order to ameliorate DP algorithm decision generation and make it very similar to real manufacturing circumstances, this article comes with a new approach that combines between two main metrics, which are the Quality index (Qi) and the Timing index (Ti), as criteria while selecting optimal and feasible DP. Qi is calculated based on the failure mode, effects and criticality analysis method (FMECA), on the other side, Ti represents the real processing time index with reference to real manufacturing constraints (workplace, lay-out, work-flow, tools, machines...). To highlight the effectiveness of the proposed approach, an industrial gear box example is simulated and compared to a literature study.

Keywords: Disassembly plan · Lean tools · 8 MUDA · Assessment of DP · CAD data · Quality Index · Processing time · Time index · Optimization

## 1 Introduction and Literature Review

While starting-up a project in a manufacturing organization, one of the most important parameters that management takes in consideration to evaluate correctly its business profit is processing time (assembly operation, disassembly operation, intervention of maintenance...). Based on this parameter definition, the enterprise management team gets engaged with its customer and has with him a partnership agreement based on: production cycle time, capacity of production per year, delivery time. In this context, industrial engineering department in every organization pays very big attention to evaluate precisely the time of an operation (whether it is a

manual operation or a machinery cycle) targeting to reduce it and eliminate wastes in case of detection. The main objective is to reach efficiency objective. This evaluation will be more less costing, if it is anticipated and defined from the feasible and optimal assembly/disassembly plans generation (AP/DP) during the design process. This paper presents a new approach that combines two main metrics which are Quality index (Qi) and Timing index (Ti) and taking them as criteria while generating an optimal DP. Quality index (Qi) is calculated based on FMECA method. On the other side, Timing index (Ti) is based on the real processing time evaluation with reference to real industrial conditions (workplace, lay-out, work-flow, tools, machines...). In order to highlight the added value of the proposed approach, the following section presents a literature review on AP/DP generation an evaluation.

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## 2 Literature Review on AP/DP Generation

The earliest works related to the AP/DP problems are only theoretical proposals and totally disjointed from CAD tools. With the progress of the informatics technologies, the recent research works are paying attention on the integration of AP/DP approaches in CAD systems. Theoretical proposals essentially use graphs, heuristic analyses, questions or tables, etc. De-Mello et al. proposed an AND/OR graph which presents the AP [1]. This approach is restricted to represent the AP only as a graph model which becomes large and not easy to handle with complex machines. Dini et al. developed, for a mechanical product, a sub-assembly identification approach based on a mathematical formulation [2]. The proposed method is performed using some essential data such as: the interference matrix, the contact matrix and the connection matrix. For the automobile domain, Zhang et al. developed a mathematical model to generate feasible APs [3]. Wang et al. proposed a precedence graph based on associated parts to reduce the number of disassembly tasks. To assess the green performance of the disassembly process, a partial disassembly line balancing model considering efficiency, profit and energy consumption is developed [4]. The principal limitation of the previously cited approaches is the need of the user intervention which grows to be hard in the case of multipart's machines.

Zha and Du proposed a method based on the STEP format to represent an assembly CAD model [5]. This approach requires prior assembly relationship knowledge. Zhang et al. developed a new hybrid graph to express constraints relationship among parts. The proposed mathematical method is built by quantifying the carbon emissions in the process of product disassembly. The total disassembly time is then optimized by taking into account the basic disassembly time, direction change time and tool change time [6]. Um and Suh proposed a design method for developing a product recovery management system based on life cycle information. The proposed approach is based on an overview of a generic architecture based on ubiquitous computing technology called ubiquitous information engineering [7]. To generate feasible APs, Su developed a methodology based on the analysis of geometric relationship [8]. Integrated to a CAD system, this approach needs a minimum intervention of the user. Mathew and Rao proposed a methodology to extract assembly constraints characteristics from the CAD system. From this proposal, the result is a generated relation matrix [9]. Qu and Xu proposed a method which automatically produces APs from a mockup. The proposed approach uses a relationship matrix, implemented as a CREO-CAD tool [10]. Morato et al. developed a spatial

encapsulated approach that combines a mobility planning procedure to generate DPs from a CAD assembly mockup [11]. Pan et al. developed an automated AP approach by improving Smith's method [12]. The proposed approach can directly extract geometric information from a STEP file, evaluating the geometric data to generate assembly constraints, and automatically producing collision matrices to characterize constraints between parts throughout the mounting operation. Ben Hadj et al. proposed an AP generation approach based on the idealization of the CAD mock-up. First, the developed methodology simplifies the CAD mock-up by removing the link parts (nut, screw, etc.). Then, the simplified AP can be generated. Finally, a case-based reasoning procedure permits the insertion of the removed link parts into the idealized AP to obtain a feasible one [13]. Issaoui et al. proposed a DP generation method by inserting an optimization and validity examinations permitting the dismantling of a user chosen part [14]. Belhadj et al. developed a methodology to generate feasible DP using a subassembly detection procedure. The proposed approach firstly elaborates a global subassemblies DP. Then, each subassembly DP is computed under the user demand [15]. The proposed approach is extended to propose an assessment of the obtained DPs using the part's disassembly time which is obtained from industrial practices [16, 17]. Wang et al. proposed an assessment method of disassembly operations in a virtual environment throughout the product design step by anticipating the production, the maintenance and the end of life aspects. In the evaluation process, some criteria are proposed such as: stability of subassemblies, disassembly angles, tool change and mounting direction change [18]. Based on the part's stability during the mounting operations, Bedeoui et al. proposed a new method to generate feasible APs. The generation of feasible APs was ensured using geometrical and topological relationships extracted from the CAD system [19]. Matthews et al. developed a design for manufacturing and assembly (DFMA) approach which integrates an iterative exchange based on the ergonomic viewpoint to generate and assess the consequence of DFMA on the time of the mechanism reassembly [20].

Based on the previous literature, it can be noticed that the automated analysis of mechanical product is very advantageous in the case of complex machines. Indeed, the complexity of AP/DP problem rises with the number of parts. The emergence of automatic approaches offers a designer ergonomic, the accuracy and the efficiency of results by reducing the user contribution.

### 3 Literature Review on Lean Tools

Good quality of outputs is an indisputable objective that organization continuously works on it. It is certainly the best way to ensure customer satisfaction and as a result reach his loyalty, as it represents the best way to activities' sustainability and flourishing. On this basis, the enterprise has to protect its financial balance and achieve profitability in order to keep safe and protect its business value, this, throw a well-organized follow-up to its key performance indicators (KPIs). Over the years, many quality approaches have appeared. Some of them will be discussed in the following section.

Quality circles approach, appeared at end of seventies at Japan, which consists on definition of self-improvement study groups. We mention also ISO 9001 which represents a set of international standards that documents and regroups quality management international standards has been developed since 1987. Furthermore, Six Sigma approach (promoted by Motorola in the late 1980s, when it is properly implemented, the organization grows) which is a disciplinary procedure that aims to detect defects/mistakes and eliminate its root causes. One of the most important methods to identify the root cause of a defect is the cause-and-effect diagram or fishbone diagram (developed by Kaoru Ishikawa) [21]. Beng and Omar proposed a new architecture based on design principles to facilitate sustainable product development. The proposed axiomatic approach has the aim of assisting analysis and decision making process to evaluate the design quality [22]. In the same context of quality management, and in order to generate an optimal DP, Belhadj et al. developed an approach that evaluates the quality of the delivered DPs. In the proposed approach, the Failure Mode, Effects and Criticality Analysis (FMECA) method and Ishikawa diagram are used [17]. This quality assessment helped to optimize the decision to generate the DP but there are still other potentials for improvement such as the processing time Mesa et al. developed a framework to designers to enhance their sustainability performance for a circular economy model, which incorporates lifecycle aspects, resource optimization, and emissions reduction. The proposed approach guarantees an effective circularity of resources during the product lifecycle by integrating manufacturing processes and material analysis to design products in accordance with the circular economy model [23]. To improve end-of-use product recyclability for circular economy, Cong et al. proposed a design method to facilitate the end of-use value recovery. Initially, product end-of-use situations are identified by optimization of end-of-use part flows. Then, bottlenecks, improvement prospects, and design propositions can be generated [24]. In the same context, the authors

developed a DP method to discover a profitable end-of-use strategy. Firstly, disassembly optimization model is developed and can be executed to obtain the optimal DP allowing maximum preservation of part function value, in a preservative disassembly scenario [25, 26].

On the other hand, Lean can be referred by lean manufacturing which is a concept that has been developed within the framework of Toyota Production System (TPS) as far back as the 1950s [27]. The fundamental concept for the perception of lean philosophy is the procedure of how to create value with no waste. Value which is defined by customer and he considers it quite necessary especially that it is done Right the First Time (RFT). In order to identify wastes and drive them out, many lean tools have been used over time. 5S is a lean tool that organizes the workplace in a way that improves efficiency and management of operations. Single Minute Exchange of Die (SMED) is a very helpful tool that helps in providing a fast and effective change from a product to another or from tool to another. One of the most known lean tools that identifies wastes and evaluate them by causes and results is 8 MUDA waste tools. Those 8 categories of waste can be recapitalized into: overproduction, waiting, excess motion, excess movement, inventory (material or transportation), rework etc.

### 4 Outcomes of the Literature Review and Main Research Objectives

The synthesis of the previously detailed literature review allows the following points to be identified:

- For the generation of APs/DPs, several criteria are retained such as: mass, center of gravity, stability, disassembly tool, trajectory of mounting tools, anteriority constraints, assembly and disassembly time, etc.
- Quality tools are widely used for production management and can make indisputable benefits. However, these tools are not sufficiently used in the generation and evaluation of APs/DPs.
- Real operating time related to motion waste, poor workplace, wrong tools and inappropriate materials dispatching are not yet considered to generate and evaluate APs/DPs.

This paper deals with a new issue which is the evaluation of the real operating time following the generated disassembly plan execution. It puts a big focus on excess motion waste detection and evaluation that can be induced by poor workplace layout and implementation, including problems of ergonomics, inappropriate tools and deficient materials feeding. Based on a real workplace setting-up, this approach

evaluates the needed processing time for every DP and generates the optimal one (the one with the less wastes).

More precisely, this paper proposes a methodology to evaluate feasible DPs which is implemented as a design help tool. The proposed approach is based on two main steps: the generation of feasible DPs and the evaluation of the generated DPs to select the optimal ones. The evaluation is based on a Quality index ( $Q_i$ ) which is based on a quality tool selected from the literature and called Failure Mode, Effects and Criticality Analysis (FMECA). The main novelty of this paper concerns the evaluation of the founded DPs which is based on the integration of a two metrics: The Timing index ( $T_i$ ) and the Quality index ( $Q_i$ ). The  $Q_i$  is widely detailed in [17], however,  $T_i$ , which is based on a Lean tools methodology, consists in computing of the real processing time. The real processing time is done with reference to real production life environment (workplace, layout, workflow, tools and machines). To each DP is assigned two metrics:  $Q_i$  and  $T_i$ . The DP with the highest  $Q_i$  and lowest  $T_i$  scores correspond to the best one in terms of disassembly tools, directions change, parts accessibility and real processing time. The developed tool can be used by users along the product development.

The remaining parts of this manuscript are planned as follows. After detailing a literature review, the second section presents a description of the two steps of the developed approach. Then, an illustrative example, identified from the literature, is treated in order to explain the different stages and illustrate the efficiency of the proposed approach.

## 5 Prerequisites: DP Generation and Quality Evaluation

In order to proceed to the main purpose research, two main levels have to be detailed. These levels are the disassembly plans generation and the quality evaluation. To highlight the results of each level, an industrial example, founded from the literature [17], is used. The treated example is a gear box which is composed of 17 interconnected parts. Figure 1 shows the exploded view and the decomposition into subassemblies of the gear box. This example was chosen from the literature in target of comparing and validating the proposed approach.

## 6 Disassembly Plan Generation Level

The DPs generation approach begins by the momentary suppression of all connecting parts (CPs). It is structured into two main phases. The first stage is the DPs generation (disassembly plan of subsets) which illustrates the DP of Subsets. A Subset can be a part or a set of parts which is

beforehand identified. The second stage is the generation of the detailed DPs which is obtained by introducing CPs (previously removed). For the illustrative example, Fig. 2 shows the DPs process to generate all feasible DPs without considering CPs. The DP process starts by browsing the interferences matrices along x, y and z axis. From the interference matrix along x axis that all elements of the column related to SUB5 and all elements of the line related to SUB3 are equal to 0. So, SUB5 can be freely dismantled in the direction of (-x) and SUB3 can be disassembled freely along (+x) axis (level 1). In this case, two possible DPs are initiated (level 2). Once SUB5 is dismantled, the associated line and column are suppressed from the interference matrix and a new square interference matrix (size n-1) is created. This routine is repeated until all SUBs are dismantled. For the treated example, Table 1 illustrates 32 feasible DPs generated from the DPs process previously detailed.

## 7 Quality Evaluation Level

Once the DPs list is produced, the quality assessment level can initiate. The principle of this stage is to evaluate the mounting or dismantling difficulty of the retained DPs by assigning a  $Q_i$  to every DP. The  $Q_i$  is calculated after assessing the  $Q_{ik}$  of each Disassembly Operation ( $DO_k$ ) composing the global DP.  $DO_k$  is a set of connecting elements, a disassembly tool and a disassembly direction, given by Eq. (1):

$$DO_k = \{CP, T, D\} \quad (1)$$

where, CP is the connecting element, T is the tool used in the  $DO_i$ , D is the direction of the disassembly operation.

The obtained DPs will be organized using the  $Q_i$  metric and the user will choose the optimal DP that has the highest  $Q_i$ . The failure mode, effects and criticality analysis tool (FMECA) is used to calculate the  $Q_i$  of each DP. The FMECA procedure is based on three basic parameters which are assessed by an FMECA group:

- Gravity (G) that designates difficulty degree to execute a  $DO_k$ .
- Frequency (F) that represents the occurrence of tool and direction change of a  $DO_k$  comparing to the preceding one.
- Detection (D) that concerns the existence of wear part in the  $DO_k$  and the difficulty degree of its accessibility.

Every parameter is associated to a score assortment (minimum of 1 to a maximum of 4: this interval is chosen by the working FMECA group). By the multiplication of the three parameters G, F and D, Eq. (2) gives the Criticality Failure Mode score (CFM) of each  $DO$ :

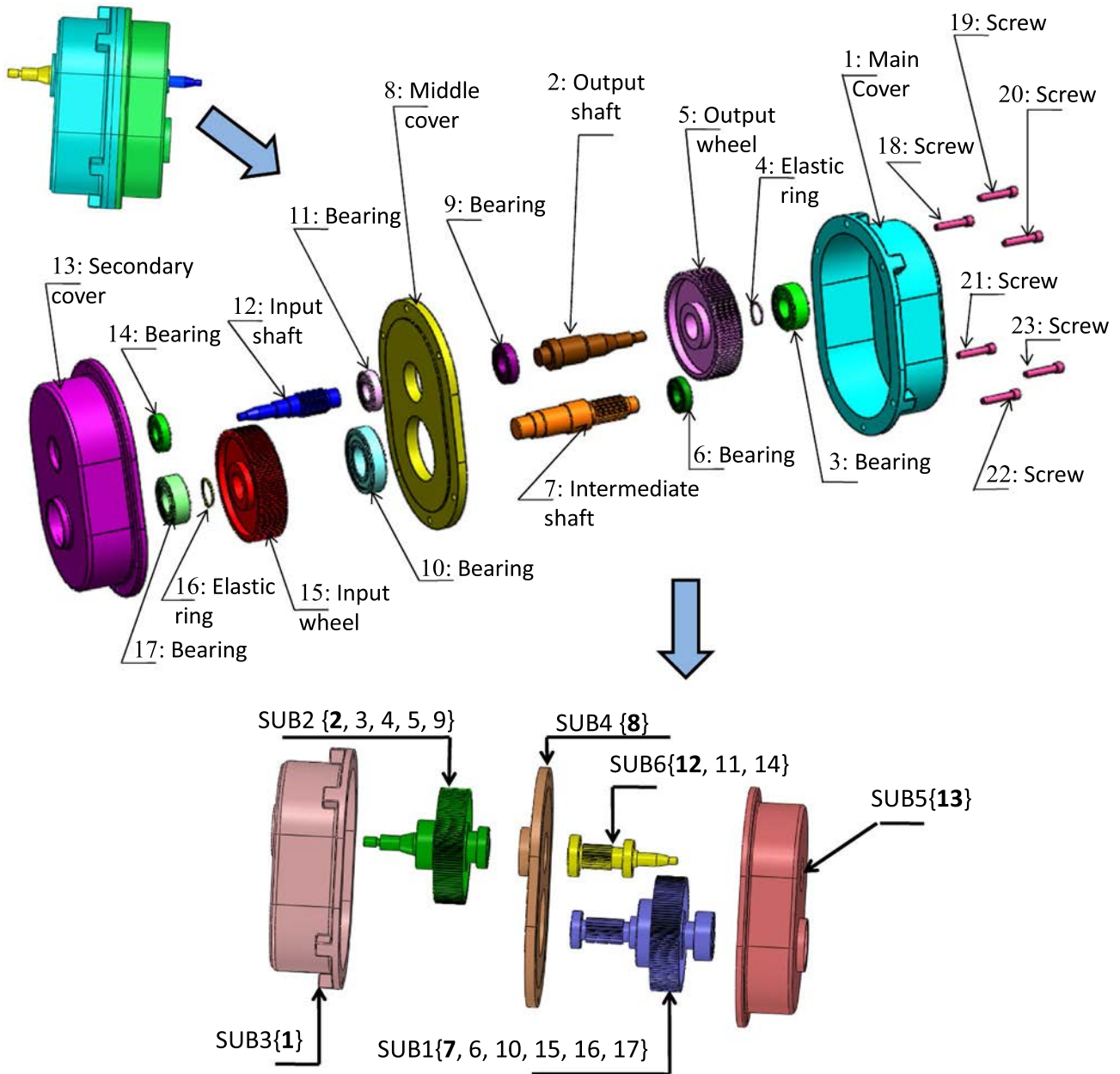


Fig. 1 Exploded view and Subset's decomposition of the gear box

$$CFM = G.F.D. \quad (2)$$

The CFM score allocates a power to every considered failure mode. The higher value of CFM corresponds to the worst product reliability. In this situation, adjustments are necessary in order to avoid failure recurrence.

For each DP, the Qi calculation process is composed of four steps and can be executed until the DP list is generated. These steps are as follow:

- (i) **Define failure mode and effects:** Which is defined as the difficulty of the DOK while the failure effect is the unsuitable DO in the DP.
- (ii) **Define failure cause:** which regroups the different causes of DO that can be acknowledged by the FMECA group using the Ishikawa diagram. This thinking tool is used to identify the potential causes of the difficulty to dismantle a part or a subset. The main causes of the difficulty to obtain a DO are given

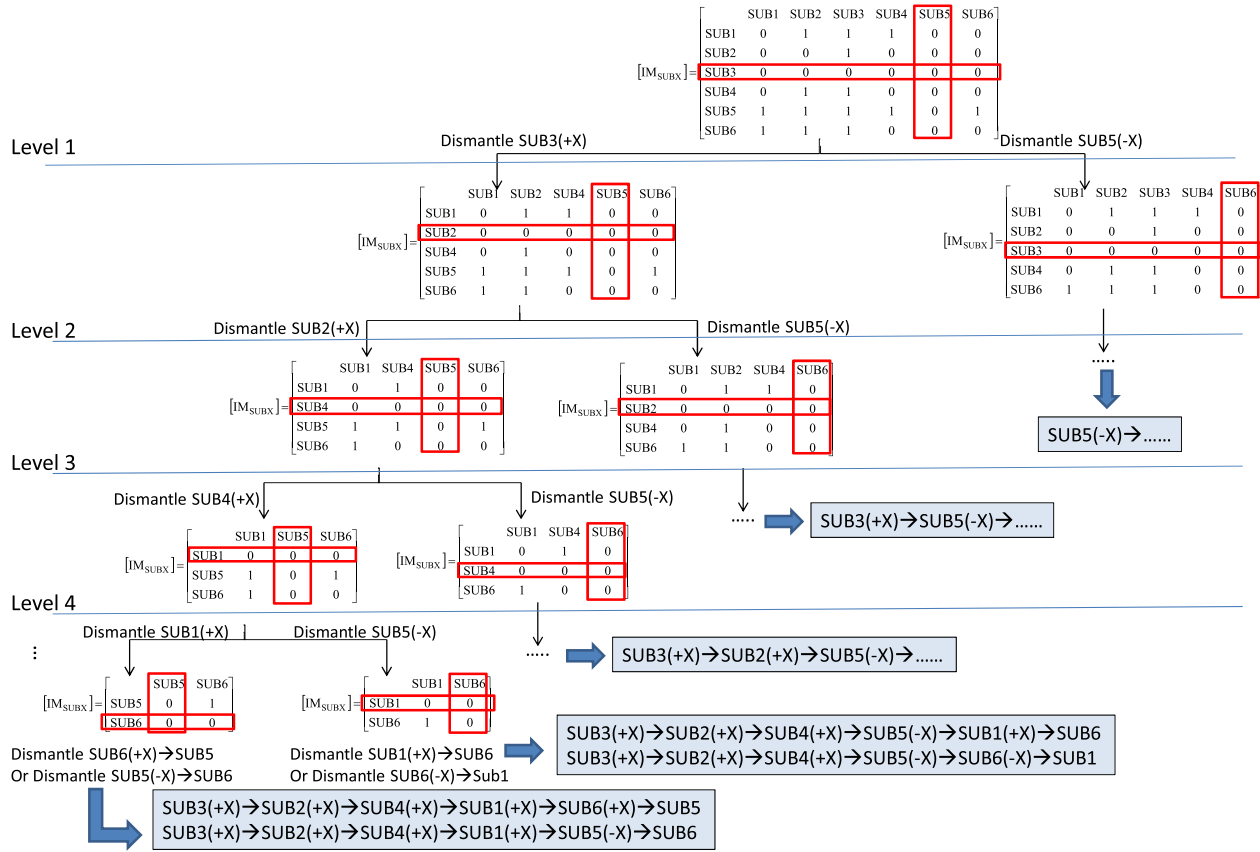


Fig. 2 DPs generation process applied to the illustrative example

by the 5 M: Machine (M1), Method (M2), Material (M3), Manpower or operator (M4) and Milieu or environment (M5).

- (iii) **FMECA parameters definition:** in this step, the working group specifies the retained criteria and the sore range of G, F and D.
- (iv) **Calculate Qi for each DP:** the Qi coefficient is given by Eq. (3), where m is the number of SUBs, Qij is obtained by the sum of the parameters (qi) and given by Eq. (4). The qi parameters are dependent on the CFM values and limits. The working group chooses the qi values, using Eq. (5). For the treated example, Fig. 3 elucidates the Qi evolution of the 32 generated DPs.

$$QI = \frac{1}{\sum_{j=1}^m QI_j} \quad (3)$$

$$QI_j = \sum_{i=1}^5 q_i \quad (4)$$

$$\begin{cases} q_i = \frac{1}{5} & \text{if } 1 \leq CFM \leq 8 \\ q_i = \frac{1}{4} & \text{if } 8 < CFM \leq 14 \\ q_i = \frac{1}{3} & \text{if } 14 < CFM \leq 24 \\ q_i = \frac{1}{2} & \text{if } 24 < CFM \leq 64. \end{cases} \quad (5)$$

## 8 Main Research Purpose: Processing Time Evaluation by Timing Index (Ti) Calculation

The proposed approach, graphically presented by the flow-chart of Fig. 4, is coming into three inter-related levels:

- **Disassembly Plans Generation Level** This step consists on the definition of a DP list by taking into account anteriority constraints and dynamic collision criteria.
- **Quality Evaluation Level** Which particularly evaluates the quality of each generated DP based on the Qi index which is estimated using the FMECA tool.

**Table 1** DPs list of the illustrative example

DP1	SUB3	SUB2	SUB4	SUB1	SUB6	SUB5
DP2	SUB3	SUB2	SUB4	SUB1	SUB5	SUB6
DP3	SUB3	SUB2	SUB4	SUB5	SUB1	SUB6
DP4	SUB3	SUB2	SUB4	SUB5	SUB6	SUB1
DP5	SUB3	SUB5	SUB2	SUB4	SUB1	SUB6
DP6	SUB3	SUB5	SUB2	SUB4	SUB6	SUB1
DP7	SUB3	SUB2	SUB5	SUB4	SUB1	SUB6
DP8	SUB3	SUB2	SUB5	SUB4	SUB6	SUB1
DP9	SUB3	SUB2	SUB5	SUB6	SUB4	SUB1
DP10	SUB3	SUB2	SUB5	SUB6	SUB1	SUB4
DP11	SUB3	SUB5	SUB2	SUB6	SUB1	SUB4
DP12	SUB3	SUB5	SUB2	SUB6	SUB4	SUB1
DP13	SUB3	SUB5	SUB6	SUB2	SUB4	SUB1
DP14	SUB3	SUB5	SUB6	SUB2	SUB1	SUB4
DP15	SUB3	SUB5	SUB6	SUB1	SUB2	SUB4
DP16	SUB3	SUB5	SUB6	SUB1	SUB4	SUB2
DP17	SUB5	SUB3	SUB2	SUB4	SUB1	SUB6
DP18	SUB5	SUB3	SUB2	SUB4	SUB6	SUB1
DP19	SUB5	SUB3	SUB6	SUB2	SUB1	SUB4
DP20	SUB5	SUB3	SUB6	SUB2	SUB4	SUB1
DP21	SUB5	SUB3	SUB2	SUB6	SUB1	SUB4
DP22	SUB5	SUB3	SUB6	SUB2	SUB4	SUB1
DP23	SUB5	SUB3	SUB6	SUB1	SUB2	SUB4
DP24	SUB5	SUB3	SUB6	SUB1	SUB4	SUB2
DP25	SUB5	SUB6	SUB3	SUB2	SUB1	SUB4
DP26	SUB5	SUB6	SUB3	SUB2	SUB4	SUB1
DP27	SUB5	SUB6	SUB3	SUB1	SUB2	SUB4
DP28	SUB5	SUB6	SUB3	SUB1	SUB4	SUB2
DP29	SUB5	SUB6	SUB1	SUB3	SUB2	SUB4
DP30	SUB5	SUB6	SUB1	SUB3	SUB4	SUB2
DP31	SUB5	SUB6	SUB1	SUB4	SUB3	SUB2
DP32	SUB5	SUB6	SUB1	SUB4	SUB2	SUB3

- *A Coupled Ti and Qi Evaluation Level* This new step represents the main added value in the proposed approach. Based on a Lean tools' methodology, it aims at defining the DP timing-process, analyze, detect different types of waste and then drive it out from the disassembly operations while taking decision.

This section presents the main added value of this work. In industries, Managers coordinate continuously between concerned departments in order to reach such fundamental balancing-case which has been treated by analogy on project management triangle (called also iron triangle, the triple constraints or project triangle). Figure 5 represents the iron triangle which has been used since 1950s to emphasize that a work is necessarily constrained by: quality, time and cost. In this approach, a deep analysis of the DP's processing time is detailed, taking in consideration many work environment parameters (layout, production

flow, ergonomics, workplace organization, etc.) that can influence the time of an activity. There are three categories of activities:

- *Value added activities* Which are essential and customer is paying for.
- *Incidental waste* These operations are wasteful, but cannot be eliminated.
- *Waste* A non-value-added activity that can be eliminated.

Industrial engineering department, quality service and continuous improvement engineers, concentrate always on how to implement lean tools in production. The main objective is to identify wastes (preparing, searching, sorting...) and reduce them or totally drives them out if possible, targeting to: ameliorate products' quality, reduce process variation, improve productivity and increase in efficiency rate.



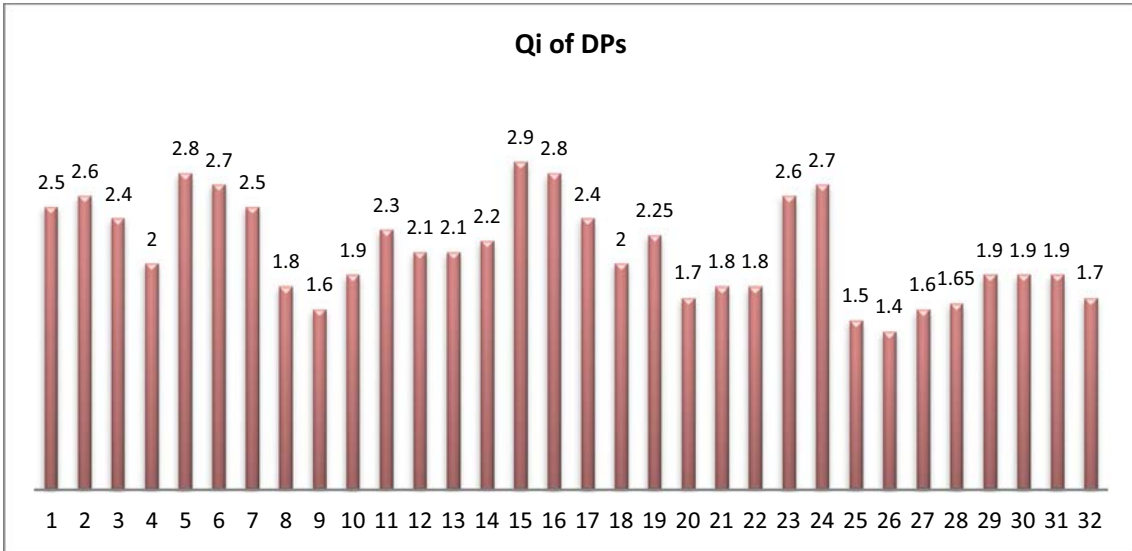


Fig. 3 Evolution of the Qi of each DP for the treated example

Fig. 4 Main research purpose

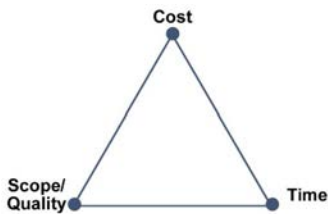
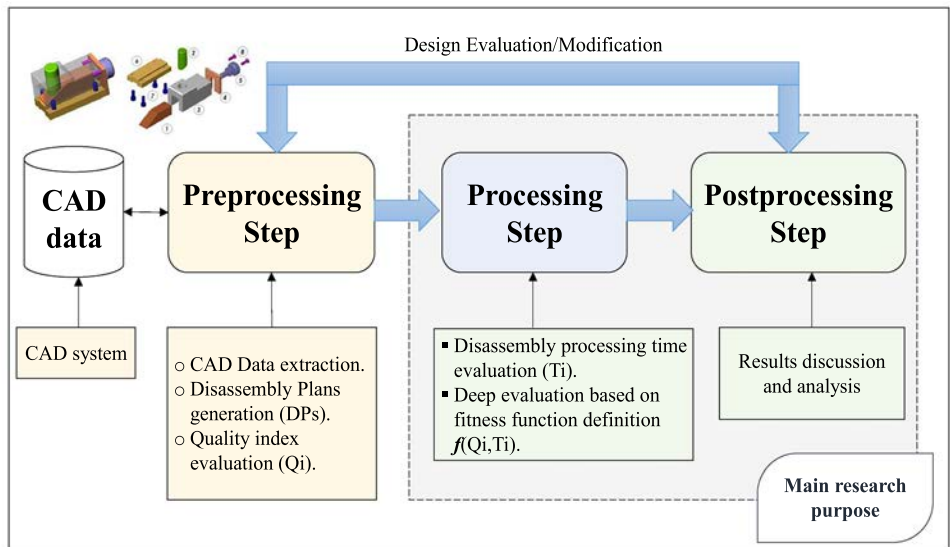


Fig. 5 Iron triangle

## 9 Disassembly Operating-Time Definitio

In order to evaluate a process time, it is quite important to measure the time of every elementary operation that sequentially composes it. In this work and by analogy on the previous section, the DP is built on multiple subsets' disassembly, which are by their own built on the disassembly of every part of it. Consequently, the processing time of a  $DP_i$  is theoretically given by formula (6):

$$T_{DP(i)}^{\text{theo}} = \sum_{j=1}^n T_{D-\text{sub}(j)} = \sum_{j=1}^n \left[ \sum_{k=1}^p T_{D-\text{part}(k)} \right]_{[j]} ; \begin{cases} 1 \leq i \leq 32, & i \in N \\ 1 \leq j \leq n, & \{j, n\} \in N \\ 1 \leq k \leq p, & \{k, p\} \in N \end{cases} \quad (6)$$

where,  $T_{DP(i)}^{\text{theo}}$  is the global theoretical time of disassembly plan “i”,  $T_{D-\text{sub}(j)}$  is the disassembly time of subassembly “j” which is given by formula (7):

$$T_{D-\text{sub}(j)} = \sum_{k=1}^p T_{D-\text{part}(k)}, \quad (7)$$

$T_{D-\text{part}(k)}$  is the disassembly time of part “k”, n is the number of subsets per DP, p is the number of parts per subset.

With reference to Belhadj et al. [16], a list of industrial timing standard operation was given to evaluate the time of the needed operations for the treated mechanism. Based on this timing and in order to calculate the processing time of a DP, it is necessary to calculate the time of every subset’s disassembly in advance. For the treated mechanism, Table 2 recapitalizes the disassembly time of each subset.

As an example, given by Table 1, the  $DP_1$  was used, to preview the associated theoretical processing time based

**Table 2** Subsets’ disassembly time

	Operation	Tool	Elementary Time (s)		Total time (s)	
SUB1	Unmount the intermediate shaft (7)	Manual	15		200	
	Remove the bearing (6)	Press-machine	45			
	Remove the bearing (10)	Press-machine	45			
	Unmount the input wheel (15)	Manual	35			
	Unmount the elastic ring (16)	Elastic-ring tool	15			
	Remove the bearing (17)	Press-machine	45			
SUB2	Remove the output shaft (2)	Manual	15		155	
	Remove the bearing (3)	Press-machine	45			
	Unmount the elastic ring (4)	Elastic-ring tool	15			
	Unmount the output wheel (5)	Manual	35			
	Remove the bearing (9)	Press-machine	45			
SUB3	Loosen screw (18)	Screwdriver	16.5	0	<b>3 → 5</b>	<b>5 → 3</b>
	Loosen screw (19)	Screwdriver	16.5	0		
	Loosen screw (20)	Screwdriver	16.5	0		
	Loosen screw (21)	Screwdriver	16.5	0	109	10
	Loosen screw (22)	Screwdriver	16.5	0		
	Loosen screw (23)	Screwdriver	16.5	0		
	Remove the main cover (1)	Manual	10	10		
SUB4	Remove the middle cover (8)	Manual	20		20	
SUB5	Loosen screw (18)	Screwdriver	0	16.5	<b>5 → 3</b>	<b>3 → 5</b>
	Loosen screw (19)	Screwdriver	0	16.5		
	Loosen screw (20)	Screwdriver	0	16.5		
	Loosen screw (21)	Screwdriver	0	16.5	109	10
	Loosen screw (22)	Screwdriver	0	16.5		
	Loosen screw (23)	Screwdriver	0	16.5		
	Remove the main cover (13)	Manual	10	10		
SUB6	Remove the input Shaft (12)	Manual	15		105	
	Remove the bearing (11)	Press-machine	45			
	Remove the bearing (14)	Press-machine	45			

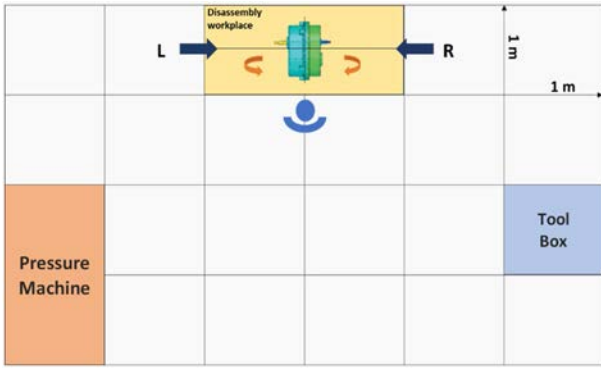


Fig. 6 Lay-out of the disassembly working area for the treated example

on formula (6): DP1: (SUB3 → SUB2 → SUB4 → SUB1 → SUB6 → SUB5),

$$\begin{aligned}
 T_{DP1}^{theo} &= T_{D-sub(3)} + T_{D-sub(2)} + T_{D-sub(4)} \\
 &\quad + T_{D-sub(1)} + T_{D-sub(6)} + T_{D-sub(5)} \\
 &= 109 + 155 + 20 + 200 + 105 + 10 \\
 &= 599 \text{ seconds.}
 \end{aligned}$$

### 9.1 Workplace representation and preparation time evaluation

In the industrial environments, in the real workplace, and after practical operative simulations and tests, there are

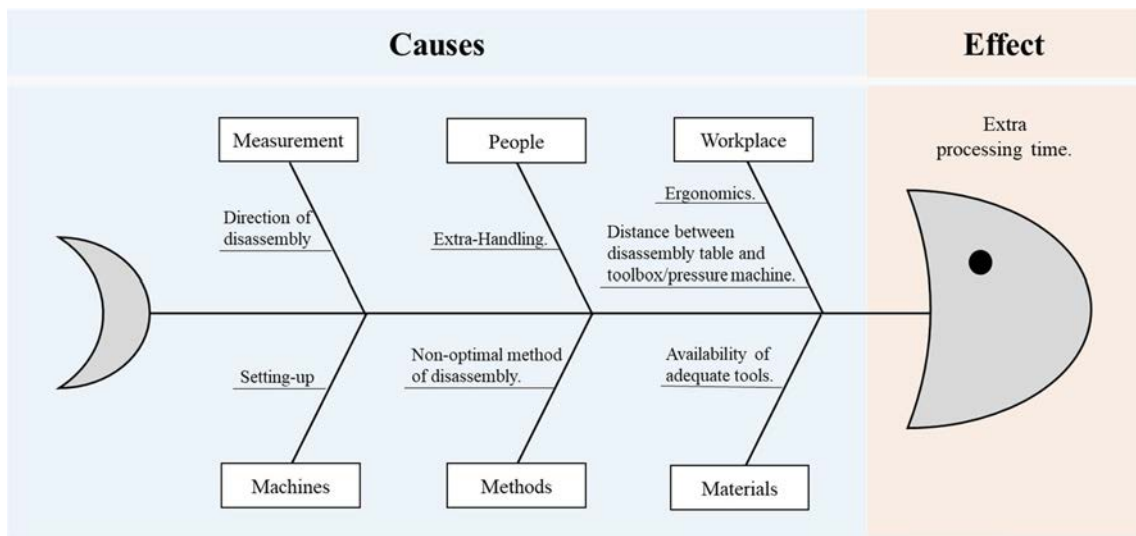


Fig. 7 Ishikawa diagram for the Workplace evaluation

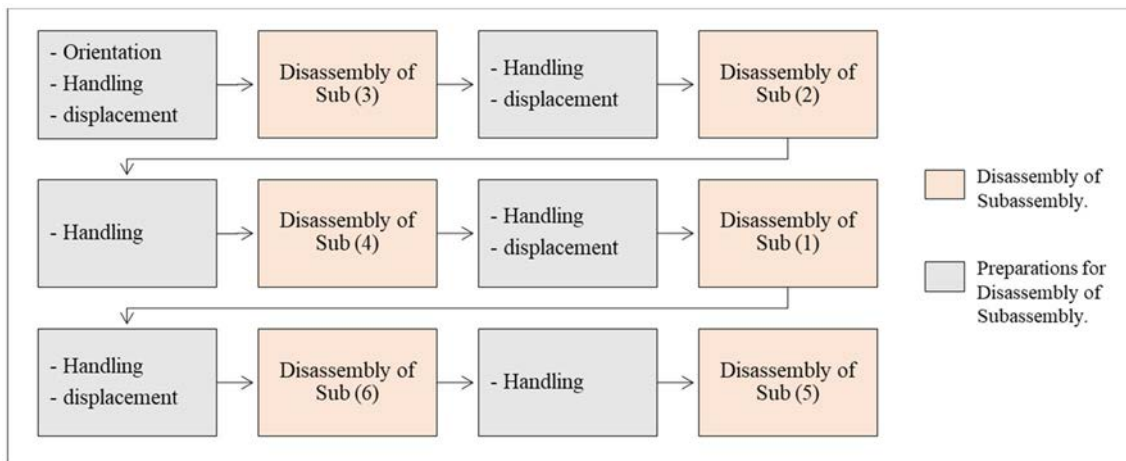
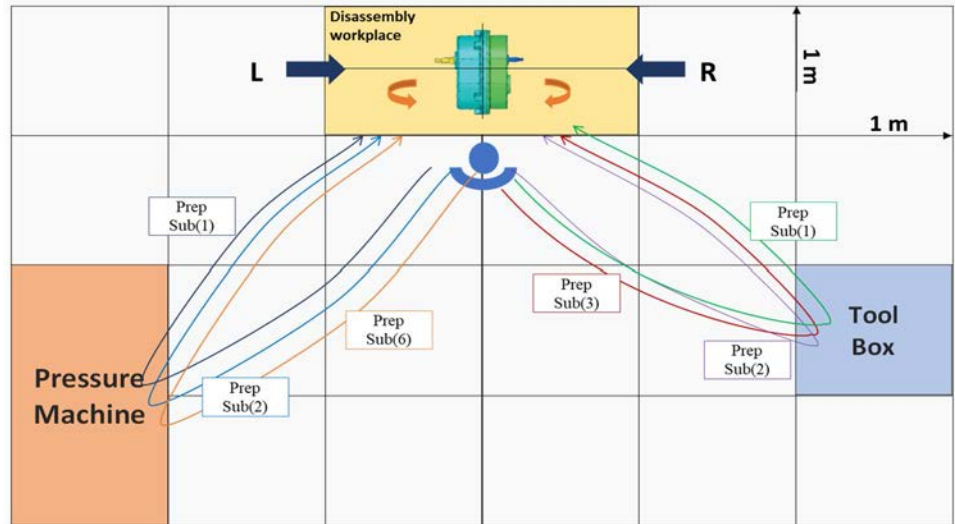


Fig. 8 Logical diagram of DP1 execution

**Fig. 9** Spaghetti diagram of DP1 execution



**Table 3** Standard preparation operations

Abbreviation			Operation of preparation	Preparation Type	Time (seconds)		
D-0°	D-90°	D-180°	Turn the assembly to the needed direction	Direction	0°	90°	180°
					0	15	30
S			Detect the Screw type	Tool	4		
E			Detect the Elastic-ring type	Tool	5		
P			Bring the sub-assembly to the pressure machine	Motion	27		
T			Bring the needed tool from the tool box	Motion	13		
H-L	H-M	H-H	Handling and manipulation	Handling	Low (H-L)	Medium (H-M)	HIGH (H-H)
					4	7	11

many internal/external circumstances and constraints that can affect tasks execution. One of the most critical parameters that often influences the processing time, is the workplace of an operator and its workflow. The workplace where the disassembly of the treated mechanism has been executed is presented in Fig. 6. The Ishikawa diagram, shown in Fig. 7, has been used to prove the impact of the workplace on the processing time.

In real operative conditions, and with reference to the working area lay-out presented in Fig. 6, operator is obliged to do many actions (motions, transport, handling, etc.) in order to be effectively prepared for the main disassembly operations. One of the most used tools by industrial engineers, which help to observe flows (workflow, material flow, informational flow, etc.) in a working area, is the Spaghetti diagram. This diagram, is used to visualize the workflow of a DP execution. To perform the Spaghetti diagram, a DP logical diagram must be performed. The logical diagram of a DP, takes in consideration all needed preparations for every dismounting of subassemblies and parts. Figure 8 illustrates the DP1 logical diagram for the treated mechanism, where DP1 is as follow: SUB3 → SUB

2 → SUB4 → SUB1 → SUB6 → SUB5. Figure 9 presents the Spaghetti diagram of the DP1.

Preparations and arrangements differ from an operation to another, it depends on several aspects such as: the needed tool, operation, motion, degree of handling, etc. Table 3 summarizes all types of needed preparation operations for the dismounting of the treated mechanism.

## 9.2 Timing Calculation of DPs

After definition of preparation time, the real processing time of DP<sub>i</sub> is given by formula (8). Based on Subset' disassembly time given by Table 2 and with reference to standard preparation operations specified in Table 3, the real processing time of every DP was calculated, with use of formula (8), and presented in Table 4.

$$T_{DP(i)}^{Real} = \sum_{j=1}^n [T_{prep(j)} + T_{D-sub(j)}], \quad (8)$$



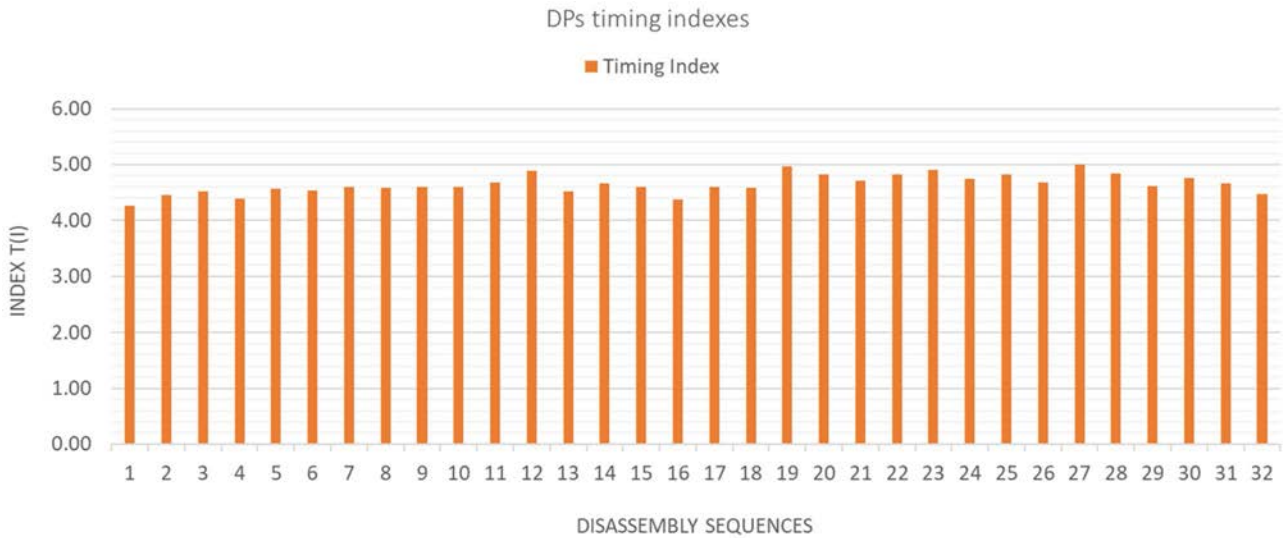


Fig. 10 Timing index evolution of each DP for the treated example



Fig. 11 Quality and timing indexes evolution of each DP for the treated example

## 10 Results Discussion: Post Processing Step

In this section, a deep analysis is elaborated based the calculated indexes (coupling between  $Q_i$  and  $T_i$ ), in target of optimizing decision for DP's selection. In fact, in addition to quality rate criterion, real processing time is obviously taken in consideration.

### 10.1 Dual ( $T_i$ , $Q_i$ ) representation and analysis

In order to visualize and compare the quality of the 32 DPs of the treated example, Fig. 11 elucidates the coupled display of  $T_i$  and  $Q_i$  indexes for each DP.

For the  $Q_i$  rate interpretation, the best DP is the one that has a maximum  $Q_i$  rate. But it is the opposite case for  $T_i$ , because the best DP is the one that must have a minimum

**Table 6** DPs Gap  $\delta$  calculation for the treated example

DP(i)	Qi	Ti	Gap $\delta$	DP(i)	Qi	Ti	Gap $\delta$
DP1	2.50	4.26	1.76	DP17	2.4	4.60	2.20
DP2	2.60	4.46	1.86	DP18	2	4.58	2.58
DP3	2.40	4.52	2.12	DP19	2.25	4.97	2.72
DP4	2.00	4.40	2.40	DP20	1.7	4.82	3.12
DP5	2.80	4.56	1.76	DP21	1.8	4.71	2.91
DP6	2.70	4.54	1.84	DP22	1.8	4.82	3.02
DP7	2.50	4.60	2.10	DP23	2.6	4.90	2.30
DP8	1.80	4.58	2.78	DP24	2.7	4.74	2.04
DP9	1.60	4.60	3.00	DP25	1.5	4.82	3.32
DP10	1.90	4.60	2.70	DP26	1.4	4.67	3.27
DP11	2.30	4.69	2.39	DP27	1.6	5.00	3.40
DP12	2.10	4.89	2.79	DP28	1.65	4.84	3.19
DP13	2.10	4.52	2.42	DP29	1.9	4.62	2.72
DP14	2.2	4.66	2.46	DP30	1.9	4.76	2.86
DP15	2.9	4.60	1.70	DP31	1.9	4.66	2.76
DP16	2.8	4.38	1.58	DP32	1.7	4.47	2.77



**Fig. 12** DPs Quality Timing and Gap indexes evolution of each DP for the treated example

$T_i$  rate. In fact, it represents the less processing time of disassembly which means, in production point of view, the higher efficiency. For a considered DP, to ensure an optimum between  $Q_i$  and  $T_i$  indexes, a difference ( $T_i - Q_i$ ) gap should be studied.

### 10.2 Difference ( $T_i - Q_i$ ) Gap representation

At this advanced level, the decision making to choose the optimal DP will be simultaneously based on the two main indexes which are  $T_i$  and  $Q_i$ . Thus, the optimum needed DP must have the minimum rate of  $T_i$  and the maximum rate of  $Q_i$ . In order to respond to these selection conditions, an objective function that aims at maximizing the rate of quality  $Q_i$  and minimize

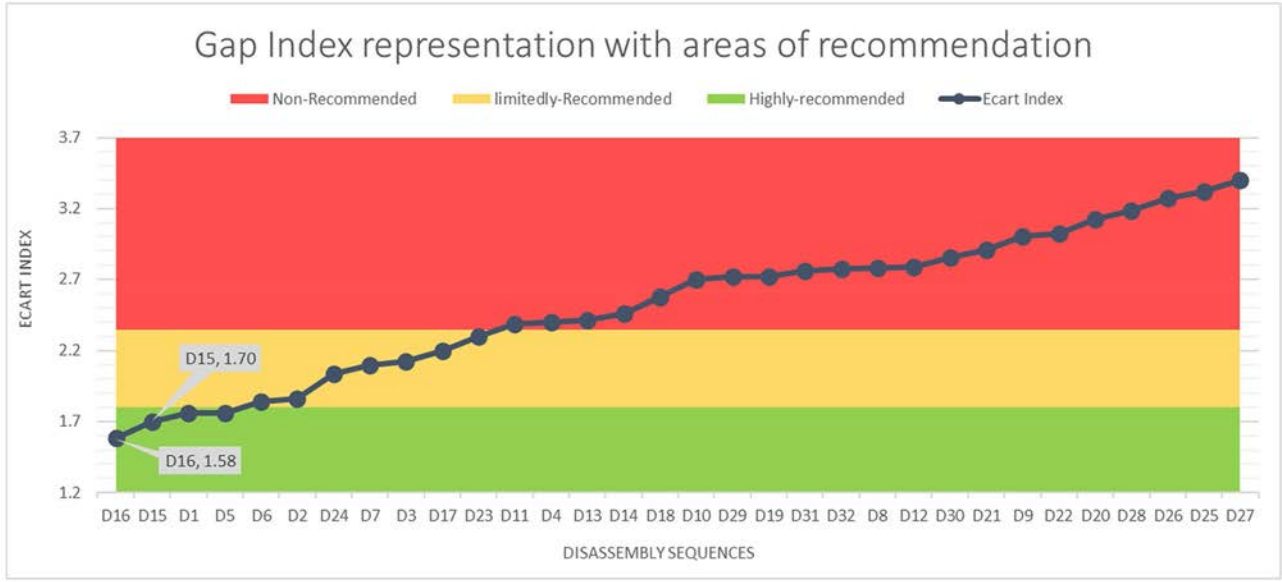


Fig. 13 Gap index evolution with recommendation areas

processing time  $T_i$  is used. This function is given by formula (10):

$$DP_{\text{optimal}} = \left[ \max_{i=1 \rightarrow 32} (Q_i); \min_{i=1 \rightarrow 32} (T_i) \right]. \quad (10)$$

In order to respond to the criterion given by Eq. (10) and determine the optimum DP, a gap parameter, defined by  $\delta_i$ , which represents the difference between  $Q_i$  and  $T_i$ , is calculated using Eq. (11). Table 6 presents  $Q_i$ ,  $T_i$  and  $\delta_i$  for each generated DP for the treated example.

$$\delta_i(DP_i) = T_i - Q_i. \quad (11)$$

At this stage,  $\delta_i$  has been added to  $T_i$  and  $Q_i$  graphs and got represented together in a same graph shown in Fig. 12. In order to fulfill condition of optimal DP by maximizing  $Q_i$  and minimizing  $T_i$ , the value of  $\delta_i$  has to be minimal and given by Eq. (12):

$$\left\{ \min_{i=1 \rightarrow 32} \delta_i(DP_i) \right\} \Rightarrow \left\{ DP_{\text{optimal}} = \left[ \max_{i=1 \rightarrow 32} (Q_i); \min_{i=1 \rightarrow 32} (T_i) \right] \right\}. \quad (12)$$

It can be concluded from Fig. 12, that the minimal value of  $\delta_i$  corresponds to  $\delta_{16}$  which is equal to 1.58. This result corresponds to DP16. As an observation, DP16 represents the optimal disassembly plan according to, simultaneously, the quality and the processing time indexes.

## 11 Discussion and synthesis

In a previous research approach [17], which represents a basis for this work, was concluded that the optimal DP is  $DP_{15}$  with a  $Q_{15} = 2.90$  (selection was done based on only one criterion which is quality index). In the current approach, decision making was taken with reference to two indexes at the same time which are the processing time index  $T_i$  and the quality index  $Q_i$ . Using the novel approach, it was deduced that  $DP_{16}$  ( $T_{16} = 4.38$ ;  $Q_{16} = 2.80$ ) is the optimal DP. At a first view  $Q_{15}$  which is equal to 2.90 is higher than  $Q_{16}$  which is equal to 2.80. But in a second level it was noticed that  $T_{15}$  which is equal to 4.60 is lower than  $T_{16}$  which is equal to 4.38. This comparison means that  $\delta_{16}$  which is equal to 1.58 is lower than  $\delta_{15}$  which is equal to 1.70. Consequently, in response to the quality–time–cost balancing triangle and with a background of productivity and efficiency, it was figured out that  $DP_{16}$  is better than  $DP_{15}$ . Furthermore, for some reasons of cost and production capacity, a tolerance can be allowed to the DP selection procedure based on  $\delta_i$ . On this basis, a conditional area of acceptance, with well-defined boundaries, is created and presented in a same graph shown in Fig. 13. Boundary-limits are defined in Eq. (13):

$$\begin{aligned} 0 < \delta_i \leq 1.80 &\Rightarrow \text{highly recommended} \\ 1.80 < \delta_i \leq 2.35 &\Rightarrow \text{limitedly recommended} \\ 2.35 < \delta_i \leq 5 &\Rightarrow \text{not recommended.} \end{aligned} \quad (13)$$



## 12 Conclusion and Future Work

This paper presents, a mathematical formulation for operating time computing in order to evaluate the generated DPs of industrial mechanisms. The proposed formulation is based on the Lean tools which are most used in today's industry. In this work a timing index ( $T_i$ ) is developed to study in depth all disassembly operations according to industrial practices. A coupling between  $Q_i$  and  $T_i$  indexes is finally considered in response to the Quality-Time-Cost balancing triangle and with a background in productivity and efficiency. The better DPs having the highest  $Q_i$  and the lower  $T_i$  which is given by the index gap  $\delta$  can be chosen for the practice industrial execution. In this work, the highest  $Q_i$  corresponds to a DP having a lowest change of disassembly tools and directions and rapidity reach to wear parts. However, a lower  $T_i$  which means, in production point of view, the higher efficiency. The main added values of the proposed work are:

- The use of Lean tools to select DP with a low timing index ( $T_i$ ) which respects the quality-time-cost balancing triangle and with a background in productivity and efficiency.
- The capability to consider complex machines with a large number of parts.
- The classification of DPs using  $Q_i$  and  $T_i$  indexes which are based on criteria related to disassembly line conditions and industrial practices.

The previous mentioned benefits are helpful to validate the design solution but can be improved by considering additional concepts in accordance with customer and especially environment requirements. As a future work, the proposed tool can be enhanced by considering the assembly and disassembly cost criterion as well as the consumed energy criterion for the assembly or disassembly plans.

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**Availability of Data and Materials** The authors declare that all relevant data are within the paper and its supporting information file.

### Declarations

**Conflict of Interest** The authors declare that they have no competing interests.

**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.

**Consent to Participate** The authors declare that there is no objection.

**Consent to Publish** The authors declare that there is no objection.

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