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From Design for Assembly to Design for Collaborative Assembly - Product Design Principles for Enhancing Safety, Ergonomics and Efficiency in Human-Robot Collaboration

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Abstract

Over the past decades, product design has been very much concerned with the topics of Design for Manufacturing and Design for Assembly. The aim was to design products in such a way that they could be manufactured easily and cost-effectively using existing production processes. In consequence of the introduction of Industry 4.0 and collaborative robotics in production, production system and process designers are facing new challenges in designing safe, ergonomic and efficient assembly processes. Cost-effective collaborative robots enable the automation of production processes even with small quantities and are therefore now of great interest also for small and medium-sized companies. In this work, we present the hypothesis, that in addition to manufacturing system design, a corresponding product design can also positively or negatively influence the feasibility of collaborative assembly and workcells. Based on the aforementioned "Design for X" methods many product designers already have certain traditional assembly technologies in mind. However, if these assembly technologies are to be substituted by more innovative approaches to assemble products using human-robot collaboration, this often leads to product design being not or only conditionally suitable for collaborative assembly. In this work we show what kind of changes occur in assembly due to the introduction of collaborative robotics and what influence product design has on these changes. As a result of this research, we present design principles and design guidelines for products to enhance safety, ergonomics and efficiency in collaborative assembly.

Keywords: design for collaborative assembly; collaborative robotics; industry 4.0; human-robot collaboration

1. Introduction to Industrial Collaborative Robotics and Concurrent Engineering

Nowadays industrial production systems are changing from mass production to mass customization [1], which means that companies have to adapt their business by improving flexibility and production efficiency in terms of products variants, customization, lot size, time-to-market and sustainability. As a consequence, adaptable, reconfigurable and sustainable manufacturing systems characterized by a scalable degree of automation are required to be competitive in a globalized and interconnected world [2]. Industrial human-robot-interaction (HRI) is a crucial cyber-physical technology of Industry 4.0. The International Federation of Robotics defines collaborative industrial robots as those able to perform tasks in collaboration with workers in industrial settings [3], which means particular kind of machines designed to allow physical and safe interaction with humans in a shared and fenceless workspace. The goal is to properly combine industrial automation strengths with inimitable human abilities in order to create efficient and human-centred production systems. This involves different levels of physical integration according to the nature of the hybrid activity. Nowadays, the collaborative robotics market is continuously growing. As a consequence, collaborative operations will probably be an interesting and widespread application in the next future. For this reason, existing approaches for the design of manufacturing products have to be adapted in order to consider the requirements for human-robot

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interaction during collaborative tasks [4]. "Concurrent Engineering" (CE) is a systematic methodology for the simultaneous and parallel implementation of products and process design activities and involves different design disciplines among the entire product lifecycle [5]. This basically needs the evaluation of the integration of product/process requirements during the design stages and according to the product stakeholders for all the product existence. In particular, the "Design for X" (DFX) concept is one of the most effective approaches to implement CE [6]. It has been utilized in order to improve the product and process design by considering a specific perspective (characterized by the "X" letter). It mainly includes Design for Manufacturing, Design for Assembly, Design for Recycling/Disposal, Design for Quality, Design for Safety, Design for the Environment, Design for Remanufacturing and Design for Ergonomics or Human-Factors [7, 8, 9]. In general, DFX and CE are proven design methodologies which aim to reduce product manufacturing costs, development time, time-to-market and sustainability. A common application of DFX is Design for Assembly (DFA), which originally was the first and ground-breaking study about the influence of assembly process on product design [10]. The introduction of Industry 4.0 and collaborative robotics is affecting the way by which products are manufactured and, as a consequence, the design methods should be consequently reconsidered and where necessary adjusted. The main critical issue in industrial HRI is to ensure a safe and ergonomic interaction while providing high production performance at the same time. These mandatory requirements are strictly related to the product features, the assembly cycle, the operator's psychophysical needs and wants, the robot systems features and the layout of the hybrid workcell. The integration of product and process design requirements in terms of safety and ergonomics has to be properly combined with the constraints related to production efficiency. This is necessary for all the activities of the product lifecycle which potentially imply HRIs (i.e. product maintenance or disassembly). This concept is summarized in Fig. 1.

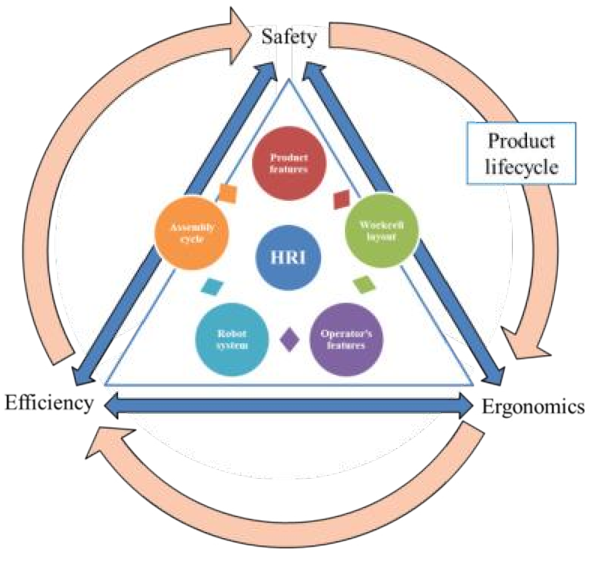

Fig. 1. Relationship of HRI requirements to be considered in an integrated product/process design concept.

In practice, a product which has to be assembled by a human and an industrial robot should imply a safe, ergonomic and efficient HRI by design. The final goal is to implement human-centered (anthropocentric) and efficient collaborative manufacturing systems [11]. As a consequence, we propose the introduction of an adapted perspective of DFA described as "Design for Collaborative Assembly". According to the abovementioned changes in production and due to the introduction of collaborative robots in the shopfloor, we define DFCA as follows:

"Design for Collaborative Assembly (DFCA) is defined as the process of designing assembly products by properly integrating the requirements of human and industrial robot interaction in terms of safety, ergonomics and production efficiency for all the shared activities of assembly or disassembly involved during the overall products lifecycle".

2. Introduction to Industrial Collaborative Robotics and Concurrent Engineering

DFCA aims to explore and evaluate the consequences of product design on the collaborative assembly cycle and hybrid production systems. This implies the consideration of the requirements in terms of HRI safety, ergonomics and production efficiency, both from the operator (manual assembly) and the robot (automatic assembly) perspective. These requirements have to be satisfied through a CE approach by properly integrating all related elements of the DFCA approach (see Fig. 2).

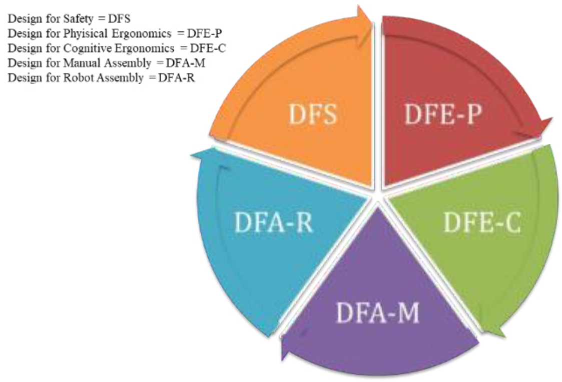

Fig. 2. Elements of the proposed DFCA approach.

2.1. Considering Safety in the Design of Assembly Products (DFS)

According to Sadeghi et al. [7] the consideration of occupational safety during design can concern product safety and human safety. The first involves a riskless utilization of a certain product [12], the latter address the prevention of accidents at work [13]. Basically, the consideration of safety requirements in product design means to eliminate or minimize all the occupational health and safety risks which can be generated during the usage of the final product or during its fabrication. In particular, in case of assembly processes in collaboration with industrial robots, main hazards are of mechanical type. Table 1 summarizes the main identified design guidelines for the improvement of operator safety during HRI assembly activities according to ISO and manufacturers of collaborative robots [14, 15, 16]:

Table 1. General product design guidelines for the improvement of operator safety during HRI assembly activities [14, 15, 16]:

Minimize all the general hazards related to human-assembly parts interaction
Design measures to minimize the effects of the following product-related hazards: • (DFS1) mechanical; • (DFS2) electrical; • (DFS3) thermal; • (DFS4) noise; • (DFS5) vibration; • (DFS6) radiation; • (DFS7) material/substance; • (DFS8) combination of hazards;
Minimize specific mechanical hazards related to the entrapment of human body parts
• (DFS9) Design measures to minimize the probability and the damage related to the entrapment of body parts (especially fingers and upper limb parts) into parts of the assembly product; This condition can cause physical damage when: ▪ human body parts are stuck into the parts of the assembly product which is handled by the robot at the same time; ▪ human body parts are stuck into the parts of the assembly product (which is firmly positioned into the workspace) making the robot systems avoidance very complex.
Minimize specific mechanical hazards related to human – assembly parts interaction
• (DFS10) Design measures to minimize the probability and the damage related to the penetration of skin by sharp edges and sharp points of assembly products; • (DFS11) Design measures to minimize the probability and the damage related to the bruising due to contacts between body parts and assembly products; • (DFS12) Design measures to minimize the probability and the damage related to the energy exchange which can occur during unexpected collisions between the human body parts and the assembly products; These conditions can cause physical damage when: ▪ the assembly product accidentally hurts the human body parts while the product or a component is handled by the robot; ▪ the assembly product is firmly positioned into the workspace and the robot systems accidentally push the human body parts against the product or a component; ▪ the assembly product is firmly positioned into the workspace or is handled by the robot and the robot systems accidentally constrain the human body parts between the product or component and the objects into the workspace.
Minimize specific mechanical hazards related to robot system parts falling
• (DFS13) Design measures to minimize the probability and the damage related to the falling out of assembly parts during the robot handling (e.g. due to a poor grip or power interruption).

2.2. Considering Physical Ergonomics in the Design of Assembly Products (DFE-P)

The International Ergonomics Association (IEA) defines physical ergonomics as the scientific discipline concerned with human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activity [17]. Product design has a great influence on manufacturing physical ergonomics since it defines the related assembly tasks [18]. In principle, a product designed in that the right way, implies a simple and quick assembly and enhances an improvement of operators physical work conditions in terms of biomechanical overload (especially for inadequate postures and stressful activities) [19], which reflects on the reduction of potentials musculoskeletal disorders. Better physical ergonomics conditions could also improve the assembly quality of the final product [9]. Even if good results can be achieved through a proper design of the assembly cycle and work environment, some dimensional and geometrical product features could imply operators biomechanical overload regardless their work conditions. Table 2 summarizes the main identified design guidelines for the improvement of physical ergonomics during assembly activities according to ISO [20]:

Table 2. General product design guidelines for the improvement of operator physical ergonomics during HRI assembly activities [20]

Minimize the bio-mechanical overload of upper limbs related to repetitive tasks
Design measures to minimize the presence of adverse features which can negatively affect a proper repetition of high frequency tasks due to dimensional or geometrical reasons: • (DFE-P1) the components imply the use of upper limbs for long time during the assembly; • (DFE-P2) the components imply the elbows position above the shoulder level for quite all the time during the assembly; • (DFE-P3) the components imply the use of moderate and continuous force to be assembled; • (DFE-P4) the components imply force peaks to be assembled; • (DFE-P5) the components imply the need of grasping using the fingers tips (all kinds) for quite all the time during the assembly; • (DFE-P6) the components imply high frequency and similar movements of upper limbs to be assembled.
Minimize the bio-mechanical overload of whole body related to manual lifting/lowering of objects
• (DFE-P7) Design measures to minimize the weight Design measures to minimize the presence of adverse features which can negatively affect a proper lifting or lowering due to dimensional or geometrical reasons: • (DFE-P8) the components present slippery contact surfaces; • (DFE-P9) the components present a not-stable center of gravity; • (DFE-P10) the components present sharp edges, surfaces or protrusions on external parts; • (DFE-P11) the components present too cold or too hot contact surfaces; • (DFE-P12) the components imply an asymmetric posture of human-body to be assembled; • (DFE-P13) the components require that the load is maintained far to the body to be assembled; • (DFE-P14) the components imply a vertical displacement outside the range between hips and shoulders to be assembled; • (DFE-P15) the components imply frequent body movements to be assembled.
Minimize the bio-mechanical overload of head/neck/trunk/upper or lower limbs related to static or awkward working postures
Design measures to minimize the presence of adverse features which can negatively affect a proper posture of head and neck due to dimensional or geometrical reasons: • (DFE-P16) the components imply an asymmetric posture of booth neck and trunk to be assembled; • (DFE-P17) the components imply unsupported trunk backward inclination or harsh flexion to be assembled; • (DFE-P18) the components imply neck extension or harsh flexion to be assembled; • (DFE-P19) the components imply unsupported head backward inclination or harsh inclination to be assembled; • (DFE-P20) the components imply a convex spinal curvature (if sitting) to be assembled. Design measures to minimize the presence of adverse features which can negatively affect a proper posture of upper limb (right and left) due to dimensional or geometrical reasons:

- (DFE-P21) the components imply awkward upper arm postures to be assembled;
- (DFE-P22) the components imply raised shoulder to be assembled;
- (DFE-P23) the components imply unsupported upper arm elevation to be assembled;
- (DFE-P24) the components imply extreme elbow flexion/extension AND extreme forearm rotation to be assembled;
- (DFE-P25) the components imply extreme wrist deviation to be assembled.

Design measures to minimize the presence of adverse features which can negatively affect a proper posture of lower limb (right and left) due to dimensional or geometrical reasons:

- (DFE-P26) the components imply extreme knee flexion to be assembled;
- (DFE-P27) the components imply flexed knee in standing postures to be assembled;
- (DFE-P28) the components imply not neutral ankle position to be assembled;
- (DFE-P29) the components imply kneeling or crouching to be assembled;
- (DFE-P30) the components imply very high knee angle (if sitting) to be assembled.

2.3. Considering Cognitive Ergonomics in the Design of Assembly Products (DFE-C)

The International Ergonomics Association (IEA) defines cognitive ergonomics as the scientific discipline concerned with mental processes, such as perception, memory, reasoning, and motor response, as they affect interactions among humans and other elements of a system (relevant topics also include work stress) [17]. In industrial product assembly, this mental process could be affected by task complexity (or difficulty), which is an inherent activity quality able to influence human cognitive resources [21]. According to [22], perception, decision-making and manipulation are sequential time components in information processing and task execution which have to be minimized through product design. Table 3 summarizes the main design guidelines for the improvement of cognitive ergonomics during assembly activities according to Helander and Richardson [22, 23]:

Table 3. General product design guidelines for the improvement of operator cognitive ergonomics during HRI assembly activities [22, 23]

Reduce the number of assembly sub-systems
• (DFE-C1) Minimize the number of components; • (DFE-C2) Minimize the number of fasten components; • (DFE-C3) Minimize the number of fastening points.
Make components well identifiable and distinguishable
• (DFE-C4) Highlight components and/or make them well visible; • (DFE-C5) Provide visual and/or tactile discrimination by size, colour, texture; • (DFE-C6) Provide visual, tactile, auditory feedbacks; • (DFE-C7) Add cues to proper orient and rotate components; • (DFE-C8) Provide distinct and readily identifiable fastening points; • (DFE-C9) Group components for a single or small number of assembly steps.
Make components easy to orient, locate and fasten
• (DFE-C10) Promote symmetrical components; • (DFE-C11) Promote obvious asymmetry for asymmetric components; • (DFE-C12) Prevent orientational ambiguity; • (DFE-C13) Provide self-locating components; • (DFE-C14) Provide spatial compatibility and/or collocation of associated components; • (DFE-C15) Promote physical affordances and constraints; • (DFE-C16) Enlarge tolerances as much as possible; • (DFE-C17) Provide easy to use fastens; • (DFE-C18) Provide easy-to-grip situations (promote the use of fixtures and avoid tangle parts).
Provide clear assembly instructions
• (DFE-C19) Provide clear general assembly procedures; • (DFE-C20) Provide dedicated and separated assembly step procedures for asymmetrical components; • (DFE-C21) Provide an own step in assembly procedures for each novel (or unique) assembly; • (DFE-C22) Provide physically labelled components with corresponding labels on the assembly procedure.
Make the work intuitive
• (DFE-C23) Support the formation of a mental model; • (DFE-C24) Reduce the choice reaction time; • (DFE-C25) Facilitate the leaning transfer; • (DFE-C26) Promote product similarity (new/old).

2.4. Considering Production Efficiency in the Design of Manual Assembly Products (DFA-M)

Design for manual assembly implies the consideration of the facility of manual assembly of a product during all the steps of its design process [24]. It allows evaluating the reduction of final costs by considering the potential decrease of assembly time which could be achieved through product design changes [10]. Considering that the total number of assembly parts and the ease of handling, insertion and fastening are the most important factors in the reduction of assembly time (and therefore costs), this methodology is based on the assumption that the best design has to be achieved by either avoiding certain assembly activities altogether or to simplifying them [10]. Table 4 will summarize these concepts.

2.5. Considering Production Efficiency in the Design of Robotic Assembly Products (DFA-R)

Basically, the core principles for the design of manual assembly products are incorporated into the guidelines for the design of automatic and robotic assembly products. In fact, large part of the requirements for product design for manual assembly are also adopted in product design for robot assembly and can provide enormous benefits if properly applied [24]. However, the evaluation of a certain design solution should carefully consider the need for any special dedicated equipment such as special grippers or feeding systems. In addition, the necessity of tool or gripper changes has to be minimized [24]. It is also necessary to consider the arrangement of assembly products to be properly recognized from an automatic vision system. In fact, in order to avoid using of dedicated and rigid feeding systems and in order to reduce the internal logistics complexity, products should be recognizable by e.g. a bin-picking vision system even if they are supplied in a random and accumulated way (as for manual assembly products). This involves particular physical features and suitable ways to arrange the components in order to simplify the vision system analysis. Table 4 summarizes the main design guidelines for the improvement of manual and robotic assembly efficiency according to [27, 28, 24, 25, 26].

Table 4. General product design guidelines for the improvement of manual and robotic assembly efficiency during HRI assembly activities [27, 28, 24, 25, 26].

Simplify object recognition activities **
• (DFA1) Design components which are not shiny on their external surfaces;
• (DFA2) Design components which are not texture-less on their external surfaces;
• (DFA3) Design components which present the simplest possible external geometry.
Simplify feeding activities
• (DFA4) Design final components by minimizing the number of assembly parts;
• (DFA5) Design components which are not magnetic or sticky;
• (DFA6) Design components which are not nest or tangle.
Simplify handling activities
• (DFA7) Design components which present symmetry axis or, if not possible, exaggerate asymmetrical features;
• (DFA8) Design components which are not-fragile or delicate;
• (DFA9) Design components which are not-flexible;
• (DFA10) Design components which are not abrasive; **
• (DFA11) Design components with a suitable dimension (avoid very small or very big components);
• (DFA12) Design stable components (so that air resistance would create conveying problems due to the light); **
• (DFA13) Design components which are not slippery
• (DFA14) Design components in such a way can be gripped and inserted using the minimum number of robot tools; **
• (DFA15) Design components which are not hazardous to the handler; *
• (DFA16) Design components which involve standardization by using common parts, processes, and methods.
Simplify assembly activities
• (DFA17) Design components which present a "datum surface" (reference surface) which simplify a precise positioning during the assembly;
• (DFA18) Design components which can be easily orientated;
• (DFA19) Design components which include features which allow a self-aligning during the assembly;
• (DFA20) Design components which can be located before they are released;
• (DFA21) Design components which avoid resistance to insertion;
• (DFA22) Design components which present chamfers or tapers that help to guide and position the parts in the correct position;
• (DFA23) Design components which have a suitable base part on which to build the assembly;
• (DFA24) Design components which can be assembled in layer fashion from directly above (z-axis assembly);
• (DFA25) Design components/design the assembly in such a way the assembly is not-overconstrained;
• (DFA26) Design components/design the assembly in such a way the assembly area and the access for assembly operations is free from obstacles and easy to reach;
• (DFA27) Design components/design the assembly in such a way the need of high physical dexterity is avoided;
• (DFA28) Design the assembly in such a way the need of high accuracy and/or demanding insertion tolerances is avoided;
• (DFA29) Design the assembly in such a way the need to reposition the partially completed sub-assembly, other components or fixtures is avoided
• (DFA30) Design the assembly in such a way the reorientation of the partial assembly or the manipulation of previously assembled parts is avoided;
• (DFA31) Design components which does not require to be compress during the assembly or which does not require the necessity for holding parts down to maintain their orientation;
• (DFA32) Design components/design the assembly in such a way the need of two hands for handling is avoided; **
• (DFA33) Design components/design the assembly in such a way typical human skills (for example touch perception, hearing, ability to interpret situations…) are avoided; **
• (DFA34) Design components which minimize connections (try to implement this hierarchy: snap fitting plastic bending, riveting, screw fastening);
• (DFA35) Design components which avoid adjustments. *

* = mainly for manual assembly
** = mainly for robotic assembly

3. Relation of DFCA guidelines to each other

Once all the single DFCA guidelines for HRI assembly are listed and explained, it is possible to identify their relation in terms of integrated product and process design requirements. As a single guideline can have a strong relationship or influence to other elements of DFCA, we preliminarily examined the dependencies in order to identify which of the proposed DFCA guidelines can be considered as more important than other ones. Table 6 visualizes the relationships of the identified guidelines according to the previously introduced elements of DFCA. The table analyzes the hypothetical link between every single DFCA guideline and the related requirements in terms of HRI. These relationships are explained by using a four equal-level scale represented by a combination of “X”. The absence of this symbol means that no relationship is supposed for a certain guideline. In order to find a final classification about the overall importance, the total number of “X” of every guideline is counted. Since the range of possible values is included between 0 (min) and 15 (max), the classification is based on five classes. According to the sum, it is possible to have the following results: (1) no influence ($0 \leq$ final score < 3), (2) low influence ($3 \leq$ final score < 6), (3) moderate influence ($6 \leq$ final score < 9), (4) good influence ($9 \leq$ final score < 12), (5) strong influence ($12 \leq$ final score ≤ 15). The relationships between the guidelines and the requirements are defined according to the following general assumptions:

a) Safety: safety guidelines are strictly related to all the other requirements except for robot assembly efficiency. In fact, safety must be an inherent and crucial part of all the activities involved in manual assembly and partially in the robotic systems safeguard.
b) Physical ergonomics: the guidelines about physical ergonomics are strictly related to the requirements about manual assembly efficiency since, in general, ergonomics deeply affects operators performance. Furthermore, cognitive aspects are also related to physical aspects since (in general) a better biomechanical condition reflects positively on the reduction of psychological stress.
c) Cognitive ergonomics: in this case, better cognitive conditions reflects positively on operators performance and therefore on manual assembly efficiency. Furthermore, large part of these guidelines are in agreement with the guidelines for the improvement of robotic assembly efficiency.
d) Assembly efficiency: due to the fact that large part of the requirements for manual assembly are also needed for automatic assembly, the guidelines for the improvement of manual assembly efficiency are strictly and positively related to the ones related to robot assembly efficiency. In addition, for the same reasons explained before, a better assembly efficiency often requires improvements in terms of physical and cognitive ergonomics.

Table 6. Relationship between the identified DFCA guidelines and the DFCA elements.

	XXX = strong effect; XX = moderate effect; X = low effect					
	Safety	**Physical Erg.**	**Cognitive Erg.**	**Manual Ass. Eff.**	**Robot Ass. Eff.**	**Final score**
DFS1	XXX	XXX	XXX	XXX	X	strong influence
DFS2	XXX	XXX	XXX	XXX	X	strong influence
DFS3	XXX	XXX	XXX	XXX	X	strong influence
DFS4	XXX	XXX	XXX	XXX	X	strong influence
DFS5	XXX	XXX	XXX	XXX	X	strong influence
DFS6	XXX	XXX	XXX	XXX	X	strong influence
DFS7	XXX	XXX	XXX	XXX	X	strong influence
DFS8	XXX	XXX	XXX	XXX	X	strong influence
DFS9	XXX	XXX	XXX	XXX	X	strong influence
DFS10	XXX	XXX	XXX	XXX	X	strong influence
DFS11	XXX	XXX	XXX	XXX	X	strong influence
DFS12	XXX	XXX	XXX	XXX	X	strong influence
DFS13	XXX	XXX	XXX	XXX	X	strong influence
DFE-P1	X	XXX	XX	XXX		good influence
DFE-P2	X	XXX	XX	XXX		good influence
DFE-P3	X	XXX	XX	XXX	X	good influence
DFE-P4	X	XXX	XX	XXX	XXX	strong influence
DFE-P5	X	XXX	XX	XXX	X	good influence
DFE-P6	X	XXX	XX	XXX	X	good influence
DFE-P7	XXX	XXX	XX	XXX	XX	strong influence
DFE-P8	XX	XXX	XX	XXX	XXX	strong influence
DFE-P9	X	XXX	XX	XXX	X	good influence
DFE-P10	XXX	XXX	XX	XXX	X	strong influence
DFE-P11	XXX	XXX	XX	XXX	X	strong influence
DFE-P12	X	XXX	XX	XXX		good influence
DFE-P13	X	XXX	XX	XXX		good influence
DFE-P14	X	XXX	XX	XXX		good influence
DFE-P15	X	XXX	XX	XXX	X	good influence
DFE-P16	X	XXX	XX	XXX		good influence
DFE-P17	X	XXX	XX	XXX		good influence
DFE-P18	X	XXX	XX	XXX		good influence
DFE-P19	X	XXX	XX	XXX		good influence
DFE-P20	X	XXX	XX	XXX		good influence
DFE-P21	X	XXX	XX	XXX		good influence
DFE-P22	X	XXX	XX	XXX		good influence
DFE-P23	X	XXX	XX	XXX		good influence
DFE-P24	X	XXX	XX	XXX		good influence
DFE-P25	X	XXX	XX	XXX		good influence
DFE-P26	X	XXX	XX	XXX		good influence
DFE-P27	X	XXX	XX	XXX		good influence
DFE-P28	X	XXX	XX	XXX		good influence
DFE-P29	X	XXX	XX	XXX		good influence
DFE-P30	X	XXX	XX	XXX		good influence
DFE-C1	X	XX	XXX	XXX	XXX	strong influence
DFE-C2	X	XX	XXX	XXX	XXX	strong influence
DFE-C3	X	XX	XXX	XXX	XXX	strong influence
DFE-C4	X		XXX	XXX	XXX	good influence
DFE-C5	X		XXX	XXX	XXX	good influence
DFE-C6		X	XXX	XXX		moderate influence
DFE-C7			XXX	XXX	XXX	good influence
DFE-C8			XXX	XXX	XXX	good influence
DFE-C9		X	XXX	XXX	XXX	good influence
DFE-C10			XXX	XXX	XXX	good influence
DFE-C11			XXX	XXX	XXX	good influence
DFE-C12			XXX	XXX	XXX	good influence
DFE-C13		X	XXX	XXX	XXX	good influence
DFE-C14			XXX	XXX	XXX	good influence
DFE-C15			XXX	XXX	XXX	good influence
DFE-C16		X	XXX	XXX	XXX	good influence
DFE-C17		XX	XXX	XXX	XXX	good influence
DFE-C18		XX	XXX	XXX	XXX	good influence
DFE-C19	X	X	XXX	XXX		moderate influence
DFE-C20			XXX	XXX		moderate influence
DFE-C21			XXX	XXX	XX	moderate influence
DFE-C22	X	X	XXX	XXX		moderate influence
DFE-C23			XXX	XXX		moderate influence
DFE-C24			XXX	XXX		moderate influence
DFE-C25			XXX	XXX		moderate influence
DFE-C26	X		XXX	XXX	XXX	good influence
DFA-1					XXX	low influence
DFA-2					XXX	low influence
DFA-3					XXX	low influence
DFA-4	X	XX	XXX	XXX	XXX	strong influence
DFA-5		XX	XX	XXX	XXX	good influence
DFA-6		XX	XX	XXX	XXX	good influence
DFA-7			XXX	XXX	XXX	good influence
DFA-8	XX	XX	XX	XXX	XXX	strong influence
DFA-9				XXX	XXX	moderate influence
DFA-10	X	XX	X	XX	XXX	good influence
DFA-11	X	XX	X	XXX	XXX	good influence
DFA-12				XX	XXX	low influence
DFA-13		XX		XXX	XXX	moderate influence
DFA-14					XXX	low influence
DFA-15	XXX	XXX	XXX	XXX	X	strong influence
DFA-16			XXX	XXX	XXX	good influence
DFA-17			XXX	XXX	XXX	good influence
DFA-18			XXX	XXX	XXX	good influence
DFA-19		X	XXX	XXX	XXX	good influence
DFA-20		X	XXX	XXX	XXX	good influence
DFA-21	X	XXX	XXX	XXX	XXX	strong influence
DFA-22			XXX	XXX	XXX	good influence
DFA-23			XXX	XXX	XXX	good influence
DFA-24			XXX	XXX	XXX	good influence
DFA-25			XXX	XXX	XXX	good influence
DFA-26	X	XXX	XX	XXX	XXX	strong influence
DFA-27		XXX	XX	XXX	XXX	good influence
DFA-28		XXX	XXX	XXX	XXX	strong influence
DFA-29	X	XX		XXX	XXX	good influence
DFA-30		XX	XXX	XXX	XXX	good influence
DFA-31		XXX		XXX	XXX	good influence
DFA-32	X	XX		XX	XXX	moderate influence
DFA-33		XX	XXX	XX	XXX	good influence
DFA-34	X	XXX	XXX	XXX	XXX	strong influence
DFA-35		XX		XXX	XXX	moderate influence

4. Conclusions

Since the industrial collaborative robotics market is continuously developing, collaborative assembly will probably be an interesting and widespread application in the next future. This condition will influence the way by which products are manufactured and assembled and, as a consequence, the product design methods should be consequently reconsidered (and where necessary adjusted) according to HRI process main requirements. A product which is supposed to be assembled in a collaborative system should present components which are specifically designed for manual assembly, for robot assembly and for collaborative assembly by considering the requirements in terms of process safety, ergonomics and efficiency. In this work, a definition of "Design for Collaborative Assembly" (DFCA) and related guidelines are introduced for the first time. The proposed guidelines should support designers to better define product features according to the requirements of HRI assembly process. The presented guidelines can be used both for new products design as well as for existing products re-design. Obviously, the impact on the collaboration will be more effective in the former case instead in the latter. According to the presented concepts, a designer should implement the guidelines according to the proposed order: safety as first, ergonomics (both physical and cognitive) as second and efficiency as third. In addition, the priority of implementation should follow the classification proposed in Table 6 which means to ignore the guidelines highlighted as "no influence" and then developing the product features by introducing sequentially the others according to their increasing influence. Of course, this approach should also consider possible mutual relationships (positive or negative) between the various guidelines. Future works should quantify the impact of every single DFCA guideline on the others. This means the categorization of the guidelines which can be classified as essential, the identification of the single relationship between the various guidelines and the attribution of the influence weight of these connections (also considering possible negative mutual effects). Further researches should also investigate some real design solution for the physical adoption of the identified guidelines. These works will be implemented into the Smart Mini Factory laboratory of the Free University of Bolzano-Bozen [29] by preparing and analyzing different case studies and eventually developing training seminars for the designers and technicians of local small and medium enterprises.

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References

[1] Pedersen, M. R., Nalpantidis, L., Andersen, R. S., Schou, C., Bøgh, S., Krüger, V., & Madsen, O. (2016). Robot skills for manufacturing: From concept to industrial deployment. Robotics and Computer-Integrated Manufacturing, 37, 282-291.

[2] Spena, P. R., Holzner, P., Rauch, E., Vidoni, R., & Matt, D. T. (2016). Requirements for the Design of flexible and changeable Manufacturing and Assembly Systems: a SME-survey. Procedia Cirp, 41, 207-212.

[3] International Federation of Robotics. 2019. IFR publishes collaborative industrial robot definition and estimates supply. https://ifr.org/post/international-federation-of-robotics-publishes-collaborative-industrial-rob. Accessed on August, 2019.

[4] Gualtieri, L., Rauch, E., Vidoni, R. & Matt D.T. (2019). An Evaluation Methodology for the Conversion of Manual Assembly Systems into Human-Robot Collaborative Workcells. In 2019 29th FAIM Conference on Flexible Automation and Intelligent Manufacturing, Limerick, Ireland.

[5] Winner, R. I., Pennell, J. P., Bertrand, H. E., & Slusarczuk, M. M. (1988). The role of concurrent engineering in weapons system acquisition (No. IDA-R-338). Institute for Defense Analyses Alexandria VA.

[6] Chiu, M. C., & Okudan, G. E. (2010, January). Evolution of design for X tools applicable to design stages: a literature review. In ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 171-182). American Society of Mechanical Engineers.

[7] Sadeghi, L., Dantan, J. Y., Siadat, A., & Marsot, J. (2016). Design for human safety in manufacturing systems: applications of design theories, methodologies, tools and techniques. Journal of engineering design, 27(12), 844-877.

[8] Högberg, D. (2005). Ergonomics integration and user diversity in product design, Loughborough University (Doctoral dissertation, Doctoral thesis).

[9] Village, J., Searcy, C., Salustri, F., & Patrick Neumann, W. (2015). Design for human factors (DfHF): a grounded theory for integrating human factors into production design processes. Ergonomics, 58(9), 1529-1546.

[10] Kuo, T. C., Huang, S. H., & Zhang, H. C. (2001). Design for manufacture and design for 'X': concepts, applications, and perspectives. Computers & industrial engineering, 41(3), 241-260.

[11] Rauch, E., Linder, C., & Dallasega, P. (2019). Anthropocentric perspective of production before and within Industry 4.0. Computers & Industrial Engineering.

[12] Rausand, M., & Utne, I. B. (2009). Product safety–Principles and practices in a life cycle perspective. Safety Science, 47(7), 939-947.

[13] Sadeghi, L., Mathieu, L., Tricot, N., & Al Bassit, L. (2015). Developing a safety indicator to measure the safety level during design for safety. Safety science, 80, 252-263.

[14] International Organization for Standardization (2010). ISO 12100: Safety of machinery—General principles for design—Risk assessment and risk reduction (ISO 12100: 2010).

[15] International Organization for Standardization. (2011). ISO 10218—2: Robots and robotic devices—Safety requirements for industrial robots—Part 2: Robot systems and integration (ISO 10218-2: 2011).

[16] Universal Robots. (2018). UR3/CB3 Version 3.6.0 Original instructions.

[17] International Ergonomics Association. 2019. Definition and Domains of Ergonomics. https://www.iea.cc/whats/index.html. Accessed on August 2019.

[18] Broberg, O. (1997). Integrating ergonomics into the product development process. International Journal of Industrial Ergonomics, 19(4), 317-327..

[19] Neumann, P. (2004). Production Ergonomics: Identifying and managing risk in the design of high performance work systems(Vol. 10). Lund University.

[20] International Organization for Standardization. (2014). ISO-TR 12295—Ergonomics—Application document for ISO standards on manual handling (ISO 11228-1, ISO 11228-2 and ISO 11228-3) and evaluation of static working postures (ISO 11226) (ISO-TR12295: 2014)

[21] Richardson, M. (2011). 12 Assembly Complexity and the Design of Self-Assembly Products. Human Factors and Ergonomics in Consumer Product Design: Methods and Techniques, 187.

[22] Helander, M. G., & Willen, B. A. (1999). Design for human assembly (DHA). The occupational ergonomics handbook, 1849-1865.

[23] Richardson, M., Jones, G., Torrance, M., & Baguley, T. (2006). Identifying the task variables that predict object assembly difficulty. Human factors, 48(3), 511-525.

[24] Boothroyd, G., Dewhurst, P., & Knight, W. A. (2010). Product Design for Manufacture and Assembly. CRC Press.

[25] Boothroyd, G. (2005). Assembly automation and product design. CRC Press.

[26] Crowson, R. (2006). Assembly processes: finishing, packaging, and automation. CRC Press.

[27] Rodrigues, J. J. M. (2018). 3D pose estimation for bin-picking: A data-driven approach using multi-light images (Doctoral dissertation, Carnegie Mellon University Pittsburgh, PA).

[28] Piccinini, P., Prati, A., Cucchiara, R., DII, D. S., & Emilia, R. (2009). Multiple Object Detection for Pick-and-Place Applications. In MVA (pp. 362-365).

[29] Gualtieri, L., Rojas, R., Carabin, G., Palomba, I., Rauch, E., Vidoni, R., & Matt, D. T. (2018, December). Advanced Automation for SMEs in the I4. 0 Revolution: Engineering Education and Employees Training in the Smart Mini Factory Laboratory. In 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) (pp. 1111-1115). IEEE.