Human robot collaborative workcell implementation through lean thinking

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Industry 4.0 stresses the importance of considering production automation as an integrated and collaborative teamwork process between human workers and intelligent machines and tools. Collaborative robotics is a recent field of study for industrial automation. Although fenceless robot systems are available, the actual implementation of collaborative schemes for the conduction of assembly jobs should be supported through dedicated procedures and guidelines. These procedures have yet to be found and defined in detail. In this work, the authors claim that it may be possible to approach the problem of collaborative cell design with the methods devised for lean thinking. In the paper, the most common lean strategies are listed and analysed from the viewpoint of setting up a collaborative work cell. The most suitable strategies and tools are then recommended in a methodology that has been proposed to redesign an industrial assembly cell. The methodology has then been adopted in the presented industrial use case which is focused on the steps of HRC design process such as tasks assignment and scheduling.

Keywords: work stand organization; robot-human collaboration; lean rules; lean tools; hierarchical task analysis

1. Introduction

Traditionally, the main purposes of upgrading manual production cells with robot automation is to guarantee the safety of workers during heavy work activities, to improve production quality and to ensure a better repeatability of the process. Robot automation requires the replacement of humans with robots in fully automated cells because of safety issues and robot limited sensory capacities (Charalambous et al., 2015a). Full automation may increase productivity, but it is expensive and does not have the flexibility required to adapt to frequent variable productions. Therefore, in the past, robot automation was mainly employed in a mass production context.

The availability of new generations of collaborative robots (named cobots) has opened new perspectives for automation (Villani et al., 2018). Cobots are equipped with high-performance sensors and are controlled by smart systems that integrate these sensors with the use of advanced software technologies. Cobots do not need safety fences, and they can interact fairly well with the environment, so as to assist humans in work cells (Hagele, 2002).

Cobots need a well-organized collaborative workspace to ensure above all the safety of the workers, as well as the quality of results, efficiency and ergonomic work conditions. Safety in Human-Robot Collaboration (HRC) is by far the most relevant topic that has been discussed in the literature (Tan et al., 2010; Michalos et al., 2015; Polverini et al., 2017; Guiochet et al., 2017; Meziane et al., 2017, Maurtua et al., 2017). The safety requirements of collaborative industrial robot systems and the work environment are defined in ISO/TS 15066:2016. Guidance on collaborative industrial robot operations is defined in ISO 10218‑1 and ISO 10218‑2 (ISO 10218-1:2011). The concepts of collaborative operation and collaborative workspace are defined in the standard. Collaborative operation is a "state in which a purposely designed robot system and an operator work within a collaborative workspace". Collaborative workspace is a "space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation". It is apparent that issues concerning collaborative workspace design and work organization, as well as task assignment, cannot be addressed using approaches that were set up for standard automation. Nevertheless, this topic has received very little attention, with the exceptions of the works by (Tsarouchi et al., 2016; Ore et al., 2017; Tsarouchi et al., 2017). The re-designing of both process tasks and workspace layout is crucial when modifying an already existing process. The optimization of a workplace using standard industrial robots has been widely discussed in literature (Tay and Ngoi, 1996; Gueta et al., 2009; Yap et al., 2014). These authors took into consideration the station (shape, access/delivery point, space allowance) and the robot (number of robots, work envelope, base mobility, application and path of travel) (Tay and Ngoi, 1996). The space needed for humans in a workplace also needs to be considered in collaborative workspaces. An ergonomic workspace organization for human operators is very important (Chaffin, 2007). The organization of HRC work represents a challenge for process engineers. They should not only ensure the quality of work, but also cooperation safety and process efficiency. There are many constrains which must be taken into consideration in a workstation organisation. In the work of (Ding and Hon, 2013), the authors emphasised such ergonomic constraints as the workstation layout and the operator’s characteristics and posture, which are important for manual assembly procedures. The work with robots should be organized, as suggested in their work, to improve the capacity, ergonomics, quality of a process, etc. It is possible, by means of HRC, to combine robot accuracy and endurance with human cognition and versatility in a joint environment (Michalos et al., 2014). The robot should support a human operator in performing his or her tasks (Weidner and Wulfsberg, 2014). However, the worker maintains the leadership role and the responsibility of the correct execution of the process.

The benefits of the presence of humans in HRC are: greater availability and flexibility, the handling and joining of complex components, the reliable execution of processes and the simple organization of warehouses for tools and parts. The advantages allowed by the presence of robots in a manual work stand can be distinguished as: integrated process control, easy handling of heavy, dangerous components, exact playback of the defined path and a reliable performance of repetitive tasks (Müller et al., 2016).

However, HRC still raises some challenges, such as: perception, decision making, signalling the undertaken decisions, planning and execution of motions, acting in a predictable way and revealing intentions (Montreuil et al., 2007; Klein et al., 2004).

The assignment of tasks and the planning of a task for humans and robots have also been discussed in the literature (Müller et al., 2016; Ranz et al., 2017). In the paper of (Thomas et al., 2016), a concept for planning and designing human-robot collaborations is presented. The key point is that the work of a robot influences the conduction of an employee’s work. Therefore, collaboration between humans and robots should be optimized taking into account several factors concerning human behaviour, tiredness and possible human mistakes. It is worth stressing that manual cells have devices and procedures to avoid or correct human errors and to minimize the causes of variability. Automatic cells, once the start-up phase has been completed, have negligible variability and possibility of mistakes, and therefore do not need such procedures. The considerations on variability and error prevention in the design of collaborative cells are as important as they are in manual work cells.

In short, in the literature review, the authors found evidence of a non-systematic and non-rigorous use of lean concepts and lean tools in the implementation of collaborative workspaces. Hence, the main goal of the paper has been to systematically review lean rules and lean tools and to consider the possibility of their transfer to the design of HRC work cells. However, the transformation of the workspace from a manual work stand to a new collaborative robotized work cell should not be limited to introducing some new machines and changing some tools. The complete work management procedure should be revised. Lean concepts could provide a reliable support to help find the enabling processes and to help choose which modifiers should be applied.

The different ways of collaborating in an HRC are discussed in section 2 of the paper. HRC implementation is proposed in section 3, taking into account lean rules. Next, an analysis of the lean tools that can be used for collaborative workspace organization and for task assignment and planning is presented in section 4. In section 5, the authors propose a methodology that indicates suitable tools for the implementation of HRC on a work stand on which a manual process is already underway. Next, a case study, concerning an assembly process, which is currently realized manually in a small company, is discussed and redesigned to introduce HRC, with the support of the selected lean tools and rules, according to the proposed methodology. A modified hierarchical task analysis (HTA) (Kirwan and Ainsworth, 1992; Stanton, 2006) has also been adopted to support the assignment of tasks to a robot or to a human operator (Arai et al., 2008). Finally, section 6 presents the conclusions and future work.

2. Categories of human-robot collaboration (HRC)

As there are several levels of automation, depending from the degree of human involvement (Parasuraman et al., 2000), so there are different types of HRC, as a function of the kind of collaboration required to properly organise a work stand. Four categories of collaboration can be defined, according to ISO-TS 15066: independent operation, synchronized cooperation, simultaneous cooperation and assisted cooperation.

They can briefly be described as (Helms et al., 2002):

- Independent operation, where a worker and robot operate independently on different workpieces.
- Synchronized cooperation (collaboration), where a worker and robot operate consecutively on one work piece.
- Simultaneous cooperation (collaboration), where a worker and robot operate on the same work piece, but without any physical contact.
- Assisted cooperation (collaboration), where a worker and robot operate on the same work piece, at the same time, and the process is done by both the robot and the worker together.

This classification is widely adopted but is mainly concerned with safety issues and not with the organization of work, that is the objective of lean thinking. In the work of (Bdiwi et al., 2017), the authors propose different categories focused on the level of interaction instead of on the level of safety. They divided the human-robot interaction into the following levels:

1. Shared workspace and separated tasks (C1) – the workspace can be virtually divided into a human zone and a robot zone, and if a human enters the robot zone, the robot will stop operating immediately. This means that, in such a situation, the robot’s work will be interrupted for a few seconds or longer. The human zone is static: its boundaries are defined once and for all. The robot zone can be static or dynamic, and in the latter case, the boundaries are reshaped according to the trajectory and speed of the robot.
2. Shared workspace and task but without physical interaction (C2) – a human has no direct contact with a robot. The robot can hold a component while the human

is performing an assembly task. In this case, the process time is just the time taken by the human to perform the task.

3. Shared workspace and passing task (C3) – a task passes between a human and a robot: a robot takes a component/a tool from a human hand, or a human takes a component/a tool directly from a robot. A special handing-over zone, where a robot reacts to the motion of the human hand and follows it in the free space, can be indicated for this case.
4. Shared workspace and task with physical interaction (C4) – robot can be guided by manual guidance to perform the task, or can just assist human to lift heavy loads (smart hoist).

The first two categories represent good practices that have already some diffusions in many factories. The last two categories are being recently introduced and require more consistent reorganization of the work stand. Lean tools that should be employed differs with the category, as will be discussed in the section 4.

According to (Bauer et al. 2008), collaboration means working with someone (human being or robot) to reach a common goal. It requires shared instructions, shared information between collaborating partners and common knowledge about the intentions of each member of the team and what they are going to do. Therefore, a partner needs to have this knowledge to plan his/her own actions to reach a common goal. Hence, all the partners need, to some degree, the abilities of perceiving and understanding the environment, planning, learning, reflection and decisions making, i.e. cognitive abilities.

Since robotization is growing by about 50% per year (Bélanger-Barrette, 2015) and because collaborative robots are intended for physical interaction with humans in a shared workspace (Peshkin and Edward, 1999), it has appeared vital to analyse how already existing devices can be used to support the organization of work stands where humans and robots collaborate. The interaction between operators and robots can, for instance, be supported by augmented reality (Makris et al., 2016).

While considering all the HRC categories, the focus of the paper is on assisted collaboration where the workpiece is processed by operator and robot together, without any physical separation. The robot and human are two operators that work together with an improved working efficiency, because the human can focus on the operations that require more skills and flexibility (Kato et al., 2010). However, like any collaboration, it involves risks, and mistakes can lead to accidents (Beauchamps and Stobbe, 1995). In order to prevent these mistakes and accidents, it is important to support the operator with fail-safe systems, either hardware devices or warning messages. Additionally, not properly organized workstation as well as collaboration can lead to creation of wastes such as defects, overproduction, waiting, transporting, overprocessing, movement and inventory (Ohno, 1988). More deeply the wastes existing in HRC are presented in other part of the paper.

According to the authors, it is possible to use lean tools in any situation to improve a HRC work stand organization and lean rules for HRC implementation. This will be discussed in the following parts of the paper.

3. Introduction of lean rules in the HRC implementation process

Plenty of information is available in the literature about how to implement lean concepts in a company. There are opinions that lean thinking can be implemented for processes where products are manufacturing in large series. It can be because the lean concepts come from car industry where car parts and cars are manufactured and then assembled in long manufacturing lines where the process is fixed and realized for a long time without big changes. However, there are many examples of lean concept implementation in other industries and even for single part production. Because, lean is about wastes eliminations and they can appear in any kind of work if it is organized inadequately. Of course, not all lean tools can be applied in every situation. The tools should be chosen carefully and it should be assessed if the game is worth the candle. If a lean tool implementation will be more time and cost consuming than savings and advantaged achievable by its implementation, the tool shouldn't be used. This will be discussed in more detail in other parts of the paper.

More and less complex frameworks have been developed to implement lean concepts (Anand and Kodali, 2010; Mostafa et al., 2013; Belhadi et al., 2016). Moreover, several rules that help in the lean implementation process also exist. This analysis identifies the rules that can assist its implementation in HRC context.

When talking about the implementation of a lean concept, one should think about the whole company, even though the implementation usually starts from a pilot area, through the application of the 5S rule and of the Deming cycle. In the case of HRC, the application target coincides with an individual work cell, which usually constitute the pilot area. **Figure 1** describes the hierarchical levels of lean implementation.

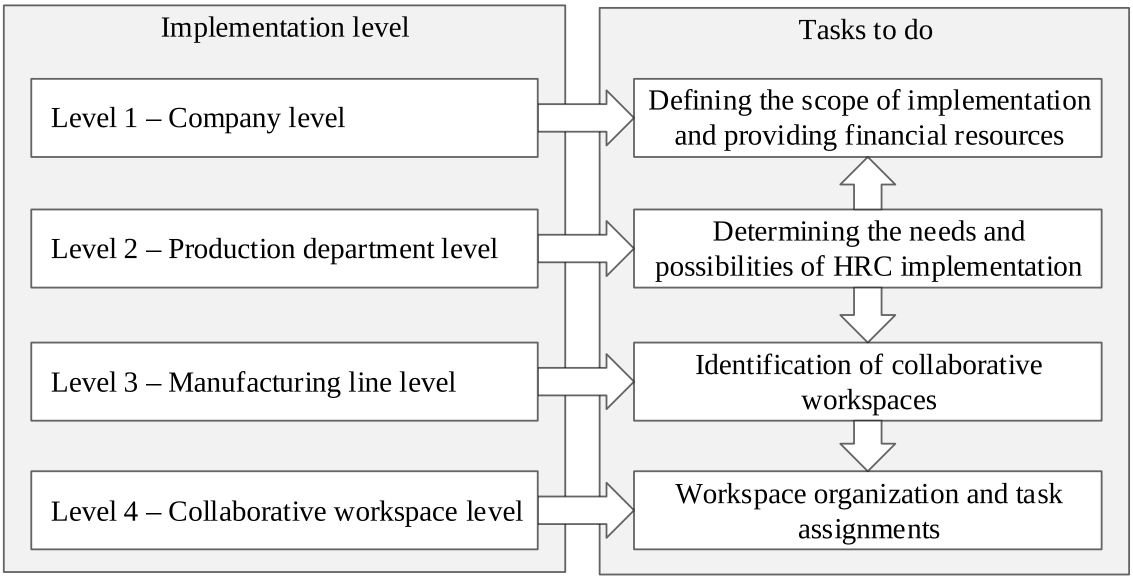


Figure 1. HRC implementation levels and corresponding tasks to undertake

HRC is one of the pillars of the Industry 4.0 strategy, in synergy with the integration and the monitoring of factory machines and tools (Moeuf et al., 2017), if a company decides to implement HRC, it should define its scope and provide financial resources for it. The decision is made at the company level (Level 1) (see **Fig. 1**). However, the needs and possibilities of HRC implementation should first be determined at the production department level (Level 2) as a function of the manufacturing processes. Collaborative workspaces should then be identified at the manufacturing line level (Level 3), their layouts should be organized at the lowest level and the tasks should be allocated to humans or to robots.

This general description of HRC implementation can be enriched with knowledge and experience obtained from lean concept implementation in companies as well as with lean rules and tools.

The most well-known rules of the lean concept were presented by Womack and Jones (2003), who called them the five principles: (1) define the value for the customers, (2) map the value stream, (3) create the value flow, (4) establish a pull system and (5) pursue perfection. The value that is created in a collaborative workspace as a result of HRC should be discussed in HRC. The value should be analysed from a customer point of view. It can be analysed on the macro and micro levels. On macro level the value for a customer is a product which is assembled in HRC work cell and for which a customer is willing to pay. On micro level the value is an activity which leads to a finished product. The value stream can be defined as a set of activities that are performed by humans and robots sequentially or parallelly. The value flow relates to the elimination of waste. In HRC, the waste refers to those types that are produced within the collaborative workspace. A pull system can be established, e.g., by using a human operator as a pacemaker. Perfection can be pursued by optimising the task allocation between a robot and a human operator (Ranz et al., 2017). Optimization can be introduced each time the process is changed.

When talking about lean rules at higher levels, their application should not differ from the standard application adopted in companies involved in manual or automatic production. However, collaborative robot implementation can increase the productivity of manual work stations (Perez-Vidal et al., 2018), and should be adopted for the bottleneck process, whenever possible.

The main goal of the lean concept is waste elimination. Taiichi Ohno identified seven different kinds of waste in organizations: defects, overproduction, waiting, transporting, overprocessing, movement and inventory (Ohno, 1988). In HRC, these kinds of waste can be explained as follows. Defects can be generated by both human operators and robots, or by their joint work. Overproduction can appear if the work stand works faster than necessary. This can happen if the work stand is not connected to other work stands on the manufacturing line through a pull system. Waiting occurs when a robot or a human wait too long to perform a task, i.e. whenever the task sequence has not been designed properly. Unnecessary transporting appears whenever the collaborative workspace has not been organized properly. This can cause a time waste. Overprocessing results in undertaking unnecessary activities during a work process. The possibility of avoiding overprocessing depends on the people who develop the standard operating procedures (SOPs), which are indispensable in HRC. Unnecessary movements depend on the work organization and should also be avoided during the SOP development stage. An inventory of the collaborative workspace is needed to ensure work continuity, although an excessive inventory should be avoided. Hence, an adequate lean tool should be implemented.

In (Netland, 2016), the author indicated the following rules that he considered indispensable for the successful implementation of lean concepts: managerial commitment, people training and education, having a plan and following it up, provision of resources and sharing the gains, lean tools and method implementation. On the other hand, in the work by (Anvari et al., 2010), the authors presented the following important issues: goals and objectives, organizational cultures, management and leadership, education and plan, skills, problem solving, continuous improvement, change, performance measure and financial capabilities.

On the basis of the presented rules, it is important to ensure that financial resources are provided in HRC, the goals and objectives are set, the people are trained and their skills are improved, people are empowered, any changes are planned and adequate tools are implemented to ensure safe and efficient collaboration.

On the basis of the risks concerning lean implementation presented by Marodin and Aurin (2015), the following risks can be identified in HRC implementation: a lack of human resources, a lack of financial resources, the operators are afraid of layoffs due to improvements, a lack of support on the shop floor, the operators are unsure about carrying out new activities, and about having difficulties in keeping up the pace of the ongoing activities.

The implementation of robots in order to collaborate with human operators requires several changes in a company as far as the work organization and the mental approach of the employees are concerned. Similarly, several changes can be expected for the implementation of lean concepts.

In the works by (Charalambous et al., 2015b), the authors presented the organisational human factors they considered of key importance that had to be introduced into industry to implement human-robot collaboration. Some of them are emphasized hereafter. The first one is communication of the change, which is necessary to promote change and inform the employees why, how and when their workplace will change and how their work will change after the implementation. The employees have to understand that, with the introduction of the new organisation, they will be able to perform better their work, which should create supportive behaviour among the employees. Another issue concerns operator participation in implementation. The participation of the operators should help in the transition from manual to automated work. Their experience and knowledge of working methods should help to share the work elements between human and robot operators. Moreover, the training of employees from the first stages should support the implementation process. The existence of a process champion was recognized as one of the major enablers. The champion should have knowledge about the manual process and one of his/her main tasks is the dissemination of important information to all the interested parties involved in the implementation change process. System implementation is also important in HRC to empower employees with additional control in order to foster acceptance of the system.

4. Lean tool implementation in companies with HRC

Different lean tools and methods are presented in the literature, together with examples of their application in companies and the advantages of their implementation (Eswaramoorthi et al., 2011; Arunagiri and Gnanavelbabu, 2014; Bhasin, 2012; AL-Tahat and Jalham, 2015; Stadnicka, 2015; Antosz and Stadnicka, 2017). Lean tools can be implemented at different levels in a company. The levels at which lean tools can be implemented are indicated in **Table 1**. The implementation of these tools and methods in HRC is discussed hereafter.

Table 1. Lean tools and methods implementation on different levels of organization; A – applied; C1, C2, C3, C4 – category of HRC the tool has to be applied; importance of a tool application on Level 4: (+) – the less important, (++) – important, (+++) – the most important.

Lean tool	Level 1 Company level	Level 2 Production department level	Level 3 Manufacturing line level	Level 4 Collaborative workspace level			
				C1	C2	C3	C4
5S	A	A	A	+++	++	++	++
Andon		A	A	++	+	++	++
Bottleneck Analysis	A	A	A				
Takt Time			A	+++	+++	+++	+++
Continuous Flow	A	A	A	+	++	+++	+
Gemba & Kaizen		A	A	++	+	+	++
Heijunka			A	+	+	+	+
Hoshin Kanri	A	A	A	++	+	+	+

Lean tool	Level 1 Company level	Level 2 Production department level	Level 3 Manufacturing line level	Level 4 Collaborative workspace level			
				C1	C2	C3	C4
Just-In-Time	A	A	A	+	+++	+++	+
FMEA			A	+++	+++	++	+++
Poka Yoke		A	A	+++	+++	+++	+++
SMED			A	+	+	+	++
Standardization	A	A	A	+++	+++	+++	++
TPM	A	A	A	+++	+++	+++	+++
Visualization	A	A	A	++	++	+	++
Time study				++	+++	+++	+++
HRC categories: C1. Shared workspace and separated tasks; C2. Shared workspace and task but without physical interaction; C3. Shared workspace and passing task; C4. Shared workspace and task with physical interaction							

The presented lean tools are discussed in relation to the collaborative workspace level (Level 4), since, in most cases, lean tool implementation can follow standard procedures for the other levels. Additionally, since HRC can be realized in four different categories, for each category it was assessed how important the specific lean tools are. The pairwise comparison method (Thurstone, 1927) was applied in the assessment process. The results of the analysis are presented in **Table 1**, where the tools are marked as the less important (+), important (++) or the most important (+++).

5S is particularly important for the collaborative workspace level (Level 4, C1), because a robot performs a programmed sequence of movements, and the tools and/or assembly parts need to be located in specific places where a robot can access them. 5S is also important for the human worker, because he or she has a pre-defined time to perform the tasks before a robot takes over. Therefore, wasting time searching for the necessary items prompts further delays in the operations. Implementing 5S ensures that just what is needed to carry out a pre-defined work task is on the work stand, everything has a specific place, the work area is clean and inspected, and that the standards (SOP) pertaining to robot and human work are developed and introduced.

Andon in a work stand with HRC can offer visual feedback that indicates the work status, can create alerts when necessary, and empower operators to stop the manufacturing process (robot movements) when necessary, i.e. in the case of nonconformity or safety threats. The Andon system, being a real-time communication tool, immediately draws the attention of the operators if a problem arises and operator action is needed. Therefore, it can prevent waste from being created.

Bottleneck Analysis is not applicable at the collaborative workspace level. Such an analysis can only be undertaken at higher levels. This analysis can help to identify the processes that limit the overall throughput, and to assess whether the HRC work cell implementation can be helpful.

Takt Time is related to the production pace that aligns production with customer demand. As robots and humans usually have different cycle times for the conduction of their respective tasks, and robots have to adopt a reduced velocity in proximity of humans for safety reasons, the respect of the takt time in a collaborative cell is a nontrivial matter. Unlike full automation, employee tiredness should be considered in HRC because of the effects on the cycle time and necessary breaks should be planned to prevent mistakes being made by the human operators. Takt time is very important in an all HRC categories.

Continuous Flow can be implemented in HRC (especially in C3) in such a way that a robot works as an element of a flow and as an effective element that performs a larger number of activities than human operators in the flow over the same takt time. By implementing a robot, it should be possible to eliminate a number of different types of waste, such as on-line inventories or waiting times.

Gemba (The Real Place) is a philosophy that can be used in the allocation of tasks to robots and humans. For example, before tasks are allocated, an observation of the manual process should be executed. It should then be repeated again after the tasks have been allocated to ensure that the tasks have been allocated properly to both the human operators and the robots, and that unexpected problems will not occur after approval of the task allocation. It is important to observe real processes on the plant floor in order to avoid mistakes in the allocation of tasks, which could cause such problems as employee overloading. Such a problem may increase when more and more RHC work stands have to be implemented, and less attention can be given to the planning of their work. Gemba can currently be preceded by computer simulations or virtual reality to predict future problems before implementing SOP in real life situations (Trebuna et al., 2014, Sütő et al., 2017; Yap et al., 2014).

In the case of HRC, Kaizen (Continuous Improvement) should be implemented, together with Gemba, in the work stand design and task allocation stages. This means that employees should be engaged in collaborative workspace organization during the validation stage. Incremental improvements could be expensive and time consuming later on, because they imply the necessity of robot re-programming.

Heijunka (Level Scheduling) can be implemented e.g. on the assembly line on which one human operator and a few robots (**Figure 2a**), one robot and one human operator (**Figure 2b**) or one robot and a few human operators (**Figure 2c**) are working on the same set of products. The robot(s) can be used to execute simple but hard work concerning a product and the work can then be transferred to a human operator, who can flexibly perform tasks on a product using his/her skills. The human can perform the tasks which requires higher dexterity. The robot(s) can work in a sequence in which products are mixed within the same assembly process. This can be organized by applying Level Scheduling, that is orders sequencing in a repetitive pattern. This way, small batches or even a one-piece flow, which can reduce the inventory and decrease the lead time, can be implemented.

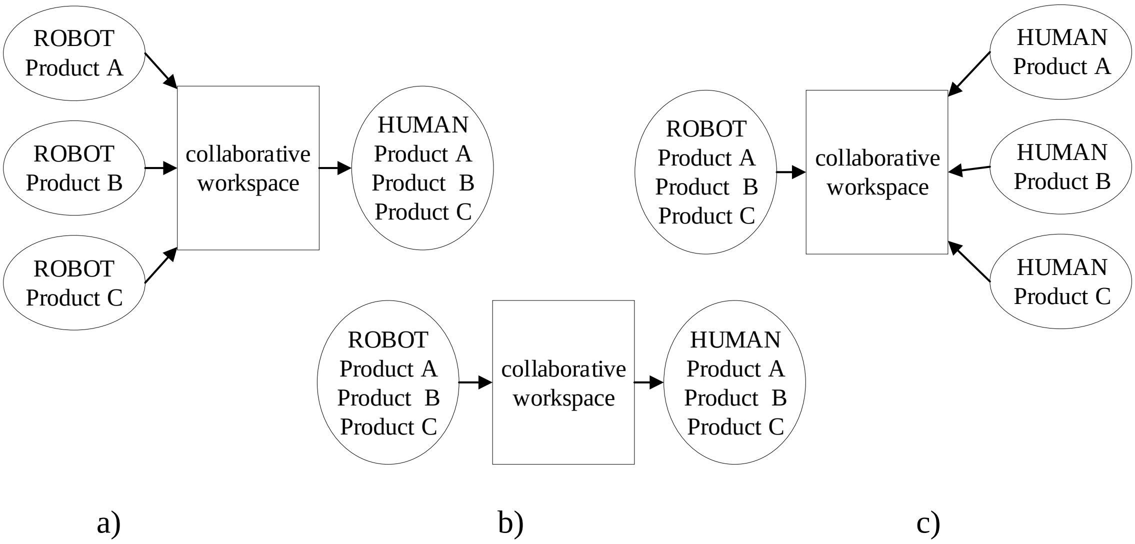


Figure 2. Heijunka implementation on a work stand with HRC.

Hoshin Kanri (Policy Deployment) can be implemented at the collaborative workplace design stage, whenever decisions are taken concerning where and why robots should be introduced. Hoshin Kanri concerns deploying a company strategy to achieve the goals of the company. The strategy involves deploying from the highest level of the company (top management) to the lower levels i.e. middle management (tactics level) and to the plant floor (operation level). Hoshin Kanri is implemented to ensure employee engagement, because they need to understand why actions are undertaken and that they can influence what has been planned to be done (implemented). Hoshin Kanri ensures top-down and down-top communication, while minimalizing the risk of threats as a result of the introduction of robots onto the plant floor.

Just-In-Time (JIT) can be implemented in an HRC work stand (especially in C2 and C3) to ensure that a robot will deliver a product to a human operator in time to ensure continuous work. However, implementing JIT on a work stand with HRC requires the implementation of other lean tools, such as Takt Time, Standardized Work, Flow and Heijunka. This tool reduces the inventory level and required space on the collaborative workplaces. JIT, together with Kanban cards, can also help support deliveries to the work stand.

PFMEA (Process Failure Mode and Effect Analysis) can be used, in relation to the work realized by HRC, to identify which steps of the process are critical (for safety and product quality reasons, etc.). PFMEA can be used as an additional method in a risk analysis (Tan et al., 2010).

Poka Yoke (Error Proofing) solutions are implemented on collaborative workplaces to avoid mistakes. A robot can make mistakes, and this is why all the implemented sensors play a role in the Poka Yoke solutions by detecting human movement and stopping a robot in order to avoid collisions. The reasons why a robot makes mistakes are related to robot programming and sensor precision. Simulations can be introduced to play the role of Poka Yoke solutions in order to anticipate any possible robot mistakes (Sütő et al., 2017).

A human can also make mistakes. Several Poka Yoke solutions can be implemented on a work stand with HRC. Technical solutions, related to work safety, may be introduced into the design of robots and collaborative workplaces. Poka Yoke can be considered as a light curtain that protects human operators from the movement of robots. It also can be considered as a SOP that presents steps on the LCD screen that should be performed by a human operator in sequence to prevent mistakes which could lead to accidents as well as to nonconformities.

SMED (Single Minute Exchange of Die) can be used in an analysis of the process in which a work stand, a human and/or a robot are prepared / trained / programmed to begin a new task. Here, the activities that take up a great deal of time in the setup process should be identified, and certain tools should be proposed to decrease any non-productive time. The SMED method is not used in HRC, but it can be used before the work process begins.

Standardization is used to create standards for the tasks that have to be performed, for the cooperation with robots (SOP), for tools, for the arrangement of collaborative workplaces, etc. Standardized work ensures that the best practices, including the time to complete each task without any unnecessary risk, are implemented.

Total Productive Maintenance (TPM) is essential to ensure a robot is continuously ready for work. TPM is equally important in all categories of HRC. This holistic approach to maintenance focuses on proactive and preventive maintenance in order to avoid robot failures, which is extremally important in HRC. However, how operators can be involved in autonomous maintenance on a HRC work stand should be the subject of deliberation.

Visualization on the work stand when humans and robots work in the same working area can indicate the way a robot or human moves. It can also help to demarcate the areas in which a robot should work and in which a human should work, and where they can work together. Visualization can also be used to mark the place where tools or working items should be placed in order to perform tasks without any problems. Visual indicators, displays and controls used on work stands with HRC can improve the communication of information between robots and humans and can show the state and condition of a process in a clear way to anyone who is interested.

Time study is used mostly to analyse the work done by the humans who collaborate with a robot. A robot can always work with the same programmed efficiency, while a human worker can become tired. A time study should be the basis of the standardization of the time that should be dedicated to performing a task. The result of a time study should also help in the planning of breaks for human workers to prevent mistakes when they are tired.

Skills Matrix (Multitasking & Multiskills) can be used to assess and improve the skills of operators, who will learn how to work on different workstations and how to perform different work activities. It develops not only the technical skills of the operators, but also the mental skills of adapting to new environments. Personal development of operators also makes them more flexible.

5. Lean tools implementation to eliminate threats in HRC

Many factors can affect HRC, as reported in the literature, and they are: trust in robots (Lee and See 2004; Hancock et al., 2011; Billings et al., 2012), mental workload (Megaw 2005), loss of situation awareness (Parasuraman et al., 2000), introduction of varying levels of automation (Balfe et al., 2011), stress and anxiety due to HRC (Zecca et al., 2007; Aria et al., 2010; Kato et al., 2010), high reliability of robots (Rovira et al., 2007), perceived attention and concentration (Talluer and Wickens 2003; Chen 2011) and attitudes towards robots (Torta et al., 2012; Nomura et al., 2006). The threats connected with the factors, that have been also identified in the literature review, are analysed hereafter, and the implementation of certain lean tools is suggested. By implementing the lean tools, the threats concerning HRC can be minimized or even eliminated. **Table 2** summarizes the factors and threats presented in the literature as well as the lean tools suggested by the authors in this work.

Table 2. Factors, threats and suggested lean tools: Human Factors at Level 4.

Factor	Threats	Proposed lean tool
Trust in robots	A robot can make a mistake	Poka Yoke solutions to prevent mistakes by robots
Mental workload	The cognitive workload in HRC to communicate and collaborate with a robot is higher than the cognitive load when a human operator communicates with another human.	Standardization Poka Yoke

Factor	Threats	Proposed lean tool
Loss of situation awareness	Being just an observer of a process for too long can make an operator lose awareness and fail to recognise unexpected or dangerous situations	Poka Yoke solutions to inform the operators about unexpected and unplanned situations Andon Visualization 5S PFMEA
Introduction of varying levels of automation	Operators skill degradation	Multitasking & Multiskills Hoshin Kanri
Stress and anxiety due to HRC (Mental strain)	Stress and anxiety caused by the size and speed of a robot can lead operators to make mistakes, even when the robot only has an increased speed in its own zone	Poka Yoke solutions to prevent the operators from making mistakes, Gemba & Kaizen
High reliability of robots	A long time is needed to eliminate failures and unexpected stoppages caused by a loss of vigilance and the failure to undertake autonomous maintenance	Total Productive Maintenance (TPM)

Factor	Threats	Proposed lean tool
Perceived attention and concentration	An operator can collaborate with a few robots and his or her attention and concentration can decrease in time, thus causing a problem to go unnoticed	Time study Takt time Visualization SOP Heijunka JIT
Attitudes towards robots	An operator can treat a robot like a human being and expect it to think, which can lead to mistakes	PFMEA Poka Yoke to prevent mistakes

The presented analysis concerns different situations in which the indicated lean tools can be used to set up and carry out HRC. Applications of lean concept at manual workstations are well known (e.g. 5S) as well as on automatic manufacturing lines (e.g. TPM, Poka Yoke). However, according to the authors knowledge, the available literature does not report analyses of the use of lean concept and lean tool in HRC. Therefore, this paper try to fill this gap. The recommendations mainly refer to collaborative workplaces and to the collaboration between humans and robots that takes place at Level 4. The selected tools are used in the following case study.

6. The proposal of an HRC implementation methodology on the work stand

In this paper, the authors propose a procedure which can be useful to implement HRC on a work stand. Work stand, also called in this paper work cell, is an area separated for the purpose of performing a specific job. In the analysed case, the HRC is carried out at the work stand. The work stand can be connected to other work stands through the flow of materials or information necessary to perform the work. The procedure indicates the activity steps that should be undertaken. They are:

Step 1. Identification of the work elements. The work conducted on a work stand should be analysed to identify the performed activities.

Step 2. Measurement of the duration of a work element. The duration of each work element should be measured. In time study it has to be taken into consideration that duration of a task performing can be influenced by worker's skills. Therefore, a standard work time should be established carefully and then solutions implemented on a work station should ensure that all workers assigned to the work will be able to perform the task in the standard time.

Step 3. Work analysis. Analysis of the nature of the activities.

Step 4. Task assignment. The tasks should preliminary be assigned to robots and human operators, taking into account the nature of the tasks, the possibilities, the safety and the weight of parts that have to be operated.

Step 5. Simulations / Experiments. Discrete Event Simulations or experiments on similar workcells already present in the factory should be undertaken to establish the correctness of the assignment of the tasks.

Step 6. Comparison of the cycle time and the takt time. The cycle time of the process should be compared with the takt time. If the cycle time is longer than the takt time, an adequate improvement of the task assignment should be undertaken to decrease the cycle time.

Step 7. Process FMEA (PFMEA). A PFMEA analysis may be performed to identify any potential mistakes that can be made in a process and to propose Poka Yoke solutions.

Step 8. Ensuring work safety. The workplace should be equipped with the necessary work safety measures (to avoid threats, to protect human operators from threats, to inform them about threats).

Step 9. Work stand organization. A work stand should be organized to ensure that everything that is needed to perform the process activities has a specific place to enable safe HRC and to prevent mistakes.

Step 10. SOP development. Development of a standard according to which HRC will be realized.

Step 11. Delivery planning. Everything that is needed to perform the process activities should be available on time.

The procedure also indicates the tools which can be used to perform certain steps what is presented in **Table 3**. The procedure can be implemented for work activities which are already being conducted by human operators. Therefore, the analysis considers steps in which the current work organization is analysed and steps for which a future state is designed. In the current state analysis, it is recommended that such tools as Gemba and time study should be implemented. In the next steps, apart from lean tools, the authors recommend using HTA (Hierarchical Task Analysis) and UML (Unified Modelling Language) Activity Diagram, as well as a Gant chart to present the sequence of the activities together with their durations. Computer simulations or physical experiments can then be performed to see the results of the new task assignment, but also to compare the cycle time of the analysed process with a takt time in order to ensure that the cycle time is no longer than the takt time. Heijunka can be implemented for production levelling. PFMEA is then recommended to identify any critical activities in which mistakes can be made, and for which the implementation of Poka Yoke solutions is justified. The results of PFMEA are also the inputs for the work stand organization, in which such tools as 5S and visualization are also implemented. The Poka Yoke solutions and Andon support work safety in an HRC work stand.

Table 3. The HRC implementation methodology on a work stand (at Level 4).

Step	Proposed tool	Results
1. Identification of the work elements	Gemba HTA UML Activity Diagram	Work sequence
2. Duration of the measurement of a work element	Time study	Duration of the activities
3. Work analysis	Gemba	Information about the possibility of assigning tasks to a robot
4. Task assignment	HTA UML Activity Diagram	Gant chart
5. Simulations / Experiments	Computer simulation On life experiment	Validated task assignment
6. Comparison of the cycle time and the takt time	Takt Time Heijunka	A cycle time that is no longer than the takt time

Step	Proposed tool	Results
7. Process FMEA	PFMEA Poka Yoke	Identification of the critical steps (activities) of the process and proposal of Poka Yoke solutions to prevent mistakes
8. Ensuring work safety	Poka Yoke Andon	Safe work place
9. Work stand organization	5S Poka Yoke Visualization	Standard, safe and well organized work place
10. SOP development	Standardization	Efficient work
11. Delivery planning	JIT Kanban	Continuous work The avoiding of waste

SOP should then be developed to support HRC with a standard and to ensure repeatability of the process. SOP is also a good support for the training of new employees. Finally, deliveries to the HRC work stand should be planned to ensure continuous work and to avoid any waste of time. In this case, JIT and Kanban systems can be introduced.

Efficiency of the proposed methodology can be assessed by the HRC system performance assessment. Different indicators can be applied. We propose to use modifications of indicators proposed in the work (Stadnicka and Ratnayake, 2018), namely:

- To assess an improvement if an existing HRC work cell was redesigned: indicator of lead time improvement (*LTI*) (equation 1) and indicator of the total time improvement due to value-added activities (*VAI*) (equation 2). The first indicator will assess how lead time was decreased, i.e. the time passing from the moment when a piece of work was begun to the moment when this piece of work was completed (e.g. one product). The second indicator will assess the improvement achieved by better tasks assignment, what will cause minimalization of total time needed to perform a work by robot and human operator.
- To assess the HRC performance: process cycle efficiency (*PCE*) (equation 3), human idleness indicator (HII) (equation 4) and robot idleness indicator (RII) (equation 5).

$$LTI = \frac{LT_B - LT_A}{LT_B} \cdot 100\% \, , \tag{1}$$

where: LT_B – lead time before changes, LT_A – lead time after changes.

$$VAI = \frac{TVA_B - TVA_A}{TVA_B} \cdot 100\% \, , \tag{2}$$

where: TVA_B – total time of value added activities before changes, TVA_A – total time of value added activities after changes.

$$PCE = \frac{\sum TVA}{LT} \cdot 100\% \, , \tag{3}$$

where: TVA – time needed to perform adding value tasks by robot and human operator, LT – time needed to complete a work (e.g. one product, a work cycle).

$$HII = \frac{LT - TVA_H}{LT} \cdot 100\% \, , \tag{4}$$

where: TVA_B – total time of value added activities performed by human operator. This indicator will allow to see a percentage of human operator waiting time.

$$RII = \frac{LT - TVA_R}{LT} \cdot 100\% \, , \tag{5}$$

where: TVA_R – total time of value added activities performed by robot. This indicator will allow to see a percentage of robot waiting time.

Additionally, an optimization process can be introduced. The objective will be to assign all activities to human and robot respecting the tasks nature in order to minimize maximum completion time. To do it, there is indispensable to know the tasks nature. If, because of its nature, the task can be performed only by a human operator it is marked as "H". If the task can be performed only by a robot it is marked as "R". If the task can be performed by a robot or by a human it is marked as "H/R". For the tasks which can be performed by a robot or a human it is necessary to know the time needed to perform the task by a robot and a human operator to use this data in optimization process. This way tasks assignment can be partially automated. However, there is still a problem of tasks nature identification. The possible automation of tasks nature identification can be a subject of future research as the topic is interesting.

7. Collaborative work stand design applying the proposed methodology

In this section, an implementation of the proposed methodology is presented through a case study. The selected case study is a manual assembly process of a 2-stage snowplow mill. The assembly is executed in a small factory which has small production volumes, and which is not suited for traditional full automation. The description of the case study was obtained by observing the actual manual process during the assembly of a small number of mills. Gemba was implemented to understand the process. The process was observed and recorded on a video in order to measure all the processing times. Time study was performed to determine the standard times, in consideration of the expected high variability of the manual processes.

The process cannot be automated due to the small production volumes. At the same time, some operations are unsafe or unfit for execution by human workers: many parts are heavy and have to be handled with the help of an overhead travelling crane. Moreover, arc welding is a risky activity and poses additional safety risks, especially for the overhead operations. The need for innovative collaborative processes in which a robot takes on the tasks of welding and moves most of the heavy parts while the human worker carries out an uncountable series of small tasks that require dexterity and flexibility, and which are always present in non-automated processes, is apparent. **Table 4** is a simplified BOM of the product, where the heavier parts have purposely been highlighted. The mill in **Figure 3** is mounted onto a dedicated holder that allows welding operations to be conducted and the correct rotation of the assembly to be set up without any interferences.

Table 4. BOM of the product with the heavier parts purposely highlighted.

Item	Quantity [pcs]	Weight [kg]
Outer Blades	4	12.00
Headstock	1	43.57
Spacer	4	0.13
Base Reinforcement	4	1.10
Inner Blades	4	12.00
Outer disk reinforcement	4	2.79
Outer Cross	1	36.60
Outer disk	1	39.26
Inner Cross	1	38.40
Protection Ring	1	21.07

Blade block Bracket	4	1.85

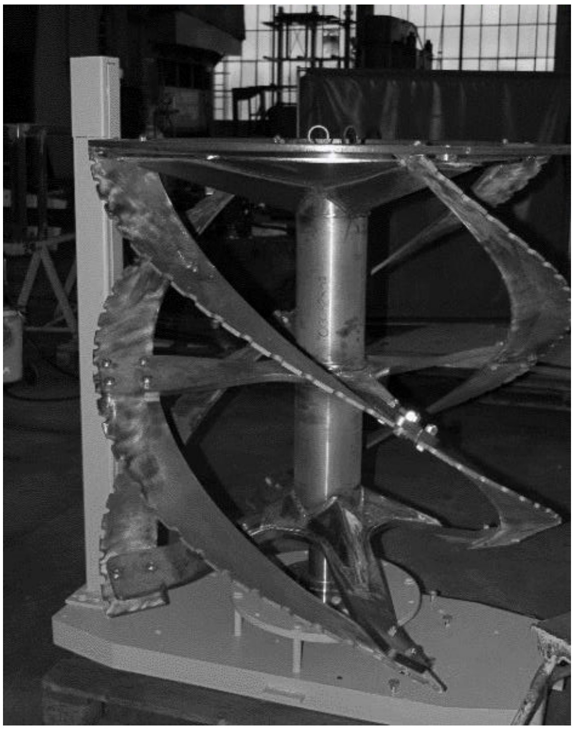


Figure 3. The assembled product (a mill).

The handling is executed by two operators working together with the help of a small crane, because of the weight of some parts. Some tasks are conducted by Operator 1, some tasks by Operator 2 and some tasks are conducted by both operators working together (**Figure 4**). A list of the identified tasks, information about which tasks are assigned to which operator(s) and the mean time of each task is presented in **Figure 4**.

Task	*Assigned to*	*Mean time [sec]*
1. Setup	░	1,200
2. Headstock positioning	░	180
3. Outer disk positioning	░	355
3a. Inner Blade bending	▓	900
4. Inner cross positioning	░	220
5. Central cross positioning	░	220
5a. Bracket bending	▓	240

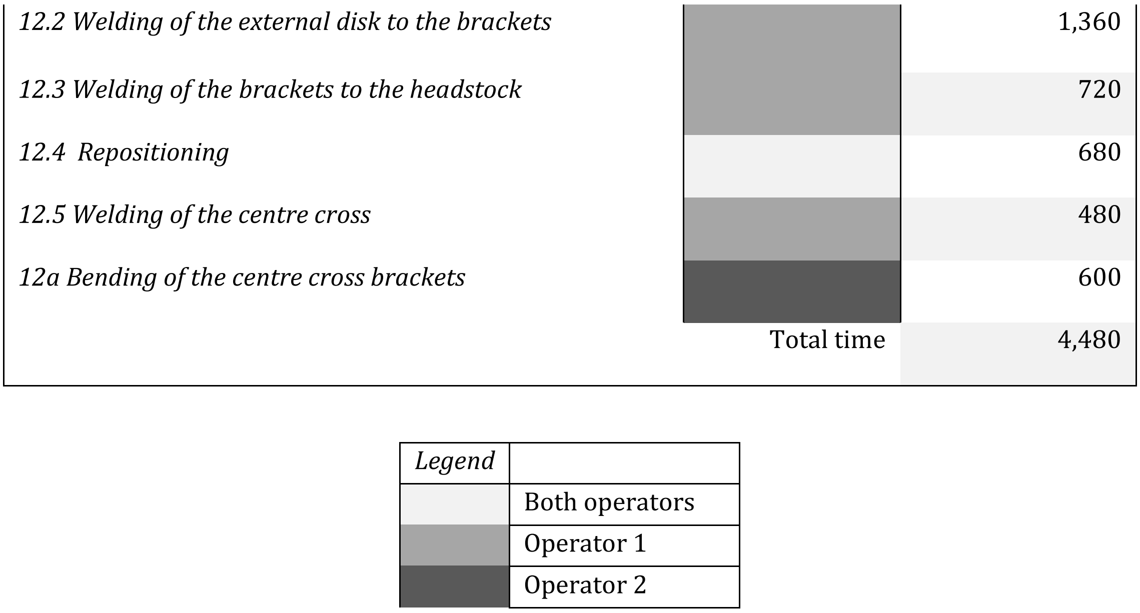
6. Inner Blade assembly	░	520
7. Bracket positioning	░	280
8. Bracket welding	░	700
9. Outer disk welding	▒	200
9a. Bracket bending	▓	360
10a Outer blade bending	▓	900
10. Positioning and welding of brackets	▒	810
11. Outer blade assembly	░	520
12. Welding	░	3,880
12a. Bracket bending	▓	600
13a. Holder positioning	▓	600
13. Holder mounting	░	1,840
14. Grinding	░	770
15. Spacer assembly	░	700
16. Outer ring assembly	░	160
17. Holder dismantling	░	60

Legend	
░	Both operators
▒	Operator 1
▓	Operator 2

Figure 4. HTA of the snowplow mill assembly

The HTA of the assembly process of the parts described in **Table 4** was performed to develop a SOP. HTA is used in the study of ergonomic operations (Kirwan and Ainsworth, 1992; Stanton, 2006) and it was extended to a task analysis in HRC by Arai et al. (2008). Using the HTA notation ('>' for sequential tasks and '+' for parallel tasks) the HTA sequence is: (1>2>3) + 3a, (4 > 5) + 5a, 6> 7, (8>9>10) + (9a>10a), 11, 12+(12a>13a), 13>14>15>16>17. For space reasons, the sub-tasks are only presented for task 12, which will be referred to when the collaborative process is discussed (**Figure 5**).

12. Bending and welding	***Assigned to***	***Mean time [sec]***
12.1 Welding of the external disk to the headstock	▒	640



12.2 Welding of the external disk to the brackets	▒	1,360
12.3 Welding of the brackets to the headstock	▒	720
12.4 Repositioning	░	680
12.5 Welding of the centre cross	▒	480
12a Bending of the centre cross brackets	▓	600
	Total time	4,480

Legend	
░	Both operators
▒	Operator 1
▓	Operator 2

Figure 5. HTA of the snowplow mill assembly – task 12

Figure 6 shows the overall process with the use of the UML Activity Diagram, without details of the sub-tasks but with the individual contribution of the two human operators highlighted.

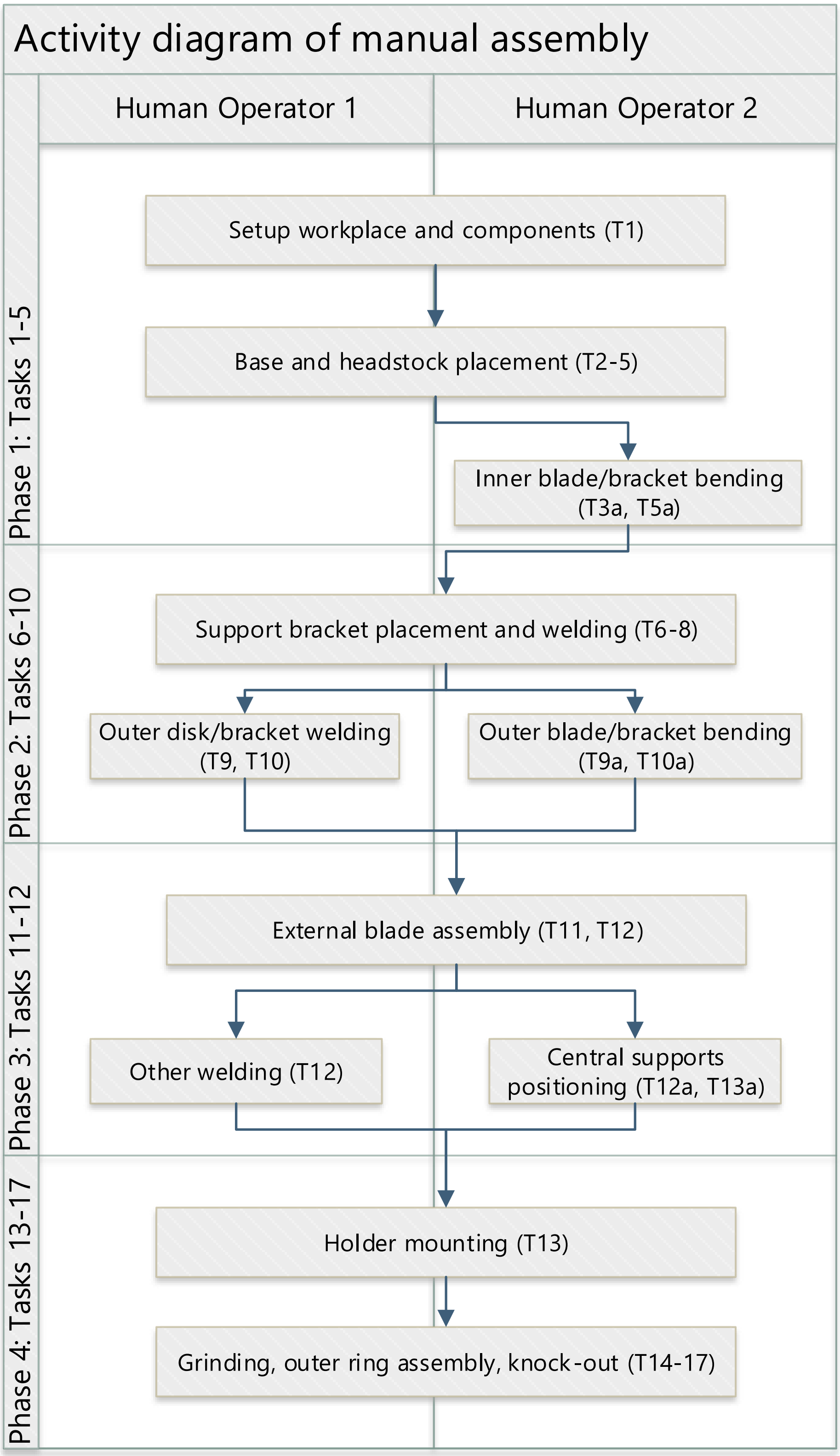


Figure 6. The activity diagram of the manual assembly.

As discussed in the preceding sections, the innovative approach involves having a collaborative assembly station where the robot executes the welding tasks and handles the heavy parts, while a human operator performs some difficult welding activities in difficult to reach places and the other remaining tasks.

The category of HRC necessary to execute the assembly process is 4, shared workspace and task with physical interaction. Obviously, choosing this category doesn’t prohibit that some or most of the tasks be executed separately by human or robot without collaboration. The HTA diagram was therefore modified by introducing the robot in the workcell and trying to exploit its specific abilities. **Figure 7** shows the new process with the same subtasks, but where the tasks, which pass from 17 to 16, are distributed differently. It should be noted that task 12 of the manual process is now renumbered task 9. In order to redistribute the tasks, 5 task features were adopted as decision support drivers:

LSO – the need to move outside a workplace (mandatory for humans);

PM – heavy weights (mandatory for robots);

DE – dexterity requirements (preferred for humans);

T – speed requirements (preferred for robots);

QE – accuracy requirements (preferred for robots).

Task	Mean Time [sec]	Assigned to	Task feature
1. Setup	*1,320*	■	LSO
2. Headstock positioning	*120*	░ ■	PM / T
3. Outer disk positioning	*230*	░ ▒	PM / QE
4. Inner cross positioning	*200*	░ ▒	PM / DE, QE
5. Central cross positioning	*200*	░ ▒	PM / DE, T
6. Bracket (blade) positioning and welding	*520*	■	DE / QE
7. Outer disk welding	*200*	▒	QE
8. Bracket (disk) positioning and welding	*660*	■	DE, T
9. Bending and Welding	*2,520*	▒	QE

10. Holder mounting	*1,800*	▓	▒	DE / QE
11. Headstock welding to the outer disk	*620*	█	▒	PM / QE
12. Outer blade assembly	*1,040*	▓		PM, DE, T
13. Grinding	*540*	▓		T, QE
14. Spacer assembly	*740*	░	▒	PM / DE, T
15. Outer ring assembly	*150*	░	▓	PM / DE
16. Holder dismantling	*180*	█		PM

Legend	
░	Collaboration
▒	Either human or robot
▓	Operator
█	Robot

Figure 7. HTA of the collaborative process.

Figure 8 presents the UML Activity Diagram of the human-robot collaborative assembly.

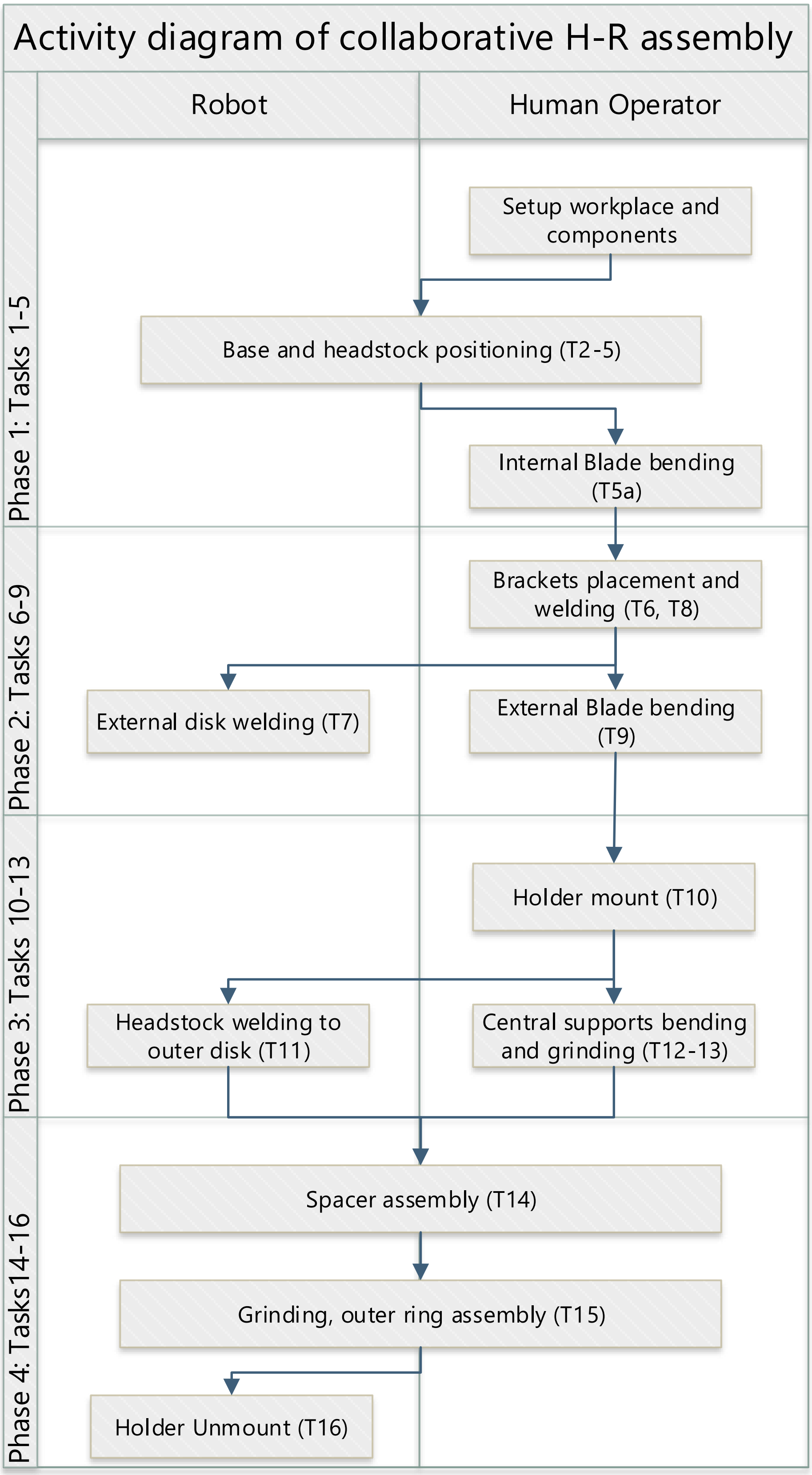
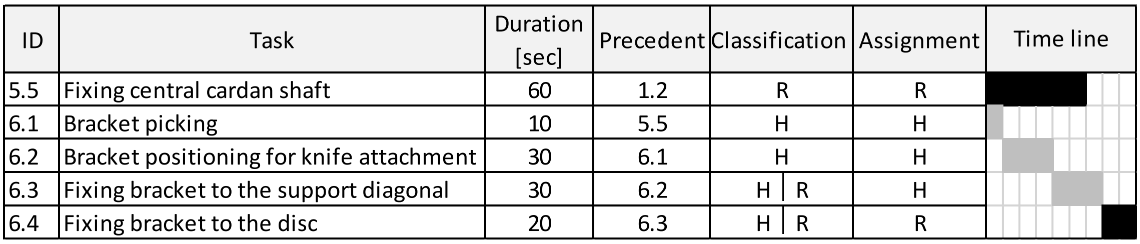


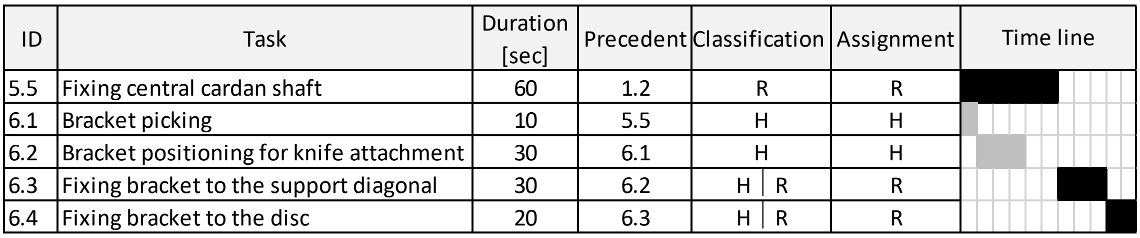
Figure 8. The activity diagram of the collaborative human-robot assembly.

The decision support drivers can be used in each task to assist assignment among human, robot or the collaborative action of human and robot. The assignment can be made by hand for a simple production or with the help of a Decision Support System (DSS), like the one presented by Bruno and Antonelli (2018). The drivers allow the operator to select what is best suited for each task or, at least, what is not incompatible with the task. For example, each time there is a task that involves the handling of a heavy workload, the robot is preferred. An assignment that complies with the support drivers cannot be considered as the definitive solution. The result may be modified to redistribute the workload between humans and robots. Unlike manual production, where workload balancing is the objective, unbalanced solutions, where the robot takes on a heavier workload, are preferred in HRC. Therefore, the adopted approach was to select the robot for the tasks where the DSS cannot express a clear preference. Then a Gantt diagram has been drawn in order to solve all the cases of resource overload, by reassigning the task to the free resource. For example, tasks 5.5-6.4 were assigned as reported in the upper part of **Figure 9**, i.e., the robot executes tasks 5.5 and 6.4, while the human executes tasks 6.1-6.3. In the case of a delay of the human operator during the execution of tasks 6.1 and 6.2, task 6.3 could be reassigned to the robot, since the task is classified as H/R and the robot is idle at that time.



ID	Task	Duration [sec]	Precedent	Classification	Assignment	Time line
5.5	Fixing central cardan shaft	60	1.2	R	R	■■■■■■□□□
6.1	Bracket picking	10	5.5	H	H	▨□□□□□□□□
6.2	Bracket positioning for knife attachment	30	6.1	H	H	□▨▨▨□□□□□
6.3	Fixing bracket to the support diagonal	30	6.2	H | R	H	□□□□▨▨▨□□
6.4	Fixing bracket to the disc	20	6.3	H | R	R	□□□□□□□■■

a)



ID	Task	Duration [sec]	Precedent	Classification	Assignment	Time line
5.5	Fixing central cardan shaft	60	1.2	R	R	■
6.1	Bracket picking	10	5.5	H	H	▨
6.2	Bracket positioning for knife attachment	30	6.1	H	H	▨
6.3	Fixing bracket to the support diagonal	30	6.2	H R	R	■
6.4	Fixing bracket to the disc	20	6.3	H R	R	■

b)

Figure 9. Assignment of tasks and the corresponding Gantt chart

(the tasks assigned to humans is in gray, while the tasks assigned to the robot are in black); a) task 6.3 assigned to humans, b) task 6.3 assigned to the robot

It should be pointed out that, in HRC context, it could be useful to change dynamically the distribution of the tasks. In this way, it is possible to overcome some extemporary delays of the human operator or a sudden stop of the robot because of nonstandard situations. The only constraint that is unmodifiable is the one pertaining to the fact that it is not possible to assign tasks in overload. In fact, it frequently happens that times are not respected in small production companies. In this case, it is advisable for the tasks to be rescheduled dynamically inside the workstation, without the intervention of the production control manager at a factory level. This is only possible when a programmed robot is available for the reassigned tasks or when a robot can be reprogrammed in a short time. It is in fact one of the main features that are common to most cobots: they can be programmed manually, just by moving the robot along the desired trajectory.

The presented analysis concerns just a part of the proposed implementation of the methodology. The next step will involve process simulation, PFMEA, SOP, and further analyses leading to the detailed design of the work stand organization.

8. Conclusions

The introduction of cobots in a factory layout cannot involve just a simple installation procedure. The work organization must be completely revised and any losses of quality and safety that could arise from a shift in the working paradigms should be carefully avoided. A suitable and established strategy for production reorganization consists of the adoption of lean concepts and the corresponding methods and tools. The proposed methodology indicates which of these concepts, methods and tools can be used to resolve the HRC implementation problem and which modifications are needed in a work stand.

From a discussion on the application of lean tools in the implementation of HRC and with the help of a case study, it has been shown that lean tools (such as Gemba, time study or standardization) can have an even greater utilization. Furthermore, it has been shown that lean concepts can also be supportive when it is necessary to use different application tools from the usual ones (e.g. HTA, UML Activity Diagram), despite having been originally developed to be applied in manual production work stands.

The case study applies just a subset of the suggested methodology, to show its feasibility and usefulness. Surely, further work is required to fully exploit lean concept in the HRC development. In a future work, the authors intend performing production simulations and implementing the second part of the proposed structured methodology, while designing an HRC work stand. The developed work sequence will be experimentally validated to confirm that the tasks were assigned properly. Moreover, the final version of SOP will be delivered and the work stand will be organized, through the use of the presented methodology and proposed tools (e.g. 5S, Poka Yoke).

The procedure with the proposed lean tools was developed to be applied to any human-robot collaborative work station. Therefore, in future research the authors are planning to implement the procedure also in other types of HRC. The procedure can be enriched by introducing other specific steps for particular industrial sectors.

References

AL-Tahat, M.D., and I.S. Jalham. 2015. “A structural equation model and a statistical investigation of lean-based quality and productivity improvement.” *Journal of Intelligent Manufacturing* 26: 571–583. doi:https://doi.org/10.1007/s10845-013-0816-0.

Anand, G., and R. Kodali. 2010. “Development of a framework for implementation of lean manufacturing systems.” *International Journal of Management Practice* 4(1): 95 – 116. doi:https://doi.org/10.1504/IJMP.2010.029705.

Antosz, K., and D. Stadnicka. 2017. “Lean Philosophy Implementation in SMEs – Study Results.” *Procedia Engineering* 182: 25–32. doi:https://doi.org/10.1016/j.proeng.2017.03.107.

Anvari, A.R., Z. Norzima, M.Y. Rosnay, M.S.H. Hojjati, and Y. Ismail. 2010. “A comparative study on journey of lean manufacturing implementation.” *Asian International Journal of Science and Technology in Production and Manufacturing Engineering* 3(2): 77–85.

Arai, T., F. Duan, J. Too Chuan Tan, and Y. Zhang. 2008. “Extending task analysis in HTA to model man-machine collaboration in cell production.” *Proceedings of the 2008 IEEE International Conference on Robotics and Biomimetics*, Bangkok, Thailand, February 21-26, 2009, 542–547. doi:10.1109/ROBIO.2009.4913060.

Aria, T., R. Kato, and M. Fujita. 2010. “Assessment of operator stress induced by robot collaboration in assembly.” *CIRP Annals* 59(1): 5–8.

doi:https://doi.org/10.1016/j.cirp.2010.03.043.

Arunagiri, P. and A. Gnanavelbabu. 2014. “Identification of High Impact Lean Production Tools in Automobile Industries using Weighted Average Method.” *Procedia Engineering* 97: 2072–2080. doi:https://doi.org/10.1016/j.proeng.2014.12.450.

Balfe, N., J. R. Wilson, S. Sharples, and T. Clarke. 2011. “Development of design principles for automated systems in transport control.” *Ergonomics* 55 (1): 37–54. doi: 10.1080/00140139.2011.636456.

Bauer, A., D. Wollherr, and M. Buss. 2008. “Human–Robot Collaboration: A Survey”. *International Journal of Humanoid Robotics* 5(1): 47–66. doi:https://doi.org/10.1142/S0219843608001303.

Bdiwi, M., M. Pfeifer, and A. Sterzing. 2017. “A new strategy for ensuring human safety during various levels of interaction with industrial robots.” *CIRP Annals* 66(1): 453–456. doi:https://doi.org/10.1016/j.cirp.2017.04.009.

Beauchamp, Y. and T. J. Stobbe. 1995. “A review of experimental studies on human-robot system situations and their design implications.” *The International Journal of Human Factors in Manufacturing* 5(3): 283–302. doi:https://doi.org/10.1002/hfm.4530050306.

Bélanger-Barrette, M. 2015. “Recent investments in collaborative robot companies.” *Robotics Industry News, Applications and Trends, Robotiq*, May 13, http://blog.robotiq.com/collaborative-robots-companies, accessed 30 Jan. 2016.

Belhadi, A., F.E. Touriki, and S.E. Fezazi. 2016. “A framework for effective implementation of lean production in small and medium-sized enterprises.” *Journal of*

Industrial Engineering and Management 9(3): 786–810. doi:http://dx.doi.org/10.3926/jiem.1907.

Bhasin, S. 2012. "Performance of Lean in large organisations." *Journal of Manufacturing Systems* 31(3): 349–357. doi:https://doi.org/10.1016/j.jmsy.2012.04.002.

Billings, D. R., K. E. Schaefer, J. Y. C. Chen, and P. A. Hancock. 2012. "Human-robot interaction: Developing trust in robots." 2012 7th ACM/IEEE International Conference on Human-Robot Interaction. 5-8 March, 109–110. doi:0.1145/2157689.2157709.

Bruno, G., and D. Antonelli. 2018. "Dynamic task classification and assignment for the management of human-robot collaborative teams in workcells." *The International Journal of Advanced Manufacturing Technology* 98(9-12): 2415–2427. doi:https://doi.org/10.1007/s00170-018-2400-4

Chaffin, D. B. 2007. "Human motion simulation for vehicle and workplace design." *Human Factors and Ergonomics in Manufacturing* 17(5): 475–484. doi:https://doi.org/10.1002/hfm.20087.

Charalambous, G., S. Fletcher, and P. Webb. 2015a. "Human-automation collaboration in manufacturing: identifying key implementation factors." *Proceedings of the 11th International Conference on Manufacturing Research (ICMR2013)*, Cranfield University, UK, 19th-20th September 2013, 301–306. URI:http://dspace.lib.cranfield.ac.uk/handle/1826/9480.

Charalambous, G., S. Fletcher, and P. Webb. 2015b. "Identifying the key organisational human factors for introducing human-robot collaboration in industry: an exploratory study." *International Journal of Advanced Manufacturing Technology* 81(9–12): 2143 – 2155. doi:https://doi.org/10.1007/s00170-015-7335-4.

Chen, J. 2011. “Individual Differences in Human-Robot Interaction in a Military Multitasking Environment.” *Journal of Cognitive Engineering and Decision Making* 5(1): 83–105. doi:https://doi.org/10.1177/1555343411399070.

Ding, Z., and B. Hon. 2013. “Constraints analysis and evaluation of manual assembly.” *CIRP Annals* 62(1): 1–4. doi: https://doi.org/10.1016/j.cirp.2013.03.003

Eswaramoorthi M., G. R. Kathiresan, P. S. S. Prasad, and P. V. Mohanram. 2011. “A survey on lean practices in Indian machine tool industries.” *The International Journal of Advanced Manufacturing Technology* 52(9–12): 1091–1101. doi:https://doi.org/10.1007/s00170-010-2788-y.

Gueta, L.B., R. Chiba, T. Arai, T. Ueyama, and J. Ota. 2009. “Compact design of work cell with robot arm and positioning table under a task completion time constraint.” 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, October 11-15, 2009 St. Louis, USA, 807–813. doi: 10.1109/IROS.2009.5354122.

Guiochet, J., M. Machin, and H. Waeselynck. 2017. “Safety-critical advanced robots: A survey.” *Robotics and Autonomous Systems* 94: 43–52. doi:<10.1016/j.robot.2017.04.004> <hal-01394136>

Hancock, P. A., D. R. Billings, K. E. Schaefer, J. Y. C. Chen, E. J. De Visser, and R. Parasuraman. 2011. “A Meta-Analysis of Factors Affecting Trust in Human-Robot Interaction.” *The Journal of the Human Factors and Ergonomics Society* 53(5): 517–527. doi:https://doi.org/10.1177/0018720811417254.

Helms, E., R. D. Schraft, and M. Hagele. 2002. “rob@work: Robot assistant in industrial environments”, *Proceedings of 2002 IEEE International Workshop on Robot and Human Interactive Communication*, Berlin, Germany, Sept. 25-27, 399–404.

doi:10.1109/ROMAN.2002.1045655

Kato, R., M. Fujita, and T. Arai. 2010. "Development of advanced cellular manufacturing system with human-robot collaboration-assessment of mental strain on human operators induced by the assembly support", *Proceedings – 19th IEEE International Workshop on Robot and Human Interactive Communication*, Viareggio, Italy, 355–360. doi:10.1109/ROMAN.2010.5598700.

Kirwan, B. and L. K. Ainsworth. 1992. *A Guide to Task Analysis*. London: CRC Press.

Klein, G., D. D. Woods, J. M. Bradshaw, R. R. Hoffman, and P. J. Feltovich. 2004. "Ten challenges for making automation a "team player" in joint human-agent activity." *IEEE Intelligent Systems* 19(6): 91–95. doi:10.1109/MIS.2004.74.

Lee, J. and K. See. 2004. "Trust in automation: designing for appropriate reliance." *Human Factors* 46(1): 50–80. doi:10.1518/hfes.46.1.50_30392.

Makris, S., P. Karagiannis, S. Koukaas, and A. S. Matthaiakis. 2016. "Augmented Reality System for Operator Support in Human–Robot Collaborative Assembly." *CIRP Annals* 65(1): 61–64. doi:https://doi.org/10.1016/j.cirp.2016.04.038.

Marodin, G. A., and T. A. Aurin. 2015. "Classification and relationships between risks that affect lean production implementation. A study in southern Brazil." *Journal of Manufacturing Technology Management* 26(1): 57–79. doi:https://doi.org/10.1108/JMTM-12-2012-0113.

Maurtua, I., A. Ibarguren, J. Kildal, L. Susperregi, and B. Sierra. 2017. "Human–robot collaboration in industrial applications: Safety, interaction and trust." *International Journal of Advanced Robotic Systems* July-August 2017: 1–10.

doi:10.1177/1729881417716010.

Megaw, T. 2005. “The definition and measurement of mental workload.” In *Evaluation of human work*. 3rd ed., edited by J.R. Wilson and N. Corlett, 525–551. London: Taylor & Francis. DOI10.1201/9781420055948.ch18.

Meziane, R., M.J.-D. Otis, and H. Ezzaidi. 2017. “Human-robot collaboration while sharing production activities in dynamic environment: SPADER system.” *Robotics and Computer–Integrated Manufacturing* 48: 243–253. doi:https://doi.org/10.1016/j.rcim.2017.04.010

Michalos, G., S. Makris, J. Spiliotopoulos, I. Misios, P. Tsarouchi, and G. Chryssolouris. 2014. “ROBO-PARTNER: Seamless Human-Robot Cooperation for Intelligent, Flexible and Safe Operations in the Assembly Factories of the Future.” *Procedia CIRP* 23: 71–76. https://doi.org/10.1016/j.rcim.2017.04.010.

Michalos, G., S. Makris, P. Tsarouchi, T. Guasch, D. Kontovrakis, and G. Chryssolouris. 2015. “Design considerations for safe human-robot collaborative workplaces.” *Procedia CIRP* 37: 248–253. doi:https://doi.org/10.1016/j.procir.2015.08.014.

Moeuf, A., R. Pellerin, S. Lamouri, S. Tamayo-Giraldo, and R. Barbaray. 2017. “The industrial management of SMEs in the era of Industry 4.0.” *International Journal of Production Research* 56(3): 1118–1136, doi:10.1080/00207543.2017.1372647.

Montreuil, V., A. Clodic, M. Ransan, and R. Alami. 2007. “Planning human centered robot activities.” *2007 IEEE International Conference on Systems, Man and Cybernetics* 2618–2623. doi:10.1109/ICSMC.2007.4413992.

Mostafa, S., J. Dumrak, and H. Soltan. 2013. “A framework for lean manufacturing implementation.” *Production & Manufacturing Research* 1(1): 44–64. doi:10.1080/21693277.2013.862159.

Müller, R., M. Vette, and O. Mailahn. 2016. “Process-oriented task assignment for assembly processes with human-robot interaction.” *Procedia CIRP* 44, pp. 210–215. doi:https://doi.org/10.1016/j.procir.2016.02.080.

Netland, T.H. 2016. “Critical success factors for implementing lean production: the effect of contingencies.” *International Journal of Production Research* 54(8): 2433–2448. doi:https://doi.org/10.1080/00207543.2015.1096976.

Nomura, T., T. Kanda, and T. Suzuki. 2006. “Experimental Investigation into Influence of Negative attitudes toward Robots on Human-Robot Interaction.” *AI & Society* 20(2): 138–150. doi:https://doi.org/10.1007/s00146-005-0012-7.

Ohno, T. 1988. *Toyota Production System: Beyond Large-Scale Production*. London: Productivity Press.

Ore, F., L. Hansson, and M. Wiktorsson. 2017. “Method for design of human-industrial robot collaboration workstations.” *Procedia Manufacturing* 11: 4–12. doi:https://doi.org/10.1016/j.promfg.2017.07.112.

Parasuraman, R., T. B. Sheridan, and C. D. Wickens. 2000. “A model for types and levels of human interaction with automation.” *IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans* 30: 286–297. doi:10.1109/3468.844354.

Perez-Vidal, C., L. Gracia, de J.M. Paco, M.Wirkus, J. M. Azorin, and J. de Gea. 2018. “Automation of product packaging for industrial applications.” *International Journal of*

Computer Integrated Manufacturing 31(2): 129–137. doi:https://doi.org/10.1080/0951192X.2017.1369165.

Peshkin, M., and J. C. Edward, 1999. “CoBots.” *Industrial Robot* 26(5): 335–341. doi:10.1108/01439919910283722.

Polverini, M. P., A. M. Zanchettin, and P. Rocco. 2017. “A computationally efficient safety assessment for collaborative robotics applications.” *Robotics and Computer–Integrated Manufacturing* 46: 25–37. doi:https://doi.org/10.1016/j.rcim.2016.11.002.

Ranz, F., V. Hummel, and W. Sihn. 2017. “Capability-based task allocation in human-robot collaboration.” *Procedia Manufacturing* 9: 182–189. doi:https://doi.org/10.1016/j.promfg.2017.04.011.

Rovira, E., K. McGarry, and R. Parasuraman. 2007. “Effects of imperfect automation on decision making in a simulated command and control task.” *Human Factors* 49(1): 76–87. doi:10.1518/001872007779598082.

Stadnicka D. 2015. “Setup analysis: combining SMED with other tools.” *Management and Production Engineering Review* 6(1): 36–50. doi:10.1515/mper-2015-0006.

Stadnicka D., and R. M. C. Ratnayake. 2018. “Development of additional indicators for quotation preparation performance management: VSM-based approach.“ *Journal of Manufacturing Technology Management* 29(5): 866-885, doi:https://doi.org/10.1108/JMTM-01-2017-0016

Stanton N.A. 2006. “Hierarchical task analysis: developments, applications, and extensions.” *Applied Ergonomics* 37(1): 55–79. doi:10.1016/j.apergo.2005.06.003.

Sütő, S., Z. Forgó, and F. Tolvaly-Roşca. 2017. “Simulation Based Human-robot Coworking.” *Procedia Engineering* 181: 503–508. doi:https://doi.org/10.1016/j.proeng.2017.02.425.

Talluer, D. A., and C. D. Wickens. 2003. “The effect of pilot visual scanning strategies on traffic detection accuracy and aircraft control”, *Proceedings of the 12th International Symposium on Aviation Psychology*. 1143–1148. Dayton, OH.

Tan J. T. C., F. Duan, R. Kato and T. Arai. 2010. “Safety Strategy for Human–Robot Collaboration: Design and Development in Cellular Manufacturing.” *Advanced Robotics* 24(5-6): 839–860. doi:https://doi.org/10.1163/016918610X493633.

Tay, M. L., and B. K. A. Ngoi. 1996. “Optimising robot workcell layout” *The International Journal of Advanced Manufacturing Technology* 12(5): 377–385. doi:10.1007/BF01179814.

Thomas, C., L. Stankiewicz, A. Grötsch, S. Wischniewski, J. Deuse, and B. Kuhlenkötter. 2016. “Intuitive work assistance by reciprocal human-robot interaction in the subject area of direct human-robot collaboration.” *Procedia CIRP* 44: 275–280. doi:https://doi.org/10.1016/j.procir.2016.02.098.

Thurstone, L. L. 1927. A law of comparative judgements. *Psychological Review* 34: 273–286.

Torta, E., J. Oberzaucher, F. Werner, H. R. Cuijpers, and F. J. Juola. 2012. “Attitudes towards socially assistive robots in intelligent homes: Results from laboratory studies and field trials.” *Journal of Human-Robot Interaction* 1(2): 76–99. doi:10.5898/JHRI.1.2.Torta.

Trebuna, P., R. Popovic, and S. Klos. 2014. “Methodology of the creation of human and robot operation in the Tecnomatix process simulate.” *Procedia Engineering* 96: 483–

488. doi:https://doi.org/10.1016/j.proeng.2014.12.119.

Tsarouchi, P., G. Michalos, S. Makris, T. Athanasatos, K. Dimoulas, and G. Chryssolouris. 2017. “On a human-robot workplace design and task allocation system.” *International Journal of Computer Integrated Manufacturing* 30(12): 1272–1279. doi:https://doi.org/10.1080/0951192X.2017.1307524.

Tsarouchi, P., J. Spiliotopoulos, G. Michalos, S. Koukas, A. Athanasatos, S. Makris, and G. Chryssolouris. 2016. “A decision making framework for Human Robot Collaborative workplace generation.” *Procedia CIRP* 44: 228–232. doi:https://doi.org/10.1016/j.procir.2016.02.103.

Villani, V., F. Pini, F. Leali, and C. Secchi. 2018. “Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications.” *Mechatronics 55:* 248–266. doi:https://doi.org/10.1016/j.mechatronics.2018.02.009.

Weidner, R., and J. P. Wulfsberg. 2014. “Concept and exemplary realization of Human Hybrid Robot for supporting manual assembly tasks.” *Procedia CIRP* 23: 53–58. doi:https://doi.org/10.1016/j.procir.2014.10.096.

Womack, J. P., and, D. T. Jones. 2003. *Lean thinking: Banish waste and create wealth in your corporation.* New York: Free Press.

Yap, H. J., Z. Taha, S. Z. Md Dawal, and S.-W. Chang. 2014. “Virtual Reality Based Support System for Layout Planning and Programming of an Industrial Robotic Work Cell”, *PLoS ONE* 9(10): e109692, doi:10.1371/journal.pone.0109692.

Zecca, M., M. Saito, N. Endo, Y. Mizoguchi, K. Itoh, H. Takanobu, and A. Takanishi. 2007. “Waseda Bioinstrumentation System WB-2 — The New Inertial Measurement

Unit for the New Motion Caption System.” *2007 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, December 15-18, 2007, Sanya, China, 139–144. doi:10.1109/ROBIO.2007.4522149.