Production & Manufacturing Research
An Open Access Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tpmr20

Augmented reality applied to design for disassembly assessment for a volumetric pump with rotating cylinder

Leonardo Frizziero, Christian Leon-Cardenas, Marco Freddi, Alessandro Grassoni & Alfredo Liverani

To cite this article: Leonardo Frizziero, Christian Leon-Cardenas, Marco Freddi, Alessandro Grassoni & Alfredo Liverani (2023) Augmented reality applied to design for disassembly assessment for a volumetric pump with rotating cylinder, Production & Manufacturing Research, 11:1, 2199815, DOI: 10.1080/21693277.2023.2199815

To link to this article: https://doi.org/10.1080/21693277.2023.2199815

Published online: 25 Apr 2023.

PRODUCTION & MANUFACTURING RESEARCH
2023, VOL. 11, NO. 1, 2199815
https://doi.org/10.1080/21693277.2023.2199815

Augmented reality applied to design for disassembly assessment for a volumetric pump with rotating cylinder

Leonardo Frizziero, Christian Leon-Cardenas, Marco Freddi, Alessandro Grassoni and Alfredo Liverani

Department of Industrial Engineering, Alma Mater Studiorum - University of Bologna, Bologna, Italy

ABSTRACT

Design for Disassembly (DfD) and Augmented Reality (AR) have become promising approaches to improve sustainability, by providing efficient delivery and learning assets. This study combines DfD and AR to deliver a method that helps to streamline maintenance processes and operator training. It focuses on a common part in the process industry that requires frequent maintenance and repair. DfD was applied to the pump's design to ease disassembly and reduce material waste, energy consumption, and maintenance time. AR was used to provide an interactive guide to improve the operator understanding of its internal parts and assembly/disassembly procedures. The resulting DfD-AR led to a reduction in maintenance time and shows potential to deliver better training. This highlights the potential of DfD and AR to enhance sustainability, learning, and productivity. The resulting disassembly sequence was taken to an AR simulation, helping process designers to better understand the procedure and further optimize the solution with other constraints.

ARTICLE HISTORY
Received 20 April 2022
Accepted 1 April 2023

KEYWORDS
Augmented reality (AR); design for disassembly (DfD); recycling; optimization

1. Introduction: design for disassembly and augmented reality

Design for disassembly (DfD) is a method that allows to find the disassembly sequence of a varying mechanical complexity (Abuzied et al., 2020; Rasmussen et al., 2019). The purpose of DfD is to obtain a sequence list of all the operations (tasks) to perform, taking account with related information (timing, methods, tools, and operators) needed to dismantle all the components of the product or only those necessary to extract a certain component (target). This is particularly useful for those operators dedicated to maintenance processes, who can follow a clear work schedule for complete or necessary disassembly of the parts (Kissi et al., 2019). It is clear how this approach provides advantages in the maintenance of industrial machinery formed by hundreds of components, particularly in terms of time, costs, and resources. The maintenance and service that is performed on the components can be preventive or corrective. In the first

CONTACT Christian Leon-Cardenas christian.leon2@unibo.it; Marco Freddi marco.freddi2@unibo.it Department of Industrial Engineering, Alma Mater Studiorum - University of Bologna, Bologna, Italy

case, the element is replaced in advance, before a possible failure. In the second case, the replacement or repair of a damaged component happens after the fact (Manfè et al., 2013). Therefore, DfD allows the straightforward servicing of a component, a portion of it, or the recovery of the material and its reuse. DfD is also important for environmental impact, since it reduces the consumption of materials and allowing reusage of components, as shown in Figure 1, decreasing the pollution generated.

In conclusion, DfD helps to develop the product life cycle by incorporating the recovery of parts or materials at the end of the life cycle, it improves the quality of processing, it offers more flexibility, and it reduces disassembly time and costs, consumption of resources, and waste (O'grady et al., 2021). An essential aspect of the DfD is the 'disassembly depth', which is the total number of disassembly steps to perform. The removing total cost curve of a component has an approximately linear trend with the depth of disassembly, unlike the revenue. Specifically, we are talking about the Disassembly Sequence Planning (DSP): a special application of DFD for the disassembly sequence planning of the product. The DSP aims to reduce the complexity of disassembly to get to the specific component that requires servicing. For this reason, it is crucial to consider some important guidelines: the choice of recyclable materials, the reduction, standardization, and simplification of fasteners and connecting elements (O'grady et al., 2021). In addition, it is necessary to consider the movements of the operators considering their fatigue and effort, the handling of work tools, the structure of the product, the removal sides of the components, the various dimensions, ergonomically and operational constraints. There are two kinds of disassembly processes: a complete disassembly when all elements are removed, or a selective disassembly, when only the necessary components are removed to get to a particular component (target). Disassembly can also be destructive or non-destructive, depending on the necessity or not to break a component to remove it. The following methods that will be presented offer non-destructive disassembly. However, researchers have found several challenges in DSP, as a different approach proved to be optimal according to the part complexity and scope of the sequence obtained, varying those results from a selective disassembly sequence planning (SDSP) for repair and maintenance; differentiated from a partial DSP (for precious material recovery) delivered by Anil Kumar et al. (Anil Kumar et al., 2021); until a complete DSP (for safe disposal at end-of-life products) as outlined by Gunji et al. (Gunji et al., 2021). Artificial Intelligence nowadays helped researchers to portray combined approaches, based on an optimal function gathering to reduce disassembly times by considering tool changes, gripper changes and directional changes as parameters. A case study on a hybrid, Exponential Moving Average (EMA) – with Particle

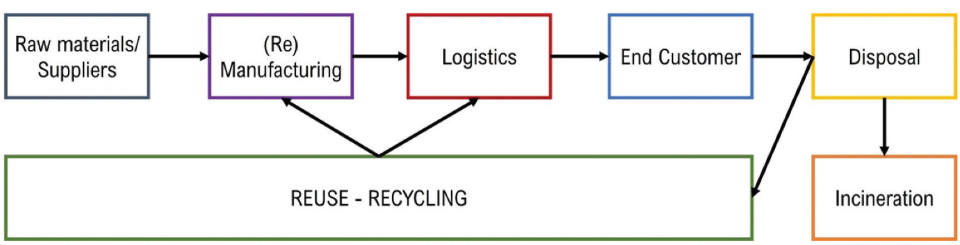

Figure 1. Resources reprocess to develop circular economy.

Swarm Optimization (PSO) was proposed by Gulivindala et al. (Gulivindala et al., 2021) and compared the calculations made by both instances.

Moreover, other research approaches on product disassembly are ruled out by the development of various mathematical models to better calculate the most energy-efficient, viable sequence by means of a stochastic disassembly network plot, combined with a number of considered disassembly decision-making properties (G. Tian et al., 2012); another proposal (G. Tian et al., 2022) handles a new heuristic method with multiple targets to minimize smoothness, as well as disassembly-related costs and energy consumption; as well as a low-carbon inspired design disassembly line balancing fruit fly optimization algorithm (MDFOA) (Yang et al., 2019); lastly, an approach to find the optimal, energy-efficient scheduling problem (Z. Tian et al., 2023) with a number of constraints of diverse resources tuned up to a small-batch, dynamic flexible job shop for the aerospace industry.

Furthermore, Disassembly Geometric feasibility (GF) is ultimately needed in order to identify potential collision paths in robotic assembly path design (Kumar et al., 2022). The gathering of a feasible assembly sequence to be performed by a robotic arm also represents utter positive assembly costs that are important to industries to develop a cost-effective manufacturing process (Raju Bahubalendruni & Biswal, 2015). Researchers have aid to develop an algorithm that can successfully solve an assembly sequence generation with account of the exploded view creation altogether (M. V. A. R. M. V. A. Bahubalendruni et al., 2019). Likewise, an assembly sequence that uses more parallel possible stable sub-assemblies proved to reduce the overall assembly time in large-scale production facilities (M. V. A. Bahubalendruni et al., 2019).

Consequently, Augmented Reality (AR) technology will be applied in this study: a highly interactive visual method used to present digital information in the physical (real) space (Chang et al., 2017; Xiong et al., 2021). AR is used in many industries: medical, education, marketing, military, video games and manufacturing. This technology can be implemented through devices equipped with a camera and AR tracking and rendering software that recognizes useful images, shapes, objects, points, and curves. The device sets the virtual elements in defined points located in the space, to reproduce them in the real space. AR instructions can be easily published and displayed on a smartphone or tablet, and in many other types of company devices. In the manufacturing industry, AR offers a better way to create work instructions that are easily accessible, by overlapping digital content to real working environments. Augmented reality also enhances the front-line workforce by improving the dissemination of information (Harikrishnan et al., 2021; Jing et al., 2021; Radu et al., 2021) resulting in faster transfer of know-how, modernized training methods (Fernández-garcía, 2021), and instant remote access to skills, and ultimately higher customer experience. Augmented reality is redefining the way frontline employees acquire information and how they can digitally interact with the physical space around them (Li et al., 2021; Masclet et al., 2021). It is transforming human processes by accelerating skills development and supporting orientation (Hassan et al., 2021; Sampaio & Almeida, 2018; Singh et al., 2021). This transformation results into faster execution, fewer manual processes, and the ability to make better decisions (Martins et al., 2021). Industrial organizations in a variety of sectors around the world are already realizing how valuable a company-wide AR implementation is from an economic standpoint as well, by improving business results to the point of achieving the fastest and most significant ROI (Return of Investment), even towards achieving sustainability at work (Joerss et al., 2021). The first industrial companies to adopt augmented reality solutions are saving millions in operating costs by improving the productivity of frontline workers and reducing scrap, rework, and waste. AR offers benefits in several areas of practical application: can be leveraged to improve production, technical support (Bolano et al., 2021), and sales (Qin et al., 2021), thus in marketing (Tan et al., 2022). For example, Toyota has improved safety and communication in its factories by connecting subcontractors and employees remotely (Langlotz & Aurich, 2021), eliminating the need for traveling in person to the site to solve problems. Volvo Group simplified its quality control processes by converting digital information into quality control operating instructions (Rosales et al., 2021). These instructions allow technicians to examine engines quickly and accurately, as they leave the production line. Lastly, in a different industry, Cannondale improved its service process for independent bicycle repair shops to adapt 3D CAD data into interactive repair manuals (Auffinger, 2021): these manuals allow technicians to quickly identify the parts to be replaced without the need to perform lengthy research through instruction manuals or catalogs to order replacement parts.

The aim of this study is to portray a solution for a Disassembly Sequence for a regularly produced element that takes into account maintainability, reuse of the parts and constraint of movements by means of the following two theoretical methods of sequence calculation. The obtained sequence will be verified in a real case-inspired, Augmented Reality application, where this information can be exploited to obtain further information in benefit of the product design, production and after-sales areas.

2. Methods

2.1. First method

The first method studied for the research of the best disassembly sequence proposed by Mandolini et al. (Mandolini et al., 2018), based on the previous study of (Yi et al., 2008) and has become a feasible approach for assessing DfD (Alrufaifi, 2021). It is based on the concept of disassembly wave propagation: we choose the target component to be worked, then we imagine that a wave starts from this component and expands through all the components adjacent (Figure 2). A first wave, at the time instant $\tau 1$, crosses all the elements adjacent to the target component; then, at the time instant $\tau 2$, a second wave will cross the adjacent components, and the process repeats on each element. We repeat the procedure until all the components of the machine are crossed. Possible disassembly sequences are generated by removing all components that are present in the various waves, starting from the outermost (at time τn) to the innermost ($\tau 1$) until the target component. An important rule to remember is that it may be necessary to remove more than one component belonging to the same wave level, so during the process several removal steps can be performed (Su et al., 2021).

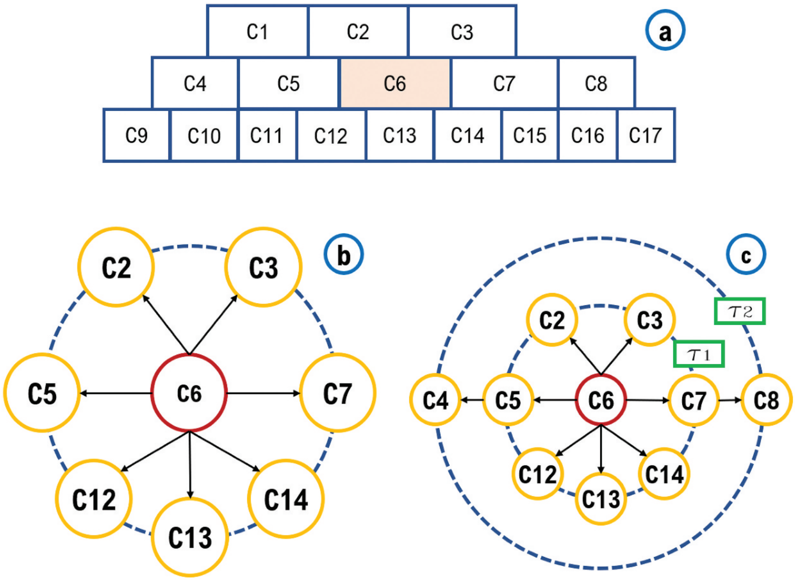

Figure 2. Example scheme for the first method. (a) Schematization of the positioning of components in the assembly; (b) Analysis of all components close to the target at time instant 1; (c) Continuation of the analysis for affected components at the next time instant.

2.2. Second method

The second method studied is based on the construction of a disassembly precedence matrix (DPM) (Laili et al., 2022), and a procedure proposed by Fei Tao et al. (Tao et al., 2018), which contains the information about the overall dimensions and spatial constraints and offers partial or parallel disassembly sequences. The DPM is a square matrix of n rows and n columns, considering the n components that form the mechanical product, and is formed in turn by four sub-matrices:

(1) The FFM (fasteners-fasteners matrix);
(2) The CFM (components-fasteners matrix);
(3) The FCM (fasteners-components matrix);
(4) The CCM (components-components matrix).

Moreover, it is important to indicate the removal directions of each component, through a sequence [-X, +X, -Y, +Y, -Z, +Z] that indicates the removal directions of the components for each vector of the three Cartesian directions (X, Y, Z). Examining the drawing of the product, we will consider the X-axis directed along the pump axis, the Y-axis upwards and the Z-axis directed out of the sheet and towards the observer. The sequence will consist of six digits of only 0 and 1, writing 1 at the component removal direction and 0 for the other directions (Table 1).

In the DPM matrix, every element contains the succession [-X, +X, -Y, -Z, +Z] of 0 and 1: the CFM submatrix, at the i-th row reports the limitations of the i-th component due to the presence of the j-th fastener in its removal direction. So, if

Table 1. Disassembly directions.

Directions	
Cartesian	Numerical
-x	100000
+x	010000
-y	001000
+y	000100
-z	000010
+z	000001

a certain j-th fastener hinders an i-th component along its removal direction, in the corresponding box will be inserted 1, otherwise 0. The same is true for the other sub-matrices. Whenever a component is removed, the corresponding row and column will be deleted, so the matrix is dynamic and decreases as disassembly process proceeds. It is possible to remove a component if a 0 appears at least in one Cartesian direction in the respective row of the DPM matrix. The method allows partial or parallel disassembly, or disassembly in modules, disassembly of blocks of several components and subsequent disassembly in parallel. We show the rules to follow for the creation of the disassembly sequences:

- R1: removal of the j-th fastener (Fj) if FCM(j,:) = 0 and FCM(j,:) = 0.

- R2: removal of the i-th component (Ci) if CFM(i,:) = 0 and CCM(i,:) = 0.

A third rule is added to these two rules in case of module disassembly, considering that within a module the relationships between the parts represent internal limitations to it, thus they do not affect the separation between modules.

- R3: module disassembly if no 1 appear in the rows of the DPM matrix, except for internal relations. So, to generate a partial or parallel disassembly sequence, five steps must be followed:

- P1: find any sequence of fasteners;

- P2: disassemble the fasteners in the order found. If a fastener satisfies the R2 rule, you can remove it and move on to step P3, otherwise you move on to the next fastener;

- P3: remove the components that satisfy the R2 rule;

- P4: if you get to the target component (partial disassembly) or complete disassembly, the final sequence has been found. If not, proceed to the next step;

- P5: check for modules that satisfy rule R3, if present disassemble them in parallel, otherwise go back to step P2. This second method, unlike the first, is not aimed at

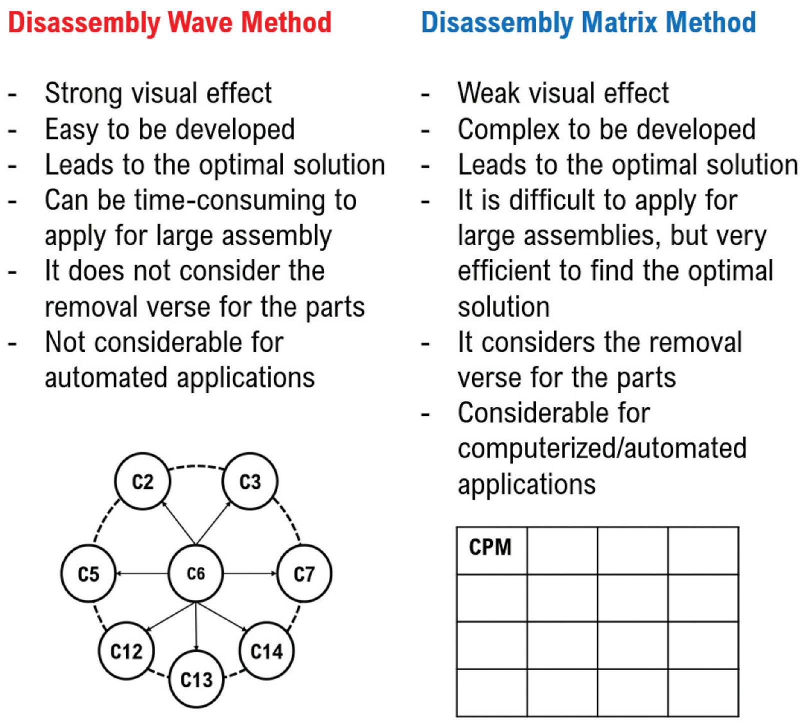

Figure 3. Comparison between the two methods.

finding a sequence for the removal of a target component but offers the possibility to find all disassembly sequences (partial or complete) that, if properly compared, can offer an optimal sequence for a target component that you choose.

A comparison between the two methods is analyzed in Figure 3.

2.3. Table of disassembly weights: time calculation

To measure the duration of the disassembly sequences found, a methodology present in research from Mandolini et al. (Mandolini et al., 2018), that allows to find out total Time Measurement Units (TMU) used by each strategy. Other outcomes of Deng-Zhi, Chen, et al. (Chen et al., 2020) optimized the time method through a flow balance in the AND/OR network for a large-scale disassembly evaluation. This method has the flexibility to optimize such time-calculus by generating disassembly subsets based on disassembly precedence relationships. In addition to the proposal of a selective parallel disassembly sequence planning (SPDSP) by Zhang, Lei, et al. (Zhang et al., 2021). However, this process establishes a summary table containing the estimates of the disassembly times of each type of component, calculated considering appropriate parameters that we will show. For each parameter, the relative weight is shown, i.e. disassembly time, expressed in TMU (Time Measurement Unit), i.e. a specific unit of measure used for these procedures. The conversion into minutes or seconds is immediate: 1 (TMU) = 0.0036 (seconds).

Proceed as follows: evaluate the weight of each parameter (force, weight, position . . .) of a component and then multiply them and obtain the corresponding value in TMU, repeat these steps for all components, add up all the values in TMU obtained and finally the final value is converted into seconds. For example, if the shaft component is considered, a weight is assigned to each of its parameters; these are multiplied to obtain the resulting value expressed in TMU. The procedure is iterated for all the components of the sequence, all the values obtained in TMU are added together and converted this value in seconds: Tot. Seconds = (Tot. TMU) * 0.036 (sec).

This mathematical procedure based on the use of tables is particularly advantageous in terms of time, compared to a practical measurement in the workplace, implemented by timing every single activity of the operators, because it allows knowing in advance, almost immediately, the duration of an activity. It is therefore easy to understand how this method facilitates the comparison between disassembly sequences during the design phase.

2.4. Augmented reality disassembly sequence simulation verification

Improvements on digital imaging technology developed during the last few years has given the possibility of improving the quality of artificial environments, by adding detail to the ambient created. High-quality environments have enabled users to portray realistic environments using fully digital platforms.

Therefore, Augmented reality (AR) is emerging as next-generation interactive element able to provide realistic three-dimensional (3D) visual experiences (Xiong et al., 2021). This technology has proven to be valuable in diverse fields such as education (Iatsyshyn et al., 2020), healthcare (Viglialoro et al., 2021), engineering (Hansen et al., 2021; Noghabaei et al., 2020) and gaming (Lehto et al., 2020), among many other areas. AR fosters the interaction between user, and the realistic ambient through digital contents, by portraying virtual images whilst maintaining a see-through capability. Nevertheless, AR has proved to be a viable alternative to enhance the understanding of production and manufacturing processes (Mourtzis et al., 2019), aiding the user to better understand the matters of a regular production environment (Lai et al., 2020), as well as quality control processes (Szajna et al., 2020).

3. Case study of a volumetric pump with rotating cylinder

3.1. Overview of piston pumps

Piston pumps are the best choice for high-pressure applications or those requiring great performances. They belong to the class of variable displacement pumps and offer a long service life and great efficiency. Radial piston pumps (Figure 4) are very robust radial devices with high volumetric efficiency, wide speed range and high reliability, even in severe conditions. The pump studied has a closed pump body, an intake line and a delivery line, is equipped with a hollow piston, with a spring inside that moves it, and radial to a shaft in which it is inserted. RN 3×11.8 type roller bearings are inserted between an inner and outer ring. The two side shims act as containment. Given the

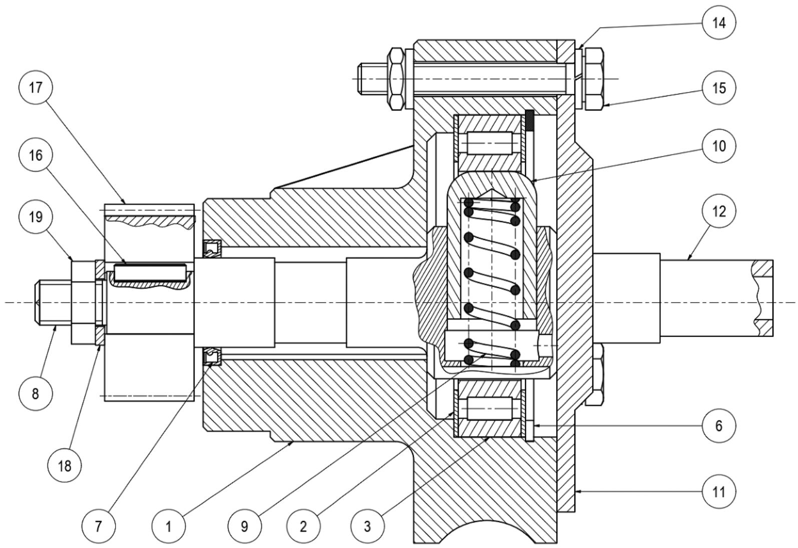

Figure 4. Representation of the constructed product.

Table 2. Bill of Materials (BOM).

No.	Description	Quantity	Material
1	Body	1	G-AlCu8 UNI 3043
2	Mech. shave	2	48S5 UNI 3545
3	Bearing	1	C10 UNI 5531
6	Ring 72 UNI 7437	1	
7	Oil seal	1	
8	Shaft	1	
9	Spring	1	
10	Piston	1	16CrNi4 UNI 5531
11	Dispenser	1	C72 UNI 5532
12	Delivery duct	1	C40 UNI 5532
13	Intake duct	1	G-AlCu8 UNI 3043
14	Rosette A 6.4 UNI 1751	3	C20 UNI 5532
15	M 6x30 UNI 5739–4.8	3	C20 UNI 5532
16	Key 3x6.6 UNI 6606	1	
17	Sprocket	1	
18	Rosette 10.5 UNI 1734	1	
19	Nut M 10 UNI 5588-5S	1	16CrNi4 UNI 5531

simplicity of the device and the small size, there are no bearings between the shaft and the body: for heavier tasks, the use of bushings or rolling bearings would be appropriate.

3.2. Cad modelling

Inventor, a 3D programming software produced by Autodesk, was used for the modelling of the product. It was chosen to use this program because it is simple, intuitive, practical, immediate and with a vast library of components, which proved to be very useful in this case. The first thing to do is to start by designing each component separately, following the Bill of Materials (BOM) of the product that is shown below in Table 2 to then assemble them.

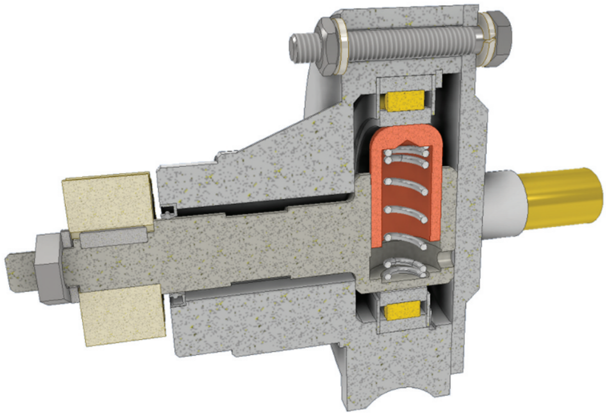

Figure 5. View of the construction in half section on Inventor.

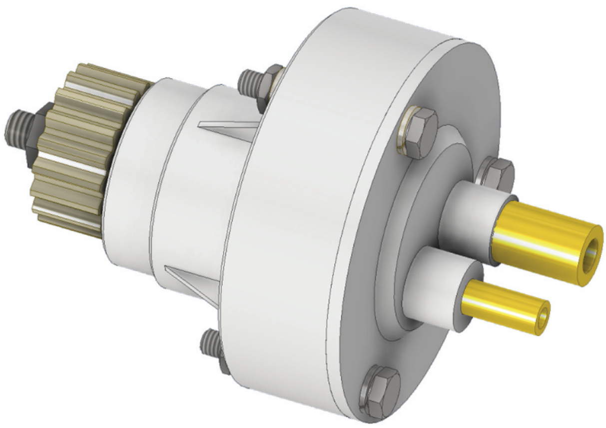

Figure 6. Representation of the final product on Inventor.

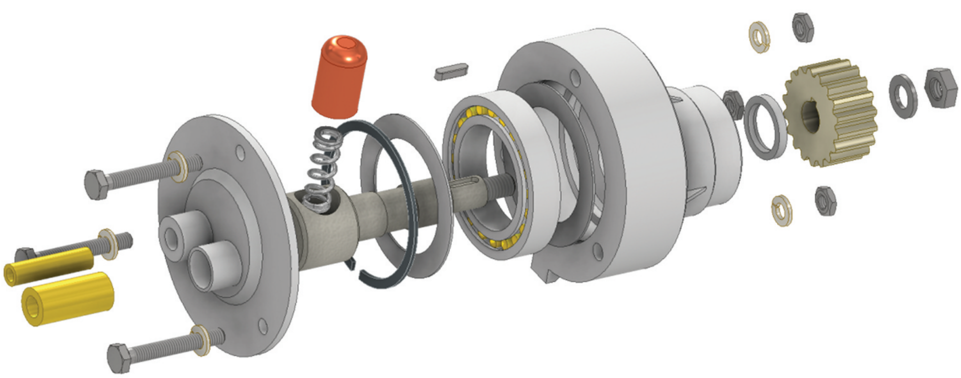

Figure 7. Exploded view of the rotary cylinder pump on Inventor.

At a first glance of the drawing, it is easy to see how this product has different types of connections:

- shaft-hub connections between the shaft and the body, between the piston and the shaft;
- elastic connection between spring and piston;
- threaded connections given by the screws and the nut;
- connection by key.

Elements such as the body, the shaft, the piston, the distributor, the delivery and suction fittings have been designed starting from the realization of the 2D sketches, respecting the dimensions detected by the drawings shown in Figures 5 and 6, and then using 3D model development functions such as *extrusion* or *revolution* depending on the components. The bearing (components 3,4 and 5) and the sealing ring were downloaded from the SKF website, a Swedish Company founded in 1907, operating in the mechanical sector, manufacturer of rolling bearings, sealing elements, lubrication systems, of which it offers downloadable 3D models. The two shims and the ring (component 6) were downloaded from the Inventor *content center*, a real library of components present in the software. The spring, pinion, screws, washers and tab elements were created in the *design section*, identifying the specific command for each component, as described below. The spring is one of the fundamental components of this device, since it guarantees the movement of the piston, but it is also one of the most stressed components and therefore subject to wear. It is a cylindrical, compression helix spring subjected to an axial load, which, acting at the ends, can cause an increase or decrease in the pitch of the helix. The spring material under load is mainly stressed in torsion. For its design, the appropriate *compression spring generator* command was used, in which it was sufficient to enter appropriate design parameters and then have the system doing the calculation. The pinion was processed through the *spur gear generator* command, another command found in the component design section. It was also necessary for this to insert appropriate calculation parameters relating to the gears. The screws and washers were made with a command *generating bolted connections*, dimensioning them on the existing holes and making the relative thread. The *key connection* generator was used for the key, entering the dimensions of the key and proceeding with the creation of the relative grooves on the shaft and pinion. Finally, only after having created all the components we did move on to the construction phase: we started from the body (component 1), to then import one component at a time and assemble it respecting constraints, joints and degrees of freedom, up to the assembly final (Figures 5 , 6 and 7).

3.3. First method application

The purpose of the first method is to find the best possible sequence to remove a certain component: the spring has been chosen as the objective component because, as previously mentioned, it represents one of the components most subject to stress and wear. Therefore, more likely its removal might be required, for maintenance or replacement.

We apply this method by reporting below the construction of the disassembly wave diagram (Figure 8): elements 3, 4 and 5 are considered as a single component, the bearing, both for simplicity in writing the program and in operation, since the removal of these components occurs in a single process.

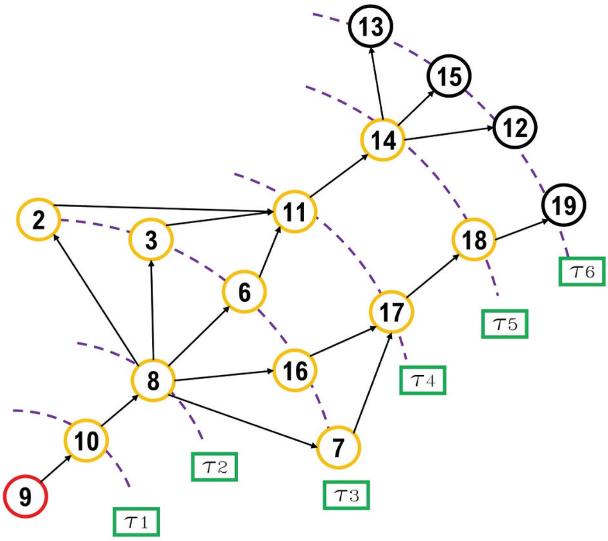

Figure 8. Wave scheme applied to the mechanical pump.

The sequence obtained is as follows: 19-12-13-15-18-14-11-17-6-2-3-16-7-8-10-9.

Remember that removing components 14 and 15 means removing three washers and three screws respectively, but for simplicity in the representation of the disassembly wave graph they are shown as single elements. However, observing the product component detail drawing it is possible to avoid removing the components present in the third disassembly wave τ3 of the diagram: the sealing ring (7), the key (16), the two shims (2), the ring (6) and bearing (3). Their permanence in the mechanism does not significantly affect the process since it is sufficient to apply a little extra force to remove the shaft (8).

Furthermore, also the components 12 and 13 cannot be removed, since they do not represent an impediment for the removal of the component 11, much less for the rest of the disassembly. Therefore, the sequence can be simplified as follows:

Table 3. Component Removal Verses.

Component	F or C	Removal verse
Body	C1	-
Mech. shave	C2	010000
Bearing	C3	010000
Ring 72 UNI 7437	C6	010000
Oil Seal	C7	100000
Shaft	C8	010000
Spring	C9	001000
Piston	C10	000100
Dispenser	C11	010000
Delivery duct	F12	010000
Intake duct	F13	010000
Rosette A 6.4 UNI 1751	C14	010000
M 6x30 UNI 5739–4.8	F15	010000
Key 3x6.6 UNI 6606	C16	000100
Sprocket	C17	100000
Rosette 10.5 UNI 1734	C18	100000
Nut M 10 UNI 5588-5S	F19	100000

Table 4. Matrices: a) FCM, b) CFM, c) FFM, d) CPM.

a) FCM

FCM	C2SX	C2DX	C3	C6	C7	C8	C9	C10	C11	C14	C16	C17	C18
F12	0	0	0	0	0	0	0	0	101111	0	0	0	0
F13	0	0	0	0	0	0	0	0	101111	0	0	0	0
F15	0	0	0	0	0	0	0	0	0	0	0	0	0
F19	0	0	0	0	0	0	0	0	0	0	0	0	010000

b) CFM Table

CFM	F12	F13	F15	F19
C2SX	0	0	0	0
C2DX	0	0	0	0
C3	0	0	0	0
C6	0	0	0	0
C7	0	0	0	0
C8	0	0	0	001111
C9	0	0	0	0
C10	0	0	0	0
C11	0	0	0	0
C14	0	0	011111	0
C16	0	0	0	0
C17	0	0	0	0
C18	0	0	0	100000

c) FFM

FFM	F12	F13	F15	F19
F12	0	0	0	0
F13	0	0	0	0
F15	0	0	0	0
F19	0	0	0	0

(*Continued*)

Table 4. (Continued).

d) CPM

CPM	F12	F13	F15	F19	C2SX	C2DX	C3	C6	C7	C8	C9	C10	C11	C14	C16	C17	C18
F12	0	0	0	0	0	0	0	0	0	0	0	0	101111	0	0	0	0
F13	0	0	0	0	0	0	0	0	0	0	0	0	101111	0	0	0	0
F15	0	0	0	0	0	0	0	0	0	0	0	0	0	100000	0	0	0
F19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10000
C2SX	0	0	0	0	0	0	10000	0	0	001111	0	001100	0	0	0	0	0
C2DX	0	0	0	0	0	0	100000	10000	0	001111	0	001100	0	0	0	0	0
C3	0	0	0	0	100000	10000	0	0	0	001111	0	001100	0	0	0	0	0
C6	0	0	0	0	0	0	0	0	0	001111	0	0	0	0	0	0	0
C7	0	0	0	0	0	0	0	0	0	001111	0	0	0	0	100000	100000	0
C8	0	0	0	001111	001111	001111	001111	001111	001111	0	0	0	10000	0	000100	001111	001111
C9	0	0	0	0	0	0	0	0	0	111011	0	00110111	0	0	0	0	0
C10	0	0	0	0	100	100	100	100	0	111011	111011	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0	0	0	0	0	10000	0	0	0
C14	0	0	011111	0	0	0	0	0	0	0	0	0	100000	0	0	0	0
C16	0	0	0	0	0	0	0	0	0	111011	0	0	0	0	0	001111	0
C17	0	0	0	0	0	0	0	0	0	011111	0	0	0	0	001000	0	100000
C18	0	0	0	100000	0	0	0	0	0	011111	0	0	0	0	0	010000	0

15-14-11-19-18-17-8-10-9.

3.4. Second method application

Before proceeding with the application of the second method, the same considerations made for the previous method are assumed regarding the choice of the target component (spring) and the bearing component 3 is renamed, as the set of elements 3,4 and 5.

It is important to identify the ways of removing the components, as explained previously in the presentation of the method, also identifying the fasteners. For the body component, the direction of removal is not indicated because it is considered fixed for the purposes of disassembly, all components are extracted from it (Table 3).

Subsequently, the precedence matrix is written (disassembly precedence matrix or DPM): for clarity, each sub-matrix is reported first and then followed by the entire matrix (Table 4). Also, in the following matrices the body component does not appear, for the same reason explained above. The element consideration is summarized in Figure 9.

Then proceed by following the steps shown previously in the explanation of the method, first removing the appropriate fasteners, and then moving on to the next components: remember that it is not necessary to remove all the fasteners before proceeding with the other components.

The sequence found by the analysis of the DPM matrix is: F15-C14-C11-F19-C18-C17-C8-C10-C9.

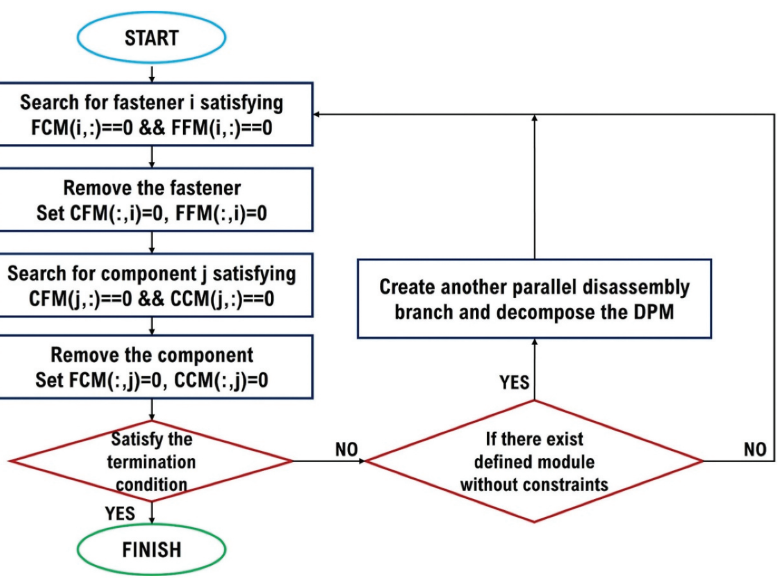

Figure 9. Flow chart for the second method.

Observing this last sequence obtained, it can be noted that the disassembly is uncomplete and components F12 and F13 had not been removed; in fact in this second method, after removing component C11, two modules M1 = (C11-C12-C13) and M2 are formed; they are composed by the remaining elements and, although the method foresees the parallel disassembly of the modules, in this case it is not necessary to dismantle the module M1, since the spring is present in the second module M2.

4. Results

4.1. Comparison of results and calculation of disassembly times

Both methods led to the same result, even though for the first case, the use of practical sense, together with the knowledge of the product component layout, allowed to exclude certain components from the disassembly process. The common result was obtained thanks to the simplicity of the product component, which allows disassembling mainly along a single direction, so there are few disassembly alternatives. However, between the two methods, the second one is what provided the optimal solution directly during its application, as it is known that the second method foresees additional complexity characteristics of the product, as summarized on Table 5 while the first served mainly to identify all possible sequences with a more simple approach. The optimal sequence is therefore the following: 15-14-11-19-18-17-8-10-9.

The next step is the evaluation of the disassembly times relatives to the best performing sequence found, using the disassembly weight tables presented previously.

Table 5. Pump component values.

Part	Force	Size	Weight	Symmetry	Tools	Access	Loc	Pas.	TMU	*SEC*
1	-	-	-	-	-	-	-	-	-	-
2	3	4	2	0.8	2	1.6	2	2	245.76	*17.69*
3	3.5	3.5	2	0.8	3	1.6	2	2	376.32	*13.55*
6	3	4	2	1.2	2	1.6	2	2	368.64	*13.27*
7	3	4	2	0.8	2	1.6	2	2	245.76	*8.85*
8	5	2	2	0.8	1	2	2	2	128	*4.61*
9	0.5	3.5	2	1.2	1	1.6	2	1.2	16.128	*0.58*
10	2.5	2	2	0.8	1	1.6	2	1.2	30.72	*1.11*
11	2	2	2	0.8	1	1	1	1.2	7.68	*0.27*
12	3	2	2	0.8	1	1	2	1.2	23.04	*0.83*
13	3	2	2	0.8	1	1	2	1.2	23.04	*0.83*
14	1	4	2	0.8	1	1	1	1.2	23.04	*0.8*
15	5.5	3.5	2	0.8	2	1	2	2	739.2	*26.6*
16	1	4	2	0.8	1	1	2	1.2	15.36	*0.55*
17	1	2	2	0.8	1	1	1.6	1.2	6.144	*0.22*
18	1	4	2	0.8	1	1	1	1.2	7.68	*0.28*
19	5.5	3.5	2	0.8	2	1	1	2	123.2	*4.4*

Table 6. Disassembly sequence values.

Part	15	14	11	19	18	17	8	10	9
TMU	739.2	23.04	7.68	123.2	7.68	6.144	128	30.72	16.128
SEC	*26.6*	*0.8*	*0.27*	*4.4*	*0.28*	*0.22*	*4.61*	*1.11*	*0.58*

Thereafter, in the construction of the table of disassembly weights of the pump components, the values of the body have not been reported since it is considered a fixed element (Table 5).

Consequently, as the disassembly sequence found the same order for both methods, the calculated duration is: 1081.79 (TMU) * 0.036 = 38.94 (seconds) (Table 6).

To conclude the discussion on Design for Disassembly, as already mentioned, for the evaluation of the best disassembly sequence other equally important factors must be taken into account in addition to the disassembly time. It is in fact essential to make an economic evaluation considering the workforce costs as well as the necessary tools and to include the cost related to the safety of the operators and the working environment, which involves the use of dangerous and harmful substances such as lubricants, oils and various residues.

4.2. AR application: unity and vuforia

An augmented reality application capable of showing a product being disassembled can play a key role in streamlining its maintenance process. Instead of equipping maintenance workers with instruction booklets and drawings difficult to understand, it makes it possible to show them how to proceed with the removal of various components. The order they will follow will be the optimal one to get to the end of the process using little time and the least number of resources (technological tools, machinery, number of workers, and so on). Both the industrial process and the learning of the workforce thus becomes immediate. This represents a factor entirely to the benefit of business productivity. The application in augmented reality here proposed shows how the costs to be faced by a company are rather small, but the potential that comes from the simplicity of applying the method is high. At the hardware level, in fact, it is sufficient to equip oneself with a few augmented reality visors.

In this case study, the augmented reality software Unity and Vuforia are used to create an explosion of the rotating cylinder pump assembly in augmented reality. Vuforia is a software development kit (SDK) of augmented reality, a sort of library that must be integrated into Unity. It provides fast and accurate image tracking allowing the virtual content to be superimposed on the images of the surrounding environment. First, a new project is created in Unity. Vuforia's online portal is used to create a license for the AR camera in Unity, characterized by an auto-generated code. Subsequently, an image target is developed: this is the object in the real world that the software recognizes when the camera records it, thanks to a set of geometrical target points located in the imagine areas with more particulars (). A very simple picture was created, and its final evaluation was 5/5 on Vuforia, which is the best. The Vuforia package was imported into Unity, then the AR camera, into which the license code and the target image were copied. It was necessary to convert the component assembly file into *obj* format and then load it into Unity and insert it as a *child* of the target image. This obj format file was recognized by the program, but it is monochrome: therefore, it was necessary to proceed with coloring each component separately using materials texture and realistic colors (Figure 10).

Finally, individual animations of the assembly were created, representing the exploded object, following the simulation of both disassembly sequences found previously and

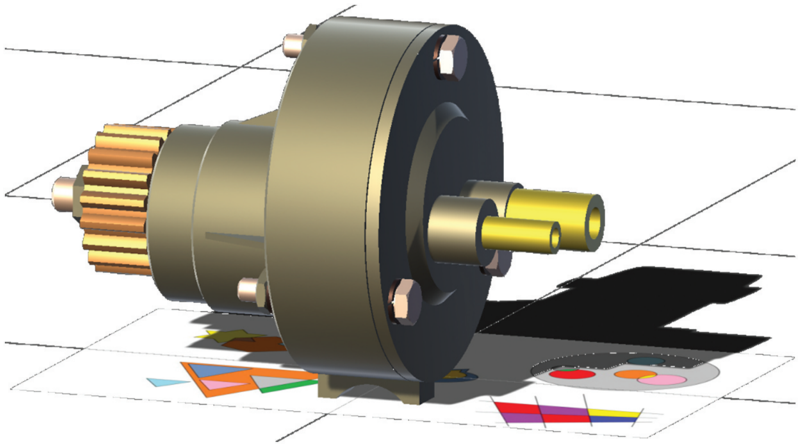

Figure 10. Assembly in Unity with the image target.

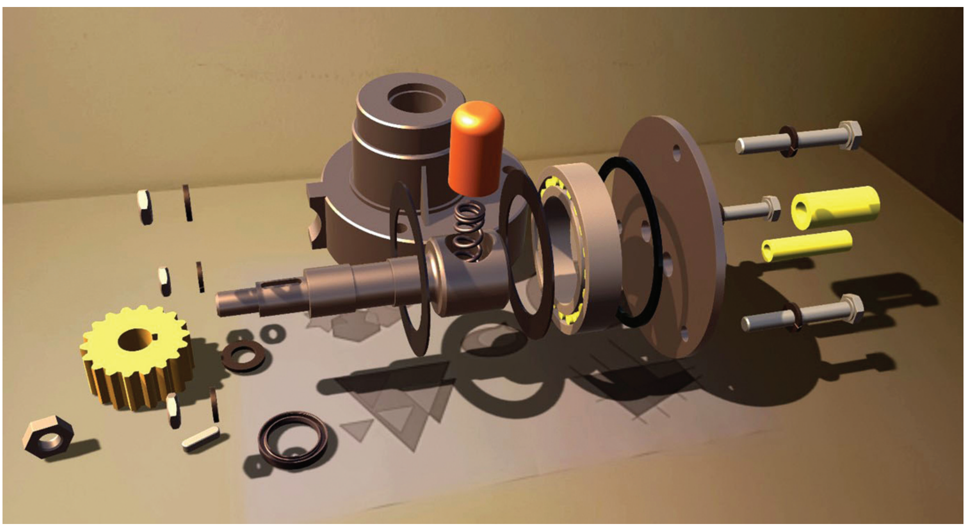

Figure 11. Augmented reality view of disassembly sequence 1.

comparing them. Each component was added to the animation and its position within the timeline was determined.

For an AR representation, the marker is framed with the webcam, so the device will automatically display the 3D assembly during the animation phase (Figures 11 to 14).

Moreover, further use of having this 3D assembly would allow to create individual scenes for every disassembly step, as well as indicate the correct direction of the parts dismantling. Figures 14 allow to see the Augmented reality video for servicing the pump. This animation would allow practitioners to be trained correctly to the handling operations of this type of mechanical element.

Finally, it is appropriate to underline the many other possibilities that can be proposed by having shown the features of the proper 3D assembly treatment possible by Unity, it is

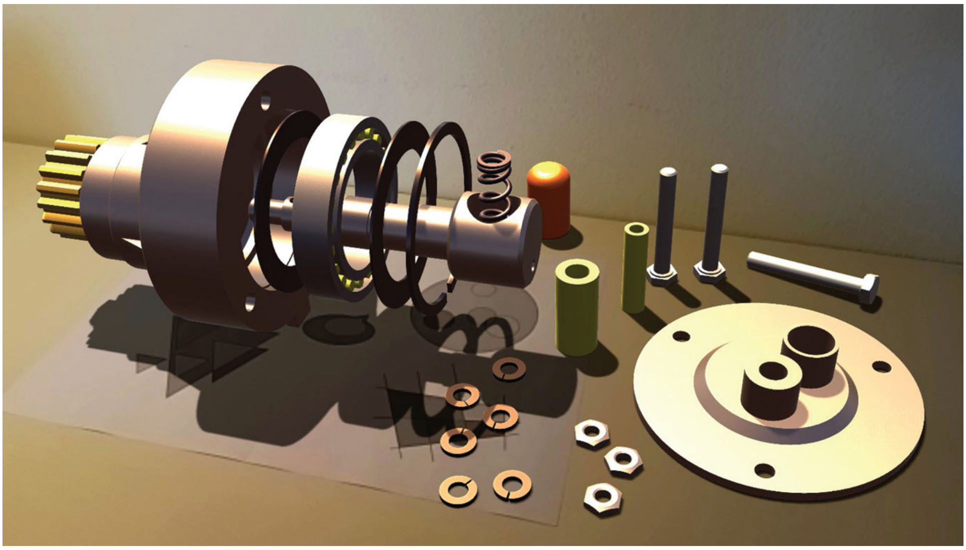

Figure 12. Augmented reality view of disassembly sequence 2.

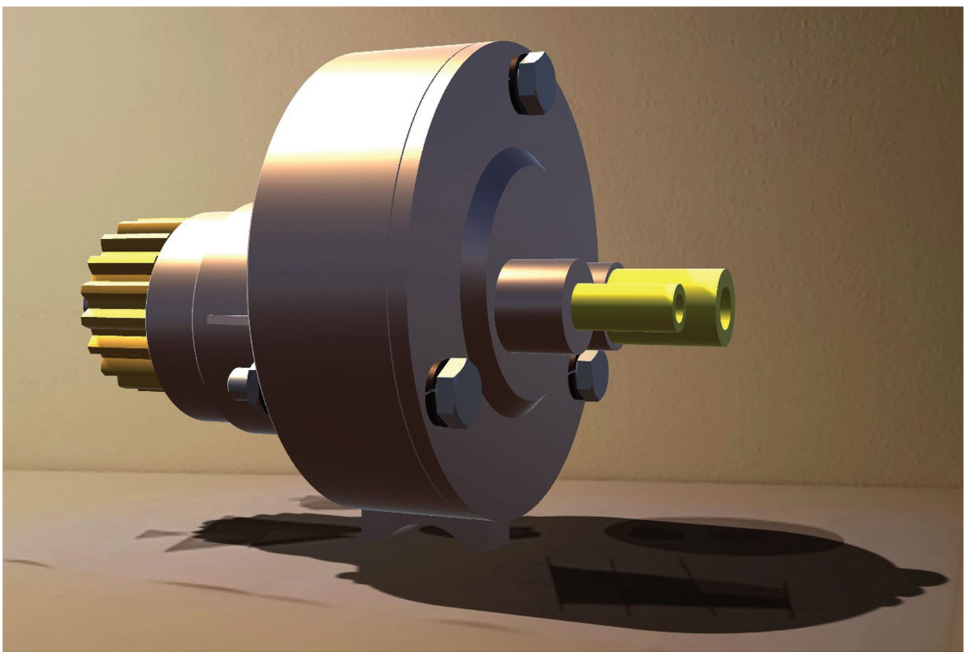

Figure 13. Augmented reality video: fully assembled pump for servicing.

easier to imagine how this technology is appropriate and valuable in a business setting, across most of its R&D, and helping thru product production, logistics, and aftersales departments, as main information for procedures, and training of worker force

Figure 14. Augmented reality video: complete disassembly exploded for servicing.

afterwards, who must handle complex devices, hence facilitating their work and learning the processes overall.

5. Discussion

This case study demonstrated that an AR solution to assist the studies of disassembly design methods and technologies that enable product servicing, maintenance processes of parts and machines, as well as to better understand product manufacturing procedures otherwise just stated mathematically.

From an economic and productivity perspective, design by focusing on disassembly deliver methods that redefine the manufacturing and production techniques to optimize the processing, working and safety conditions, as well as reducing time, costs and overall resources needed.

Accurate servicing attention is also important for environmental sustainability: It allows for the recovery and recycling of components or materials, to reduce consumption, waste, and pollution. The technology of AR is a guide to understanding the processes and activities of industrialization, thus improving the productivity.

6. Conclusions

- The effectiveness of the design for disassembly applied to a small product such as the rotating cylinder has been demonstrated.
- This methodology is particularly useful and convenient in a series production context with hundreds of components and machines to be checked. Its convenience

for the management of resources and from an economic point of view have been verified.
- A correct sequence assessment would allow to considerably reduce resources and direct and indirect dismantling costs.
- The advantages can also be evident in the speed of intervention, having the immediate availability of the necessary processing sequences and times.
- The methodology of Augmented Reality assessment, used in numerous sectors in addition to the industrial one, has been applied to ease the virtual verification of the theoretical process portrayed by two sequence methods calculated in this exercise.
- The methodologies used in this study are not much widespread among companies yet, as resources and necessary skills that are not guaranteed for the use of this tools.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Abuzied, H., Senbel, H., Awad, M., & Abbas, A. (2020). A review of advances in design for disassembly with active disassembly applications. *Engineering Science and Technology, an International Journal*, *23*(3), 618–624. https://doi.org/10.1016/j.jestch.2019.07.003

Alrufaifi, H. M. (2021). *Predicting the geometrical disassembly feasibility of mechanical assemblies in design phase*. Wayne State University.

Anil Kumar, G., Bahubalendruni, M. V. A., Prasad, V. S. S., & Sankaranarayanasamy, K. (2021). A multi-layered disassembly sequence planning method to support decision making in de-manufacturing. *Sādhanā*, *46*(2), 1–16. https://doi.org/10.1007/s12046-021-01622-3

Auffinger, C. E. (2021). *Evaluation and implementation of augmented reality for aerospace operations and sustainment*. Massachusetts Institute of Technology.

Bahubalendruni, M. V. A., Gulivindala, A. K., Varupala, S. S. V., & Palavalasa, D. K. (2019). Optimal assembly sequence generation through computational approach. *Sādhanā*, *44*(8), 1–9. https://doi.org/10.1007/s12046-019-1157-2

Bolano, G., Fu, Y., Roennau, A., & Dillmann, R. (2021). Deploying multi-modal communication using augmented reality in a shared workspace. *2021 18th International Conference on Ubiquitous Robots (UR)*, Gangneung, Korea (South) (pp. 302–307).

Chang, M. M. L., Ong, S. K., & Nee, A. Y. C. (2017). AR-guided product disassembly for maintenance and remanufacturing. *Procedia CIRP*, *61*, 299–304. https://doi.org/10.1016/j.procir.2016.11.194

Chen, D. -Z., Wei, C., Jia, G. -L., & Hu, Z. -H. (2020). Shortest-path optimization of ship diesel engine disassembly and assembly based on AND/OR network. *Complexity*, *2020*, 1–15. https://doi.org/10.1155/2020/2919615

Fernández-garcía, C. (2021). Effect of augmented reality on school journalism: A tool for developing communication competencies in virtual environments. *Electronic Journal of Information Systems in Developing Countries*, *87*(4), e12169. https://doi.org/10.1002/isd2.12169

Gulivindala, A. K., Bahubalendruni, M., Chandrasekar, R., Ahmed, E., Abidi, M. H., & Al-Ahmari, A. (2021). Automated disassembly sequence prediction for industry 4.0 using enhanced genetic algorithm. *Computers, Materials & Continua*, *69*(2), 2531–2548. https://doi.org/10.32604/cmc.2021.018014

Gunji, B. M., Pabba, S. K., Rajaram, I. R. S., Sorakayala, P. S., Dubey, A., Deepak, B., Biswal, B. B., & Bahubalendruni, M. V. A. (2021). Optimal disassembly sequence generation and disposal of

parts using stability graph cut-set method for End of Life product. *Sādhanā*, *46*(1), 1–15. https://doi.org/10.1007/s12046-020-01525-9
Hansen, L. H., Fleck, P., Stranner, M., Schmalstieg, D., & Arth, C. (2021). Augmented reality for subsurface utility engineering, revisited. *IEEE Transactions on Visualization and Computer Graphics*, *27*(11), 4119–4128. https://doi.org/10.1109/TVCG.2021.3106479
Harikrishnan, A., Abdallah, A. S., Ayer, S. K., El Asmar, M., & Tang, P. (2021). Feasibility of augmented reality technology for communication in the construction industry. *Advanced Engineering Informatics*, *50*, 101363. https://doi.org/10.1016/j.aei.2021.101363
Hassan, S. A., Rahim, T., & Shin, S. Y. (2021). ChildAR: An augmented reality-based interactive game for assisting children in their education. *Universal Access in the Information Society*, *21*(2), 1–12. https://doi.org/10.1007/s10209-020-00790-z
Iatsyshyn, A. V., Kovach, V. O., Romanenko, Y. O., Deinega, I. I., Iatsyshyn, A. V., Popov, O. O., Kutsan, Y. G., Artemchuk, V. O., Burov, O. Y., & Lytvynova, S. H. (2020). *Application of augmented reality technologies for preparation of specialists of new technological era*.
Jing, A., May, K., Lee, G., & Billinghurst, M. (2021). Eye see what you see: exploring how bi-directional augmented reality gaze visualisation influences co-located symmetric collaboration. *Frontiers in Virtual Reality*, *2*, 79. https://doi.org/10.3389/frvir.2021.697367
Joerss, T., Hoffmann, S., Mai, R., & Akbar, P. (2021). Digitalization as solution to environmental problems? When users rely on augmented reality-recommendation agents. *Journal of Business Research*, *128*, 510–523. https://doi.org/10.1016/j.jbusres.2021.02.019
Kissi, E., Ansah, M., Ampofo, J., & Boakye, E. (2019). Critical review of the principles of design for disassembly. *Modular and Offsite Construction (MOC) Summit Proceedings*, Alberta Canada (pp. 251–258).
Kumar, G. A., Bahubalendruni, M. V. A. R., Prasad, V. S. S. V., Ashok, D., & Sankaranarayanasamy, K. (2022). A novel geometric feasibility method to perform assembly sequence planning through oblique orientations. *Engineering Science and Technology, an International Journal*, *26*, 100994. https://doi.org/10.1016/j.jestch.2021.04.013
Laili, Y., Wang, Y., Fang, Y., & Pham, D. T. (2022). Product representation for disassembly sequence planning. In *Optimisation of Robotic Disassembly for Remanufacturing*, Springer Series in Advanced Manufacturing (pp. 27–45). Springer.
Lai, Z. -H., Tao, W., Leu, M. C., & Yin, Z. (2020). Smart augmented reality instructional system for mechanical assembly towards worker-centered intelligent manufacturing. *Journal of Manufacturing Systems*, *55*, 69–81. https://doi.org/10.1016/j.jmsy.2020.02.010
Langlotz, P., & Aurich, J. C. (2021). Causal and temporal relationships within the combination of lean production systems and industry 4.0. *Procedia CIRP*, *96*, 236–241. https://doi.org/10.1016/j.procir.2021.01.080
Lehto, A., Luostarinen, N., & Kostia, P. (2020). Augmented reality gaming as a tool for subjectivizing visitor experience at cultural heritage locations—case lights on! *Journal on Computing and Cultural Heritage (JOCCH)*, *13*(4), 1–16. https://doi.org/10.1145/3415142
Li, Y., Ch'ng, E., Cobb, S., & See, S. (2021). Presence and communication in hybrid virtual and augmented reality environments. *PRESENCE: Virtual and Augmented Reality*, 1–40. https://doi.org/10.1162/pres_a_00340
Mandolini, M., Favi, C., Germani, M., & Marconi, M. (2018). Time-based disassembly method: How to assess the best disassembly sequence and time of target components in complex products. *International Journal of Advanced Manufacturing Technology*, *95*(1), 409–430. https://doi.org/10.1007/s00170-017-1201-5
Manfè, G., Pozza, R., & S, G. (2013). *Disegno Meccanico* (*vol. 1*, *2*, *3* (Principato Editore, Ed.)). Principato Editore.
Martins, N. C., Marques, B., Alves, J., Araújo, T., Dias, P., & Santos, B. S. (2021). Augmented reality situated visualization in decision-making. *Multimedia Tools and Applications*, *81*(11), 1–24. https://doi.org/10.1007/s11042-021-10971-4
Masclet, C., Boujut, J. -F., Poulin, M., & Baldaccino, L. (2021). A socio-cognitive analysis of evaluation and idea generation activities during co-creative design sessions supported by spatial

augmented reality. *International Journal of Design Creativity and Innovation*, *9*(1), 20–40. https://doi.org/10.1080/21650349.2020.1854122
Mourtzis, D., Zogopoulos, V., & Xanthi, F. (2019). Augmented reality application to support the assembly of highly customized products and to adapt to production re-scheduling. *International Journal of Advanced Manufacturing Technology*, *105*(9), 3899–3910. https://doi.org/10.1007/s00170-019-03941-6
Noghabaei, M., Heydarian, A., Balali, V., & Han, K. (2020). Trend analysis on adoption of virtual and augmented reality in the architecture, engineering, and construction industry. *Data*, *5*(1), 26. https://doi.org/10.3390/data5010026
O'grady, T., Minunno, R., Chong, H. -Y., & Morrison, G. M. (2021). Design for disassembly, deconstruction and resilience: A circular economy index for the built environment. *Resources Conservation and Recycling*, *175*, 105847. https://doi.org/10.1016/j.resconrec.2021.105847
Qin, H., Osatuyi, B., & Xu, L. (2021). How mobile augmented reality applications affect continuous use and purchase intentions: A cognition-affect-conation perspective. *Journal of Retailing and Consumer Services*, *63*, 102680. https://doi.org/10.1016/j.jretconser.2021.102680
Radu, I., Hv, V., & Schneider, B. (2021). Unequal impacts of augmented reality on learning and collaboration during robot programming with peers. *Proceedings of the ACM on Human-Computer Interaction*, Merced California, *4*(CSCW3), 1–23.
Raju Bahubalendruni, M. V. A., & Biswal, B. B. (2015). An intelligent method to test feasibility predicate for robotic assembly sequence generation. In M.V.A. Raju Bahubalendruni (Ed.), *Intelligent computing, communication and devices* (pp. 277–283). Springer.
Rasmussen, F. N., Birkved, M., & Birgisdottir, H. (2019). Upcycling and design for disassembly–LCA of buildings employing circular design strategies. *Iop Conference Series: Earth and Environmental Science*, West Java, indonesia, *225*(1), 12040.
Rosales, J., Deshpande, S., & Anand, S. (2021). IIoT based augmented reality for factory data collection and visualization. *Procedia Manufacturing*, *53*, 618–627. https://doi.org/10.1016/j.promfg.2021.06.062
Sampaio, D., & Almeida, P. (2018). Students' motivation, concentration and learning skills using augmented reality. *Proceedings of the 4th International Conference on Higher Education Advances (HEAd'18)*, Valencia, Spain.
Singh, D., Banerjee, A., & Nath, I. (2021). Application of augmented reality and virtual reality in education. In *Implementing augmented reality into immersive virtual learning environments* (pp. 89–101). IGI Global.
Su, Y., Mao, H., & Tang, X. (2021). Algorithms for solving assembly sequence planning problems. *Neural Computing & Applications*, *33*(2), 525–534. https://doi.org/10.1007/s00521-020-05048-6
Szajna, A., Stryjski, R., Woźniak, W., Chamier-Gliszczyński, N., & Królikowski, T. (2020). The production quality control process, enhanced with augmented reality glasses and the new generation computing support system. *Procedia computer science*, *176*, 3618–3625. https://doi.org/10.1016/j.procs.2020.09.024
Tan, Y. -C., Chandukala, S. R., & Reddy, S. K. (2022). Augmented reality in retail and its impact on sales. *Journal of Marketing*, *86*(1), 48–66. https://doi.org/10.1177/0022242921995449
Tao, F., Bi, L., Zuo, Y., & Nee, A. Y. C. (2018). Partial/Parallel disassembly sequence planning for complex products. *Journal of Manufacturing Science and Engineering*, *140*(1). https://doi.org/10.1115/1.4037608
Tian, Z., Jiang, X., Liu, W., & Li, Z. (2023). *Dynamic energy-efficient scheduling of multi-variety and small batch flexible job-shop: a case study for the aerospace industry*. Computers & Industrial Engineering.
Tian, G., Liu, Y., Tian, Q., & Chu, J. (2012). Evaluation model and algorithm of product disassembly process with stochastic feature. *Clean Technologies and Environmental Policy*, *14*(2), 345–356. https://doi.org/10.1007/s10098-011-0406-9
Tian, G., Zhang, C., Fathollahi-Fard, A. M., Li, Z., Zhang, C., & Jiang, Z. (2022). An enhanced social engineering optimizer for solving an energy-efficient disassembly line balancing problem based on bucket brigades and cloud theory. *IEEE Transactions on Industrial Informatics*, Perth, Australia.

Viglialoro, R. M., Condino, S., Turini, G., Carbone, M., Ferrari, V., & Gesi, M. (2021). Augmented reality, mixed reality, and hybrid approach in healthcare simulation: A systematic review. *Applied Sciences*, *11*(5), 2338. https://doi.org/10.3390/app11052338

Xiong, J., Hsiang, E. -L., He, Z., Zhan, T., & Wu, S. -T. (2021). Augmented reality and virtual reality displays: Emerging technologies and future perspectives. *Light: Science & Applications*, *10*(1), 1–30. https://doi.org/10.1038/s41377-021-00658-8

Yang, Y., Yuan, G., Zhuang, Q., & Tian, G. (2019). Multi-objective low-carbon disassembly line balancing for agricultural machinery using MDFOA and fuzzy AHP. *Journal of Cleaner Production*, *233*, 1465–1474. https://doi.org/10.1016/j.jclepro.2019.06.035

Yi, J., Yu, B., Du, L., Li, C., & Hu, D. (2008). Research on the selectable disassembly strategy of mechanical parts based on the generalized CAD model. *International Journal of Advanced Manufacturing Technology*, *37*(5), 599–604. https://doi.org/10.1007/s00170-007-0990-3

Zhang, L., Wu, Y., Li, Z., Zheng, Y., Ren, Y., & Zhu, L. (2021). A systematic approach in remanufacturing for high efficiency and low cost: The selective parallel disassembly sequence planning. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 09544054211041036.