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Inventive Re-Design for Automatic Assembly in the Household Appliances Industry

Abstract

Purpose –In the re-design process of assembly components that need adaptation to robotic assembly, designers can find support from structured methodologies for innovation, such as the Theory of Inventive Problem Solving (TRIZ). This paper aims to illustrate the authors' methodology for re-designing gas hobs components for adaptation to robotic assembly.
Design/methodology/approach –A designer approaching a re-design task of an assembly component of any kind for adaptation to robotic assembly must consider, first of all, the features and limitations of existing robotic assembly systems; the generation of new design ideas that best fit the requirements may result to be a very challenging task. Here, the TRIZ methodology has proven useful for generating design ideas and finding the best solution.
Findings – The authors' methodology approaches the challenges of re-design tasks for robotic assembly adaptation, which exploits knowledge of automatic and robotic assembly systems and the TRIZ method for innovation; it has proven useful in the re-design, checks, and prototyping of gas hobs components.
Originality/value –This paper shows how the TRIZ methodology can be integrated into the re-design process and its impact on an industrial environment. The work's main value is to provide a set of steps to help the designers change their design components approach that is necessary but not still implemented to optimize the use of the automation.

Keywords Robotic assembly, Design for Automatic Assembly, TRIZ method, re-design, process modeling

Paper type Research paper

1. Introduction

Assembly is the most labor-intensive process along the manufacturing process of durable goods (Boothroyd, 1984); as a consequence, the new Industry 4.0 program aims to push automation in factories. In the past three decades, the increase in production paces in the modern industry has been more noticeable: manufacturing companies worldwide have been forced to automate the assembly processes to remain competitive. This is especially true in the Covid-19 scenario where the proximity of people has been detected as one of the most critical issues to reducing the infection spreading: the man-intensive approach typical of traditional assembly lines was revealed to be unsustainable in this scenario where social distancing is fundamental (D'Angelo *et al.,*2021). Also, ergonomics requirements and more strict health-oriented regulations reduce humans' tasks (Faccio *et al.,* 2019). On the other hand, advances in robotics are fast nowadays, and techniques that help robots perform various tasks (e.g., vision systems for bin-picking, collaborative robots) are becoming common on robotic systems for assembly. Nevertheless, most products assembled manually in an assembly chain are still hard to be assembled robotically, requiring re-design actions. When dealing with new product design and re-design, it is straightforward, taking into consideration the capabilities of the robotic assembly system (Manoharan *et al.,* 1990). A set of product design rules must be followed to make it possible for robot operations. Several design approaches have been developed in the literature, and there are different requirements on which a designer can focus his/her job. Hence, as an example, Eskilander (2001) introduces the concept of 'DFX', that is 'Design for X', where X can stay for Fabrication, Assembly, Installation, and Recycling (Aicha *et al.*, 2022), Reliability, Maintenance, Additive Manufacturing, minimum weight. When the attention is focused on the assembly features of designed components, it is Design for Assembly (DFA). According to the bibliography, DFA can bring benefits to both manual and automatic ways of assembling components: reduced number of components (Nichols, 1992), reduced assembly times (Desai, 2019), increased productivity, reduced manufacturing and assembly costs, and reduced dull/heavy operations for workers is a non-inclusive list of these advantages. However, given the limitations of a robotic assembly system highlighted in the literature (Du *et al.,* 1999), the focus of this work is shifted to the need for guidelines for the design of components keeping into consideration the easiness of robotic assembly so that the term DFAA, that is Design for Automatic Assembly, better suits the application. As a demonstration of the criticality of DFA, the paper by Soh et al. (2016) illustrates an approach developed to keep into account the operators, and tailored to the solution of typical conflicts between DFA and Design for Disassembly (DFD). The paper by Lowe et al. (2007) lists the most important DFD concepts and focuses the attention on the strategies to implement them in an industrial environment. Topics related to design are straightforward in the modern industrial engineering because the final product success is built in the early product development phases. To support this statement, Dalgleish *et al.* (2000) states that companies are struggling to cut down the costs and lead times not only in their product cycle (Bedeoui *et al.*, 2021) but also in their design/engineering cycle (Brahmi *et al.*, 2021), which requires the introduction of new design methods. Moreover, different issues can arise during a re-design project, requiring intensive brainstorming to develop a good solution: in these cases, a multidisciplinary approach must be carried out, and several conflicting needs must be harmonized. One of the possible ways to increase the design variety of solutions and thus innovate is the application of structured methodologies of design. Quality Function Deployment, Taguchi methods, TRIZ (Russian acronym for Theory of Inventive Problem Solving), Design of Experiment, Failure Mode Effect Analysis, and Axiomatic design (Shirwaiker et al., 2008) are design techniques developed to support the designer in his/her complex task. TRIZ technique is one of the most powerful tools to develop inventive solutions and solve problems with innovative approaches worth of being patented. TRIZ was invented and developed by Russian engineer Genrich Altshuller and his colleagues starting in the '40s in the former Soviet Union. This structured method is useful in almost every problem and helps generate innovative ideas by picking hints from past inventors' knowledge in various engineering fields. It is well described in the literature to solve engineering problems. For instance, the book by Savransky (2000) details the procedure to apply TRIZ methodologies to the industrial domain, providing guidelines for its application to real cases. According to Krasnoslobodtsev and Langevin (2006) and Trela et al. (2015), the methodology has been successfully introduced in major companies, leading to several patents. To cite the most updated literature, Kandukuri et al. (2022) proposes an improved TRIZ methodology to support the development of rules for the re-manufacturing of industrial products using Additive Manufacturing. Just to provide the reader with an idea of the wide range of applications where TRIZ can be used, the work of Hsieh *et al.* (2017) describes its application to the innovative design of machine tools. Although the TRIZ methodology has proven to be a reliable systematic methodology for innovation (Petković *et al.*, 2013), its specific application to the re-design of parts for adaptation from manual to automatic assembly continues to be scarce in the literature. In the work Petković *et al.* (2013), the authors exploited TRIZ tools to design an adaptive robotic gripper. In Bariani *et al.* (2004) the authors merged the DFMA (Design for Manufacture and Assembly) and the TRIZ methods to re-design a satellite antenna. However, the application of the TRIZ methodology in industrial problems is quite challenging, as declared by (Ilevbare, 2013), where a set of comments on the evaluation of the methodology by designers and the list of the most easy-to-learn tools is included. This work aims to evaluate the potentiality of the TRIZ method in terms of enhancing design capabilities and overcoming design problems specifically in the context of DFAA, thus contributing to the existing literature. The re-design of gas hob components has been set as a case study. In this scenario, the application of TRIZ methodology was necessary because the typical practical approach of adapting the automation to the existing designed components was not convenient. This approach would have led to oversized automatic plants and machines to ensure operations that are typically possible for manual assembly without any benefit. Consequently, it was necessary to change the approach in thinking about the design of components. In this context, the authors of this work propose a structured methodology to be followed by the designer in case he/she is facing a re-design task of assembly parts for adaptation to robotic assembly; a first step is the gaining of knowledge on DFAA rules, widely present in literature (see Section 2.1), so to have a clear understanding on how to properly optimize the design, and successively the TRIZ method is applied to the re-design task, so to generate innovative ideas to overcome design difficulties.

The structure of this paper is organized as follows: Section 2 introduces the methodology, along with a description of its steps; Section 3 presents the application of the methodology to a re-design case study; Section 4 contains comments on the effectiveness of the proposed methodology, along with problems faced during its application; lastly, Section 5 concludes the study, summarizing the results obtained and suggesting possible future developments.

2. Methodology

This chapter presents the proposed methodology, which includes the application of TRIZ to support the re-design of components and adapt them to robotic assembly requirements. A general overview of the methodology consists of the steps summarized in Figure 1.

Figure 1 Steps of the methodology followed by the authors

2.1. Methodology – Step 1: Analysis of Robotic Assembly Systems and DFAA Rules

In the current product development cycle, the designer must possess a general understanding of how robotic assembly systems work (both feeding methods and assembly robots), plus a good knowledge of the design guidelines for DFAA. It is thereof necessary to possess this knowledge before starting the design and re-design of parts that will be assembled automatically. For briefness, information on the different types of robots and tools is not given here; the reader is referred to the work of Blakeshwar *et al.* (2013) for information on the evolution of industrial robots and their applications.
This section shows the main concepts related to DFAA already developed in the literature. There is no single unique approach to DFAA, but the guidelines have been collected so far due to experience since the beginnings of robots used in the industry during the 1960s. What is true is that, even though new technologies are making robotic assembly ever easier and smarter, some basic design rules still apply all the time and must be adopted in the design phase.
The conventional approach to DFAA is thus called the "axiomatic method" (Du *et al.,* 1999), i.e., applying a set of design guidelines derived from years of experience in design and assembly operations. The authors of this paper have mainly based their work on the set of guidelines contained in the works of Eskilander (2001), Scarr *et al.* (1986), and Boothroyd *et al.* (2010). A well-recognized authority in design for automatic assembly is indeed Geoffrey Boothroyd, author of various publications and books on the topic. The reader is recommended to refer to his works for a more detailed description of issues related to DFAA. Some authors, such as Eskilander (2001) and Hoekstra (1989), suggest assigning scores to each axiom (i.e., to each guideline), creating a sort of 'evaluation tool', which the designer can use to analyze an existing assembly for re-design, and thus check the level of adaptation of the product using a DFAA index.
When designing new mechanical components or re-designing products that robots will manipulate, the focus is on PRODUCT LEVEL (an assembly of parts or modules) and PART LEVEL. A list of points to be analyzed (each having a related design guideline) is presented in the work of Eskilander (2001) and is shown for reference purposes in Figure 2.

Figure 2 Summary of design rules to be considered at Product and Part level (adapted from Eskilander, 2001)

Without going into deeper detail on each guideline for the sake of briefness, a recall of the most relevant rules for the present study is the following:

- **2.1.1 Product Level:**

The general rule suggested for the design of an assembly to be mounted robotically is to reduce the number of different parts in the assembly itself, i.e., to remove them or standardize them (e.g., try to use the same type of screw wherever possible); ensure a base object on which to build the assembly, possibly all in the vertical direction (the so-called 'sandwich assembly'), which does not require to be re-oriented along the assembly chain. The vertical assembly direction is fundamental because most the robot types work this way: it allows better reachability of the location of the components in the assembly and it exploits gravity to hold down movable parts during the assembly. It is suggested to avoid as much as possible the build-up of tolerances chains, given that they can lead to assembly difficulties: errors are summed up in this case, magnifying errors dramatically.

- **2.1.2 Part Level:**

When dealing with the design of single parts, it is fundamental to consider that they will interact with the robotic system (feeding and handling operations) and with the rest of the assembly. In this way, design parts that do not nest, hook or tangle together when stored in bulk and do not overlap during the feeding to the robot are suggested; in such a critical scenario it will be very difficult for the robot to avoid damage not only to the assembled products, but to itself as well. Parts should be symmetric and have a position of the center of gravity that helps the part's orientation in the right way: this will facilitate the feeding of the part.

Although many advances in the robotics field, such as vision systems and artificial intelligence, dealing with flexible parts (e.g., cables) is still hard nowadays: multiple coordinated robotic arms and vision systems for the assembly (refer to the work of Jiang *et al.,* 2010) for robotic assembly of a car wire harness) could improve the scenario; gripping surfaces on the parts to facilitate the grabbing and to avoid the change of gripper by the robot are recommended; also, the reachability by the gripper of the assembly zone of the part is fundamental, ensuring that there is enough space for the robot to access it. It is really important to provide guiding surfaces and chamfers to facilitate the insertion of parts into others: this will require less precision by the robot and avoid insertion problems that may cause a stop of the assembly line, damages to products or personnel in case objects are projected outside the working cell.

Another important aspect being considered is the chosen fastening method for the parts. Connections using nuts and bolts should be avoided because they require a special tool for fastening. They are not always well referred on the part: they can move during handling, changing reference attitude in pitch or yaw angles. Snap-fit connection methods should be applied wherever possible (those that permit the part removal in case disassembly may be needed should be considered). If fastening with screws is necessary, it is required to standardize them as much as possible and choose a type of screw that is easy to insert (e.g., cone point or oval point screws).

- **2.1.3 Evaluation Tool:**

All the design rules described in the previous sections have been considered during the inventive design process; on the other hand, approaches well documented in literature have been applied to set rules to score the new solutions developed applying the methodology herein described. In addition to the axioms on how to design a part for robotic assembly, Eskilander (2001) and Hoekstra (1989) suggest assigning points to each axiom while analyzing an existing assembly so to make the axiomatic method more evaluative. This approach is beneficial for the design process because it is meant to assign a total score to the product and check the areas that lack affinity to the automatic mounting: this should be considered a guideline to set the best re-design solutions developed. A brief insight into this tool is given in the following.

The evaluation procedure suggested by Eskilander is based on an evaluation first at the product level and then for every single part, by assigning a score between the values 1, 3, or 9 basing the ranking on how much the design rules are met by the part or product, in the following way:

- **9→** Best solution in terms of automatic assembly, meaning the solution fully meets the design rule.
- **3→** The solution is acceptable but does not completely satisfy the design rule.
- **1→** Unwanted solution for automatic assembly; a re-design action is required.

An example of this evaluation for the design rule Insertion at part level is given in Table I.

Table I Scores assignment considering the easiness of insertion for a part (image source: Eskilander, 2001)

The scores are then collected in a table, indicating the total score. The total score of the product is divided by the maximum possible score (9 points to each criterion), while at the part level, the total score is divided by the maximum possible score multiplied by the number of parts, giving as output the DFAA Index:

$$\frac{\text{Total score of the product}}{\text{Maximum ideal score}} * 100 = DFAA\ Index(\%)$$

$$\frac{\text{Total score of the product}}{\text{Maximum ideal score} * \text{number of different parts}} * 100 = DFAA\ Index(\%)$$

Hence, the highest the DFAA index obtained by a product and its parts, the highest the fit for automation of that product. A low DFAA index means that the product/part needs re-design actions. The table collecting all the scores is a useful tool for visualizing the product's weak areas and parts. An application to the case study is presented in Section 3.1. Therefore, the authors followed this approach to score the re-design solutions developed using inventive design methodologies.

2.2. Methodology – Step 2: integration of TRIZ tools into the re-design

The TRIZ methodology was developed in the '60s by the Russian engineer Genrich Altshuller who, working for the Russian Navy at the end of the '40s, started to analyze various patents to understand the existing similarities among them. With the help of his colleagues, he was able to screen over 200˙000 patents, selecting among them some 40˙000, i.e., those presenting clear innovative ideas; the rest of the analyzed patents were straightforward improvements of past innovations. By studying the 40˙000 most relevant patents, he understood how the innovations have come out and their evolutionary trends. In the light of this, he built the TRIZ theory with its fundamental tools: the list of 39 engineering parameters used to characterize contradictive problems, the Contradiction Matrix that provides the 40 inventive principles useful to overcome the contradictive problems and generate innovative ideas, the separation principles to solve physical contradictions; the ARIZ algorithm should be listed in this non-inclusive list of available tools useful to solve complex problems.
The authors applied TRIZ basic tools in this paper, particularly the Contradiction Matrix and the 40 Inventive Principles. The TRIZ algorithm for solving complex problems has not been

investigated. For more information on Altshuller's work, refer to Altshuller (1999), where an outlook of all the available tools is described.
The idea at the basis of TRIZ is to avoid solving a specific problem by trials and errors (using common methods such as Brain Storming) but to generalize the problem and find general solutions to it by applying the TRIZ tools. These general solutions are then fitted back to the specific problem (in this case, by considering the robotic assembly rules), and the best ones are selected.
The TRIZ methodology is beneficial in such a way that it permits to:

- Follow a new type of structured approach to problem-solving.
- Eliminate psychological inertia that leads to always following the same path in problem-solving (based on the personal knowledge of the designer).
- Simplification of information sharing (everything regarding the problem is documented, including past ways followed to solve the problem).

For briefness, this article does not report a detailed description of how to perform a single step of the method (Figure 3), along with practical examples. However, the reader is referred to the book by Terninko *et al.* (1998), on which the authors have based their work.

Figure 3 Steps of the TRIZ methodology

A short description of the steps follows:

- *TRIZ Step 1.* A detailed description of the problem using the Innovative Solution Questionnaire (ISQ), describing all available information on the considered system, the situation that generates the problem, the possible and the forbidden modification to the system, and the past solution attempts.
- *TRIZ Step 2.* The ISQ identifies 'Useful' and 'Harmful' functions, graphically related in a Flow Chart. From this representation of the overall problem, so-called 'technical contradictions' are immediately recognizable.
- *TRIZ Step 3.* Each technical contradiction expresses a 'feature to improve' and an 'undesired result', identified using the TRIZ 39 parameters and resolved by applying the 'Contradiction Matrix', which provides a list of technical solutions.
- *TRIZ Step 4.* If no workable solutions result from the previous step, the technical contradiction is identified as a 'physical contradiction' and solved through the 'separation principles'.
- *TRIZ Step 5.* Solutions coming from Steps 3 and 4 are analyzed, and the best ones are selected and adapted to the specific problem.

The TRIZ methodology has been applied to involve the company's technical staff involved in this research. A set of meetings has been held showing the theory behind the TRIZ methodology. A set of solutions has been presented to the company design, production, and maintenance staff for evaluation. One of the problems in applying the TRIZ contradiction methodology is that the step from the 40 inventive solution principles to the specific application solution can be hard to implement for people without technical competence in the specific field. External designers have developed new solutions and evaluated/adapted them to the internal ones using this approach. In this way, the problem of breaking the psychological inertia was solved, but on the other hand, solutions tailored to the specific applications have been developed. This hybrid solution proved effective in exploring new solutions tailored to the specific application.

2.3. Methodology: Steps 3, 4 and 5

The applicative steps of the methodology will be presented in Section 3 concerning a specific case study. Step 3 regards the adaptation to the re-design case of the best solution obtained by the application of Step 2. In contrast, Step 4 regards selecting a prototyping method to craft the adapted solution, given its assembly simulation in Step 5, which is meant to study the feasibility of robotic assembly. The highly applicative nature of steps 3, 4, and 5 suggests applying them to a specific case study. However, similar steps could be followed in the case of any mechanical component adapting the methodology to the specific application in terms of ways to demonstrate the feasibility of the assembly process in an automated way. Different ways of compliance using robots or automatic machines could be possible.

3. Case Study

Steps 3, 4, and 5 represent the practical section of the methodology itself. Firstly, it is shown the practical application of Step 2 to the re-design case study, which is that of the gas tubes of gas hobs. These components have always been assembled manually, and the methodology has been applied to assist in re-designing the components themselves in view of their robotic assembly. The gas tubes are extruded aluminum UNI900, which carry the gas from the gas valves to the burners (see Figure 4).

Figure 4 Gas tubes assembled to gas valves and burners

The application of TRIZ tools was then started with the drafting of the ISQ. The active participation of the company's personnel is fundamental so that the innovation team (in this case, the authors of the paper) can thoroughly understand the system and its properties. Major information from Chapters 1 and 3 of the ISQ is shown in the following, so the reader can grasp the reasons behind the re-design actions.

As is shown in Figure 5, on both the extremities of the tube, two boule-shapes go inside the inlets of the valve and burner and are connected to them using a nut and nipple, respectively; two washers are also present. The tubes present curvatures both in the horizontal and vertical plane to reach the valve and burner's inlets and facilitate the operator's assembly phase.

Figure 5 Current design of a gas tube, where more curvatures on the horizontal plane are present

The manual assembly of the tubes is carried out in the following sequence and is shown in Figure 6.

(1) The operator withdraws the tube from a drawer;
(2) He/she then brings the correct extremity of the tube to the inlet of the burner;
(3) Once inserted in the tube, the operator gives the first screwing to the nut (a robot on the following station makes the complete screwing with tightening);
(4) He/she then brings the other extremity to the entrance at the gas valve; for this, flexion of the tube is required;
(5) After inserting the tube inside the valve's inlet, he/she gives the first screwing to the nipple.

Figure 6 Manual assembly sequence

Considering the DFAA guidelines (refer to Section 2.1), it can be easily understood that the current design poses different challenges to adapting the component to the robotic assembly. The following points can summarize these:

- The tubes are provided to the operator in a confused manner inside some drawers (a drawer for each tube type); see Step 1 in Figure 6. This feeding method would require a complex vision system connected to the robot; moreover, the shape of the tubes may cause them to hook together, making the feeding to the robot almost impossible.
- The nuts, nipples, and washers can move along the tube. It causes problems referencing these elements and interference with the correct assembly procedure.
- There is difficulty in aligning the tube to the gas valve and burner's inlets if the tube is gripped from the nut or nipple.
- The initial screwing of the nut and nipple should be precise to have a correct, complete screwing and tightening. Otherwise, the robot can damage the threads.
- The high number of variants of tubes is not helpful in the case of automatic assembly, both for the reference of the extremities of all different tubes and for their singularized feeding.

An action of re-design of the component is thus mandatory to help the robotic handling (feeding + assembly) of the component. The main results obtained from applying the TRIZ tools are described. After drafting the ISQ, the flow chart relating the different contradictions resulting from the re-design problem has been constructed and is illustrated in Figure 7.

Figure7 Flow Chart connecting the useful and harmful functions of the problem in a logical way

So-called "technical contradictions" are evident in the Flow Chart. Solutions to them can be found by applying the Contradiction Matrix. For briefness, we will consider only the application of the matrix, which led to the solution implemented afterward.
Consider the following contradiction: The useful function 7 (Confused feeding of tubes) has to improve and has been identified by the parameter 33 (Convenience of use), but this causes the worsening of the harmful function 1 [Complexity of automation], identified by the parameter

38 (Level of automation). By entering the Contradiction Matrix from the rows with parameter 33 and the columns with parameter 38, the resulting Inventive Principles are the following:

- Inventive principle 1 – SEGMENTATION
- Inventive principle 34 – REJECTING AND REGENERATING PARTS
- Inventive principle 12 – EQUIPOTENTIALITY
- Inventive principle 3 – LOCAL QUALITY

In particular, here, the first principle of segmentation suggests applying the following actions in an attempt to solve the contradiction:

a. Divide an object into independent parts.
b. Make an object sectional (for easy assembly or disassembly).
c. Increase the degree of an object's segmentation.

This principle brought to the idea of dividing the tubes into parts to have simpler shapes and thus an easier feeding and assembly. This idea is the one that has then been implemented; its adaptation is presented in Section 3.1.
This application of TRIZ shows its intrinsic potential to help generate innovative ideas to find solutions to the contradictions faced during the analysis of the re-design task.

3.1. Methodology – Step 3: Adaptation of the Best Solution

As described above, the 'Segmentation' principle suggested to 'sub-divide' the gas tube in such a way to render the robotic feeding and assembly easier and more feasible. The first implementation of this principle to the re-design problem of the gas tubes was to have a simple tube with a 90° curvature on both ends, which are connected to two junctions which are in turn connected to the inlets of both gas valve and burner, as shown in Figure 8. This solution brings a great simplification of the shape of the tubes, reducing thus the number of codes and simplifying their feeding to a robot. Another good aspect of this solution is that, in this case, nuts are kept as a connection method; they are kept down by gravity when the robot picks the tube so that there are no referencing problems with the nuts and washers as it was before. As for cons, there is the fact that this solution requires the introduction of two new components, i.e., the junctions, and the re-orientation of some burners and leveling of gas valves and burners.

Figure 8 First adaptation of the Segmentation principle: the yellow lines represent the tubes, while the red segments represent the junctions

At this stage, the solution has gone through some refinements, which led to the final solution; the main changes also regarded the assembly of the spark plug/thermocouple and the burner and are:

- create a gripping surface on the tube.

- Replace nuts and nipples with a fast-assembly connection method; the tube will be firstly placed in its assembly position and then pressed to be locked.
- Modify the valve's inlet to allow for the vertical insertion of the tube.
- Create a gripping surface on the valve.
- Introduce an adapter on the burner's side, allowing for the tube's vertical connection(fast assembly type) and the spark plug/thermocouple.
- The burner's cup is laid on the adapter; then, the gas injector is screwed to the adapter, blocking thus also the burner on the adapter.

The resulting model is shown in Figure 9.

Figure 9 CAD model of the complete solution and its components

Regarding the assembly of the spark plug (the component that generates the spark for flame ignition) and thermocouple (the safety component which detects the presence of the flame), the idea is to have two connection holes, one with an electric contact that provides the current for the spark plug, and the other for the connection of the thermocouple, where the cables go through a coaxial tube from the adapter to the gas valve. Another idea is to have only one connection for an ionization spark plug, which works both as a spark plug and thermocouple; in this case, a tube that is coaxial to the main tube is required for the passage of the wires which send the electric signal to the valve for its opening/closing, i.e., the safety system. The fast-assembly connection method for the tube is only conceptual and has not been designed at this stage.
At this point, the Evaluation Tool mentioned in Section 2.1 can be applied to check for the improvements in terms of the DFAA index achieved with the new design and for possible areas of further improvement. For details on the design guidelines, the reader is referred to Eskilander's (2001) work. We consider the module of a gas valve, burner, tube, adapter, and ionization spark plug, thus not considering the crown assembly and portion of the worktop. The lower protection (i.e., the base for the assembly) is unaltered and not considered here. The module is made up of the following parts:

(1) Gas valve
(2) Gas tube
(3) Burner with the gas injector
(4) Thermocouple
(5) Spark plug with locking spring

Analyzing this module by assigning scores (both at module/product level and part level) as previously explained in Section 2.1, the resulting tables are shown hereafter, along with the respective value of the DFAA index. At the product level, the Maximum ideal score is 9*7=63, where 7 is the number of design guidelines. Table II shows the points assigned to each design guideline at the product level.

Table II Scores obtained by the current design at the product level

$$DFAA\ index = \frac{\text{SUM}}{\text{Maximum ideal score}} * 100 = \frac{35}{63} * 100 = \mathbf{56}\ \%$$

The situation at the part level is shown in Table III. The burner is screwed to the lower protection (with a screw M4x8) while the valve is screwed to the gas ramp, which is not considered here. The Maximum ideal score at part level is 9*18=162. The number of identical parts is to be considered at this step. The total score for each part is to be multiplied by the number of identical parts, which in this case resulted in being 1 for each part.

Table III Scores obtained by the current design at the part level

$$DFAA\ index = \frac{\text{SUM}}{\text{Maximum ideal score} * \text{number of parts}} * 100 = \frac{732}{162 * 7} * 100 = \mathbf{65}\ \%$$

- **New design:**

Figure10 Re-designed module

The re-designed module is made up of the following parts:

(1) Gas valve with a gripping surface
(2) Burner's cup
(3) Gas injector
(4) Tube
(5) Ionization spark plug
(6) Burner's side adapter

The situation at the product level is shown in Table IV.

Table IV Scores obtained by the new design at the product level

$$DFAA\ index = \frac{\text{SUM}}{\text{Maximum ideal score}} * 100 = \frac{41}{63} * 100 = \mathbf{65}\ \%$$

The improvement brought by the re-design is on the Assembly directions, which obtained a score of 9 since there is one assembly direction (vertical) into the base object (the lower protection in this case). The DFAA index has increased from 56% to 65%. The part-level situation is shown in Table V.

Table V Scores obtained by the new design at the part level

$$DFAA\ Index = \frac{\text{SUM}}{\text{Maximum ideal score} * \text{number of parts}} * 100 = \frac{804}{162 * 6} * 100 = \mathbf{83}\ \%$$

It can be noticed that the DFAA index at the part level has increased from 65% up to 83%. Thus, a great improvement has been achieved through the re-design actions. As the green areas emphasize, the improvements are the following:

- The tube is easier to orient for feeding.
- There will be no problems with hooking between the tubes during feeding.
- The gripping has improved by adding a gripping surface to the valve, the burner's cup (the gripping surface was added at prototyping level, see Section 3.2), and the tube.
- Assembly reachability has improved for the tube.
- There is no more need to hold the tube during its assembly, but being the part not directly locked, the guideline 'Holding assembled parts' scored 3 instead of 9 points, which is for a part that is directly locked after insertion.
- Being the burner's cup simply laid on the adapter (and then blocked by screwing the gas injector) and the tube locked by a fast assembly connection, these two components received 9 points on 'Joining'.
- The adapter for the connection of tube, ionization spark plug, and gas injector performed well and received 1 point only on 'Shape', which is not symmetrical.
- The new spark plug, made of the main body assembled vertically into the adapter, improved on many aspects of the old design of the spark plug and thermocouple.

Figure 11 Comparison between the current design and the re-design of the spark plug; the re-design is way easier to manipulate by a robot given the absence of wires, and given that it is an ionization spark plug, it will also work as a thermocouple

- Moreover, the simple shape of the new tube leads to a reduction in the number of codes and a reduction in production costs.

Figure 12 New design of the tube; to be noted is the simplification in terms of the shape of the tube, the creation of a gripping surface, and the removal of nuts, nipples, and washers

There are nevertheless some disadvantages to this solution, which are:

- There is a need to add one component that does not exist at the moment, i.e., the adapter at the burner's side.
- Modifications to the gas valve are required to create the vertical inlet.
- A reliable and safe fast-assembly connection method for the tube is to be designed, which can also ensure its disassembly; the existing fast-assembly connection methods for the tubes are way too expensive.
- If the simplification of its shape reduces costs for the tube, the cost faces an increase due to the need to have a coaxial tube for the passage of the wires for the ionization spark plug to the valve.

3.2. Methodology – Step 4: Additive Manufacturing of the Solution

Given an assembly simulation, the components of the solution of Step 3 (except the section of the worktop and the burner's crown) have been created through AM (Additive Manufacturing) with a 3D printer (Makerbot 5th Generation). This method has been chosen for easiness and fastness of production of the components. Considering the aperture of the available type of gripper on the robot (a pneumatic claw by Schunk), an internal gripping surface has been added to the burner's cup (see Figure 13) so that the robot can grip it from the inner surface.

Figure 13 Components prototyped using a 3D printer

3.3. Methodology – Step 5: Assembly Simulation

An assembly simulation has been set up to show a possible assembly sequence and the easiness of assembly movements for the robot to be performed. The robot used for the simulation is a Mitsubishi RV-4FM-1Q1-S15, equipped with the Schunk pneumatic gripper. The simulation has been performed at the TAILOR laboratory of the University of Bologna. The setup and performance of the simulation are herein described.
The parts to assemble are placed in a semi-random layout (predisposed from the PC simulation to ensure the right pick-up of the parts and avoid collisions) on a conveyor (Figure 14-1), which stops first when the components are under a camera (Figure 14-2) so that it can take a picture of the disposition of the components, which is used as input for the robot for the picking of each part. The conveyor moves again to bring the parts near the robot (Figure 14-3).

Figure 14 First steps of the simulation: (1) the parts are disposed of in a semi-random fashion on a conveyor, which first stops below a camera (2) for visual recognition of their disposition and then stops near the robot (3)

The parts are then positioned by the robot one per time on a base near the robot, where is also located support that is used to re-orient the tube and one containing the gas injector and the spark plug/thermocouple.

Figure 15 Bases used to support the assembly: the first from the left is the main base on which the parts are assembled, the robot exploits the central one to re-orient the tube for its vertical assembly, and finally, the one on the right holds the spark plug/thermocouple and the gas injector

The robot starts the assembly by first positioning the gas valve and the adapter on the burner's side; subsequently, it picks up the tube and re-orients it by placing it on the support (Figure 16-1) so that to grip it then from the gripping surface (Figure 16-2) and assemble it on the two adaptors. The fast-assembly connection is not prototyped. Thus, in this case, the assembly consists only of positioning the tube in the holes of the adapters (Figure 16-3). In the real case, the additional task of the robot will be that of reaching both extremities of the tube and exerting a vertical force to lock the tube inside the adapter.

Figure 16 Assembly sequence for the gas tube

To conclude the assembly task, the robot grips the burner's cup (Figure 17-1) from its inner gripping surfaces and positions it on the adapter, then picks and assembles in the vertical direction both the spark plug/thermocouple and the gas injector (Figure 17-2).

Figure 17 Assembly of the burner's cup and the spark plug/thermocouple and finalized assembly (right)

3.4 Discussion

Even if, in this phase of the research, it is difficult to evaluate the impact of automation quantitatively from an economic point of view, some comments can be drawn. First of all, automation reduces the risk of the wrong assembly due to the human factor: a fault detected when a product had been sold has a dramatic economic impact because of the need to supply a new product to the customer. Moreover, the Industry 4.0 factory tends to avoid using operators in dull and repetitive operations that could be frustrating and wearing for humans: this is especially true when bulky objects must be turned or operated. Another strength of this approach is that automation increases the repeatability of the assembly process, which is recognized as an index of quality with approaches like the six-sigma or Taguchi Method. Lastly, the automation allows more intensive exploitation of the factory space, thus allowing a higher production volume without the need for additional spaces. This aspect may be a pro in a context where environmental needs push towards reducing the environmental footprint, land consumption, and less energy for conditioning/heating.

On the other hand, automation also shows some cons: robots increase the need for energy; workers can view it as a competitive activity that may reduce workers. Finally, the human operator has the big advantage of being more flexible and capable of solving unexpected situations. To sum up, the decision to automate a process must consider several aspects. As a general rule, when errors in assembly can lead to accidents like in the gas hobs case study, the increase in safety that can be achieved with automation is a factor of paramount importance. Based on the experience gained applying the procedure in a real industrial case study, the following graph compares the manual and the automated assembly with scores (0 to 5) attributed to some of the most important factors at play.

Figure 18 Manual vs. Automated assembly scoring

Finally, the pie chart below illustrates the time spent on the single task of the whole methodology. It provides the reader with an assessment of the methodology's most time demanding task of the whole methodology. As appears from the chart, the most demanding phase is the translation into the specific problem of the inventive solutions derived from the TRIZ contradiction matrix. Another time-consuming task has been detected in the sketching of the Useful/Harmful functions.

Figure 19 Time spent in each phase of the methodology

4. Conclusions and Future Work

This paper presents the authors' approach methodology to the re-design process of components of gas hobs given their robotic assembly, particularly in the case study of gas tubes.
After the end of this research, it can be stated that the results have proved the effectiveness of the TRIZ method in the analysis of the re-design problem and in the generation of innovative ideas to find solutions; moreover, the single starting solution coming from the 'segmentation' principle has been adjusted and improved leading to re-design actions not only for the gas tube but also for other components, achieving a complete re-designed module. The validity in terms of the robotic assembly of the new module has been checked using the Evaluation tool and resulted in being more 'robotic-friendly' than the current design, given, for instance, the presence of gripping surfaces and the vertical assembly directions, leading to a substantial increase of the DFAA index from 65% to 83%.
The presented solution is, however, at its conceptual phase; future work will include the design of features and parts such as the coaxial tube for the passage of the wires, the fast assembly connection method for the tube, a snap-fit connection to assemble the burner's side adapter to the lower protection, and the electric connection of the adapter to bring electric current to the ionization spark plug. Most importantly, tests must be carried out to see if the new design meets safety regulations, given inflammable gas in the system. Lastly, an economic feasibility study needs to be carried out to check the economic advantage brought by the re-design and the automation of its assembly.

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