Master Degree Course

Engineering and Management

Assembly Task Assignment and Scheduling in a Human Robot workcell, exploiting Dynamic Programming

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To all of "mine" you are the people I aspire to be,
the best I could wish for.

A tutti i “miei” siete le persone che aspiro a diventare,
le migliori che potessi desiderare.

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Abstract

Human-robot collaboration is made possible by the digitalization of production and has become a key technology for the factory of the future. It combines the strengths of the human worker with those of the auxiliary robot and allows the implementation of a variable degree of automation in the workplace to meet the growing demand for flexibility required by production systems, whether they are more or less complex. Intelligent planning and control algorithms are needed for the organization of work in hybrid teams of humans and robots. It is therefore necessary to introduce an approach to the use of a standardized job description for the automated generation of control procedures for mobile assistant robots. It is also relevant to consider the functioning of the assignment methodology for the allocation of tasks in human-robot teams for a given workplace. It is considered necessary to evaluate different distributions of tasks, taking into account the dynamics of interaction between the worker and the robot in their shared workplace. Using the optimal allocation approach, for a given workplace, the goal is in fact to achieve an ideal distribution of human-robot tasks, in which tasks are assigned in an intelligent and functional way, in terms of characteristics and respective strengths. The evaluation of the planning scenario with respect to a number of criteria of ergonomics, quality and productivity, is oriented precisely to the satisfaction of this purpose. The implementation of this type of method, in its form of a planning tool, indicates that it can be used to provide solutions with respect to the chosen criteria and therefore has a potential applicability as a decision support tool in the planning phase.

Introduction

Modern production faces a number of challenges. Customer demands regarding the quality and variety of products are increasing. Manufacturing companies that want to remain competitive in global markets must meet these demands while keeping their costs low. Assembly has great potential for rationalization, as many processes are still carried out manually. Due to the small batch size and high product variability, full automation is not an option. Instead, more flexible systems are needed. Another challenge is the increasingly older workforce, which requires changes to the current work environment to meet their needs. Lately, research has made considerable progress in the development of collaborative systems, which offer the possibility of integrating the skills of humans and robots. These systems are becoming increasingly attractive to companies, as they are easily programmable and adaptable to different applications, improving productivity and saving costs.

To date, the assembly process of manufacturing companies can generally be decomposed into two categories of assembly steps. First, there are many assembly steps that can be carried out autonomously effectively and efficiently using standardized industrial robots or handling devices. The corresponding automation technologies have been developed rapidly in recent decades and can be easily used to build a stand-alone assembly line for simple products. However, the second category includes tasks that cannot be fully automated, mainly due to the special sensory skills needed to accomplish such tasks.

In order to compensate for these developments, service technologies and automation solutions must be implemented on assembly lines, where most of the work is now done manually. In recent years, research carried out in both the industrial and academic communities has recognized the merits of cooperative assembly applications of human robots. The combined effect of robot precision, repeatability and strength together with human intelligence and flexibility provides several advantages, especially in the case of small-scale production, where agility, reconfigurability and adaptability are of utmost importance.

Since 2013, the demand for industrial robots has increased by an average of 19% per year due to the global trend towards automation in industry. In absolute terms, this number translates into annual global sales of $16.5 billion in 2018 (IRF, 2019). This growth is expected to continue, particularly with the emergence of collaborative robots (cobots), which are expected to be responsible for 24% of robot sales in 2021 (Statista, 2019). Cobots belong to a new generation of robots, capable of working alongside humans, forming so-called Human-Robot

Teams (HRTs).
HRTs benefit from the distinctive characteristics of these two resources. Humans are efficient in a wide range of tasks and adaptable to change, while robots are precise and not subject to fatigue. Therefore, these teams combine productivity and flexibility while improving general working conditions. The close collaboration between the two parties opens up new possibilities for the manufacturing process. Therefore, they have received a lot of interest from practitioners in recent years (Weber, 2018).
Human-robot collaboration in its concept promises substantial improvements, for example in efficiency and ergonomics for the worker. In the fourth industrial revolution, the digitalization of production allows the use of new technologies, connected sensors and learning algorithms. As a result, new designs and products have been introduced to exploit the flexibility and productivity potential of these hybrid systems, while research attempts have been made to deepen emerging issues, such as human-robot coexistence and safety. The more humans and machines work together, the more employees' working lives will change. If this collaboration is to be successful, it is essential not only to think about technology. Without considering human factors, restructuring is likely to fail. The imminent transformation of assembly to collaborative workstations requires a comprehensive understanding of how people perceive this transformation and under what circumstances they are willing to accept the introduction of human-robot collaboration (HRC).
In the factory of the future, mobile robotic assistance systems will collaborate with human operators as envisaged by Teiwes et al. (2016). Hybrid teams of humans and robots sharing the same workspace at the same time enable an individual degree of automation in each workplace. Therefore, robots must be flexible and must not have to be programmed manually except when strictly necessary. Work orders and control commands must be generated locally, based on information from the production database.
The human operator will still be involved for a long time in the assembly process of many products, both for performing certain assembly tasks and for supervising the automated assembly process. Combining the benefits of both, the human operator and robotic assembly systems, increases system performance in the most efficient way. If the products were assembled in collaboration by man and robot, the robot could take on monotonous and tiring tasks, in order to ensure constant quality and improve ergonomic working conditions. In addition, heavy weights or dangerous parts can be handled by the robot to relieve humans. As a result, the human being is able to focus on tasks that require his/her special abilities, such as

sensory perception skills and creative problem solving.
The first examples of basic industrial applications of human-robot processing have already been realized, and in these pilot applications, the main incentive is the implementation of a safe human-robot interaction and the achievement of acceptance by the workers involved of this new technology. The implementation of intelligent assistant robots is of great complexity since different sensors, actors and interfaces must be integrated. Therefore, new methodologies are needed for the implementation of mobile robots in adaptive manufacturing production environments, as concluded by Nielsen et al. (2017). With online planning and real-time decision-making of robots, the distribution and assignment of tasks must be carried out intelligently, as concluded by de Gea Fernández et al. (2017). Variables such as time, cost and quality, and constraints such as worker and robot capabilities, should be considered in order to maximize the objectives required by the application. In addition, the workspace must be precisely shaped, and social aspects, such as workers' preferences, must also be taken into account.
Krüger et al. identified through the two systems "job sharing" and "job and time sharing" the main categories for the classification of robot-human cooperative cells. In both categories, human operators and robots coexist within the same space and are able to perform tasks, either individually or in cooperation.
In this sense, it should be considered that current European laws and standards do not allow direct cooperation between currently available industrial robots and humans. DIN EN ISO 10218-1, for example, prescribes a strict separation of the working space of the man and the robot or at least an observed stop of the robot in the event that man enters the collaboration space. Due to the high forces evoked by traditional robots, mechanical protections, such as safety fences, or electro-optical sensors guarantee the safety at work of the human being. However, such a strict separation of workspaces prevents direct human-robot cooperation and, in particular, simultaneous interaction between humans and robots within the same space. Support actions such as dynamic adjustment of the position of the workpiece are not achievable while the operator processes the object at the same time.
In fact, the current industrial deployments strictly separate the working areas of humans and robots in order to ensure the safety of the operators. The work areas of humans and robots are not designed to effectively accommodate both types of production entities. On the one hand, the design of a robotic cell neglects the ergonomic placement of components, since robots are not affected by such efforts. On the other hand, a workplace designed for humans fails to meet

the reachability constraints of a stationary robot, since operators can move freely within the cell. Therefore, in order to enable the systematic design and implementation of human-robot task-sharing applications, planning tools and methods are needed with the ability to simultaneously perform: a) the effective assignment of production tasks to humans and robots, based on their intrinsic characteristics, and b) the generation and examination of detailed alternative cell layouts that can effectively accommodate these assignments of homework. The latter requires improved methods to assess the ergonomic impact of different tasks and the optimization of individual activities (e.g., movement and route planning).

To solve this dilemma, as a starting point, new norms and laws are needed. The draft ISO/TS 15066 standard promises to fill this gap by specifying, among other things, the maximum force of action for collaborative robots. Other than new regulation, new technologies and control paradigms could help reduce the risk to humans to an acceptable level. Some of them are retro-adaptable to existing robots, such as cameras, which are able to recognize the position of man, or capacitive shells for the robot, which predict and avoid collisions with humans. These technologies would have bypassed the great barrier for companies to buy new robots.

In contrast to standard industrial robots, lightweight robots represent a new generation of robots, which are limited in strength but are still able to carry large weights relative to their own weight. In addition, some of them are equipped with numerous sensors to measure the forces raised by objects or humans in the event of contact. Assuming that the conditions for human-robot cooperation were defined by new standards, such lightweight robots would be collaborators for the human operator.

The requirements arising from the above challenges are then defined and discussed for employment in the workplace, where humans and robots can work together at the same time without any separation of workspaces. In addition, social and ethical aspects must be considered, including the degree of replacement of the human being with the robot tolerated by humans and the degree of acceptance for the technical collaborator.

Finally, a method for modeling the assembly procedure and a new approach for finding an optimized distribution of human-robot work for a given workplace on an assembly line are then presented. The procedure template is based on information from the job description, shop-floor layout, and product database. It can then be used for automated generation of instructions for human workers or commands for robots. A simulation tool is developed to implement the proposed procedure model. The advantage of the new tool is the ability to simulate different job assignments of the worker and the robot for a given workplace, based solely on the procedure model. Addictions such as collision prevention movements between the human worker and the robot are taken into account. Therefore, an approach is presented in which the allocation of human-robot tasks is optimized using dynamic programming. The method presented in this document is able to consider the highly dynamic interaction between the worker and the robot in the same workspace. Using the approach presented, an optimized assignment of human-robot tasks is found for a workplace located in the production chain.

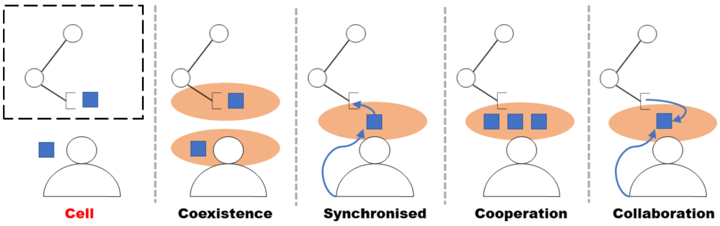
Background

Despite their relatively recent spread, the concept of cobots was invented in 1996 by J. Edward Colgate and Michael Pashkin. These devices were passive and operated by humans, and are quite different from modern cobots that are more represented by the likes of lightweight robots such as KUKA LBR iiwa, developed since the 1990s by KUKA Roboter GmbH and the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR), or the first commercial collaborative robot sold in 2008, which was a UR5 model produced by the Danish company Universal Robots.

First of all, it is important to distinguish the different ways of collaboration, since the term collaboration often generates misunderstandings in its definition.

Müller et al. proposed a classification for the different methodologies in which humans and cobots can work together, as summarized in figure.

- Coexistence, when the human operator and cobot are in the same environment but generally do not interact with each other.
- Synchronised, when the human operator and cobot work in the same workspace, but at different times.
- Cooperation, when the human operator and cobot work in the same workspace at the same time, though each focuses on separate tasks.
- Collaboration, when the human operator and the cobot must execute a task together; the action of the one has immediate consequences on the other, thanks to special sensors and vision systems. It should be noted that neither this classification nor the terminology used are unique, and others may be found in the literature.



Types of use of a collaborative robot.

To provide definitions and guidelines for the safe and practical use of cobots in industry, several standards have been proposed. Collaborative applications are part of the general scope of machinery safety regulated by the Machinery Directive, which defines the RESS (Essential Health and Safety Requirements).

The reference standards as reported in the Machinery Directive are:

- UNI EN ISO 12100:2010 “Machine safety, general design principles, risk assessment, and risk reduction”.
- UNI EN ISO 10218-2:2011 “Robots and equipment for robots, Safety requirements for industrial robots, Part 2: Systems and integration of robots”.
- UNI EN ISO 10218-1:2012 “Robots and equipment for robots, Safety requirements for industrial robots, Part 1: Robots”.

In an international setting, the technical specification ISO/TS 15066:2016 “Robots and robotic devices, Collaborative Robots” is dedicated to the safety requirements of the collaborative methods envisaged by the Technical Standard UNI EN ISO 10218-2:2011.

According to the international standard UNI EN ISO 10218 1 and 2, and more widely explained in ISO/TS 15066:2016, four classes of safety requirements are defined for collaborative robots:

- Safety-rated monitored stop (SMS) is used to cease robot motion in the collaborative workspace before an operator enters the collaborative workspace to interact with the robot system and complete a task. This mode is typically used when the cobot mostly works alone, but occasionally a human operator can enter its workspace.
- Hand-guiding (HG), where an operator uses a hand-operated device, located at or near the robot end-effector, to transmit motion commands to the robot system.
- Speed and separation monitoring (SSM), where the robot system and operator may move concurrently in the collaborative workspace. Risk reduction is achieved by maintaining at least the protective separation distance between operator and robot at all times. During robot motion, the robot system never gets closer to the operator than the protective separation distance. When the separation distance decreases to a value below the protective separation distance, the robot system stops. When the operator moves away from the robot system, the robot system can resume motion automatically according to the requirements of this clause. When the robot system reduces its speed, the protective separation distance decreases correspondingly.
- Power and force limiting (PFL), where the robot system shall be designed to adequately reduce risks to an operator by not exceeding the applicable threshold limit values for quasi-static and transient contacts, as defined by the risk assessment.

Collaborative modes can be adopted even when using traditional industrial robots; however, several safety devices, e.g., laser sensors and vision systems, or controller alterations are required. Thus, a commercial cobot that does not require further hardware costs and setup can be a more attractive solution for industry.

Lastly, cobots are designed with particular features that distinguish them considerably from traditional robots, defined by Michalos et al. as technological and ergonomic requirements. Furthermore, they should be equipped with additional features with respect to traditional robots, such as force and torque sensors, force limits, vision systems (cameras), laser systems, anti-collision systems, recognition of voice commands, and/or systems to coordinate the actions of human operators with their motion.

Why collaborative robots?

The choice towards human–robot collaborative systems is mainly dictated by economic motivations, occupational health (ergonomics and human factors), and efficient use of factory space. Another advantage is the simplification in the robot programming for the actions necessary to perform a task.

Furthermore, the greater convenience of collaborative systems is their flexibility: theoretically, since collaborative cells do not require rigid safety systems, they could be allocated in other parts of plants more easily and more quickly; therefore, they could adapt well to those cases in which the production layout needs to change continuously. However, it should be noted that high-risk applications have to be constrained as in any other traditional system, thus restricting the flexibility.

Collaborative systems can also achieve lower direct unit production costs: it can be observed that a higher degree of collaboration, has a high impact on throughput; moreover, depending on the assembly process considered, the throughput can be higher than in traditional systems.

	Human Operator	**Collaborative Systems**	**Traditional Robot**	**Handling Systems**
Assembly	High dexterity and flexibility	Combines human dexterity with robot capabilities	Dexterity/flexibility could be unreachable	No complex tasks with commercial end-effectors
Placement	High dexterity	Commercial cobots have lower repeatability	High repeatability and payload	High payload
Handling	Product weight restricted	Typical cobots have low payload	High payload and speed	High payload
Picking	Product weight restricted	Typical cobots have low payload	High payload and repeatability	Bin picking difficult due to size

Qualitative evaluation of the most suitable solutions for the main industry tasks.

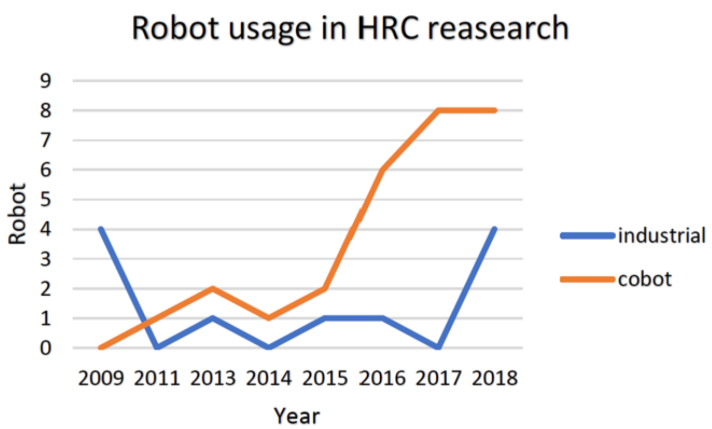
The table provides a comparison between collaborative and traditional systems for four different jobs: assembly (the act of attaching two or more components), placement (the act of positioning each part in the proper position), handling (the manipulation of the picked part), and picking (the act of taking from the feeding point). In order to adapt to market needs, a manual assembly system could be used, though this can lead to a decrease in productivity due to variations in quality and fluctuations in labor rates. Comparing the human operator capabilities to automated systems, it is clear that the performance of manual assembly is greatly influenced by ergonomic factors, which restrict the product weight and the accuracy of the human operator. Therefore, these restrictions limit the capabilities of human operators in the handling and picking tasks of heavy/bulky parts. These components can be manipulated with handling systems such as jib cranes: these devices could be considered as large workspace-serving robots, used for automated transportation of heavy parts. However, there are no commercial end-effectors that allow these systems to carry out complex tasks, such as assembly or precise placing, since they are quite limited in terms of efficiency and precision.

Traditional robotic systems bridge the presented gap, presenting manipulators with both high payload and high repeatability. However, the flexibility and dexterity required for complex assembly tasks could be too expensive, or even impossible, to achieve with traditional robotic systems. This gap can be closed by collaborative systems, since they combine the capabilities of a traditional robot with the dexterity and flexibility of the human operator. Collaborative robots are especially advantageous for assembly tasks, particularly if the task is executed with a human operator. They are also suitable for pick and place applications, though the adoption of a traditional robot or a handling system can offer better results in terms of speed, precision, and payload.

State of the Art

Human-Robot Collaboration has received increasing attention during the last few years, in very different research areas. In robotics, works refer to the need for improving collision detection (Lee et al., 2015) and the optimization of robots' motion planning (Pellegrinelli et al., 2017). In some contexts, human-factors are critical elements. Thus, several studies report an empirical examination of human-robot trust (Hancock et al., 2011). Machine learning algorithms are being developed to enhance gesture recognition (Liu and Wang, 2018) and human activity prediction (Zanchettin et al., 2019) so that the robot can identify and adapt to the operators behavior. There are also concerns about plant layout design (Tsarouchi et al., 2016) and about designing tasks in a collaborative assembly cell, considering the different capabilities of humans and robots (Mateus et al., 2019).

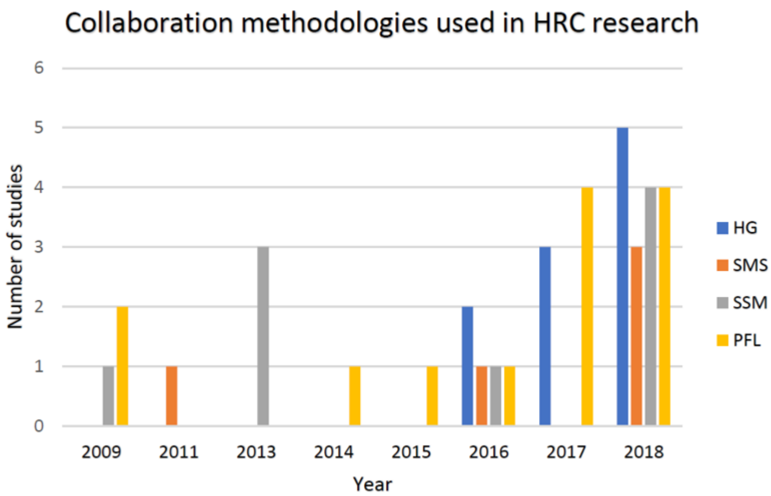
Although early researches utilized traditional industrial robots, the subsequent spread of cobots led to several studies based on more advanced models of cobot. Several researchers applied the collaborative methods to industrial robots, usually due to their increased performance and widespread availability; however, the disadvantage of this choice is the increase in cost and complexity due to the inclusion of several external sensors and the limited HRC methodologies available.



Robot usage in selected HRC studies in the period 2009-2018.

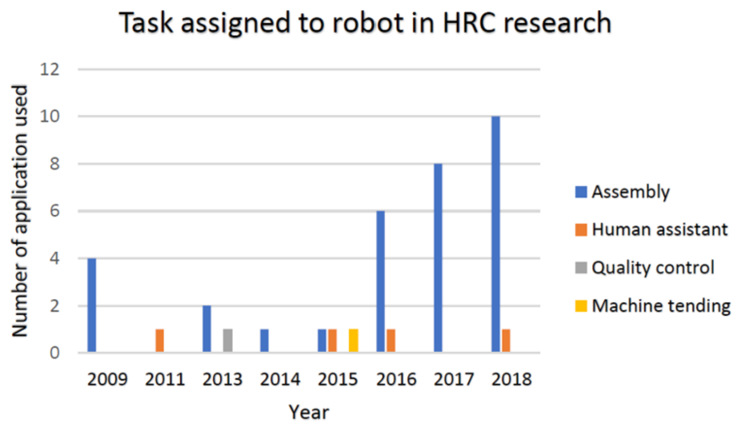
Position control systems were only used for traditional industrial robots, often using extra vision systems for safety reasons. Due to the inherent compliance of cobots, impedance control was more commonly chosen for these systems, though in many cases where an inherently compliant cobot was used, vision was also included for feedback. Robot compliance can often be a trade-off with robot precision, so including a separate channel for feedback to monitor collisions and increase safety can be a useful method of maintaining manipulation performance. Vision is indeed the prevalent sensor used in HRC studies, also due to the flexibility and affordability of the systems, especially when using depth cameras such as Microsoft Kinect cameras. It is interesting to note that in recent years, Augmented Reality (AR) systems, such as the Microsoft Hololens, have been used more in HRC research, as they are able to provide information to the operator without obscuring their view of the assembly process.

Since 2016 and the introduction of ISO/TS 15066:2016, researchers began to study newborn methodologies, such as the Hand Guiding method, which, as shown in figure, has become prevalent in recent years. The HG method is indeed a representative function of collaborative robots, since it allows even unskilled users to interact with and program the cobot, which can allow some degree of flexibility - even if the robot moves only on predefined directions - without the need for expensive algorithms. It should be noted that the HG method could also be employed with traditional industrial robots; this allows one to take advantage of the robot's characteristics, such as high speed and power, and increase the system's flexibility.



Collaboration methods used in selected HRC in the period 2009-2018: HG hand guiding; SMS Safety-rated Monitored Stop; SSM Speed and Separation Monitoring; PFL Power and Force Limiting.

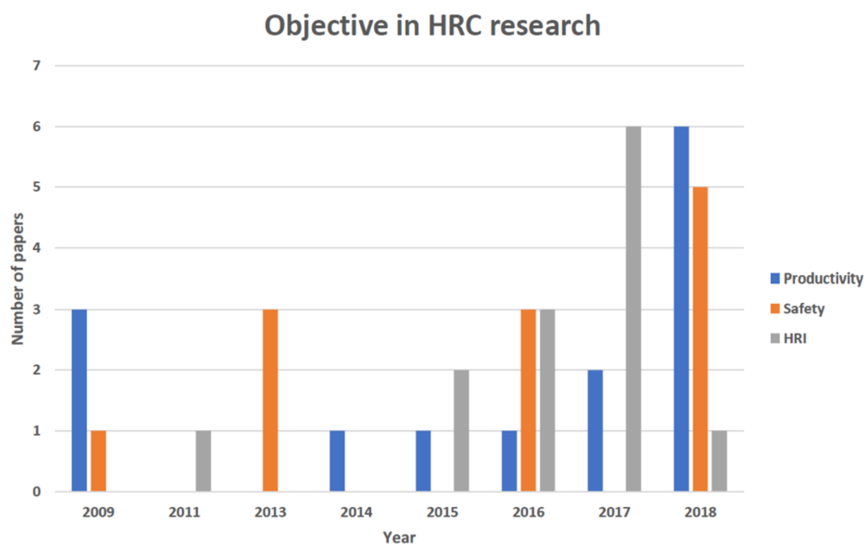
As stated previously, the collaborative mode depends on the considered application. The most studied task is assembly, likely due to the required flexibility in the task, which makes traditional robotic systems too expensive or difficult to implement. However, the task of production also requires flexibility, and could greatly benefit from collaborative applications. Likely, until the fundamental challenges of setting up collaborative workcells are solved for the easier tasks of assembly, we will not see many case studies targeting production.



Tasks assigned to the robot in selected collaborative applications in research in the period 2009-2018.

It is interesting to note that the first phase of HRC study was more focused on increasing the production and safety aspects of HRC, at least in a manufacturing context. As the research progressed, an increasing number of studies were focused on HRI methodologies, becoming a predominant objective in 2017. The ostensible reduction in 2018 should not mislead us to believe that HRI studies were abandoned in that year: As stated before, the presented classification is not univocal, thus studies such as could also be considered HRI studies.

The key findings of these studies highlight challenge areas that research has successfully addressed, or even solved, when cobots are used for industrial tasks. Multiple studies reported an increase in task performance - e.g., by reducing completion time and minimizing error - as well as a better understanding of the operator space and higher precision of workpiece manipulation. Thematic areas of research intent can be identified, such as increasing and quantifying the trust of the operator in the robotic system, as well as improving safety by minimizing collisions.



Main topics or objectives in HRC studies.

Concerning the organizational questions that the HRC/HRI is introducing, there are some studies report dynamic scheduling problems, in which, the authors consider that the assembly paths may be decided in real-time and the different assembly routes are described in a AND/OR Graph. In these, the assignment of tasks is multimode, given that the algorithm may also determine which tasks should be executed by both human and robot. Dynamic scheduling is also present in Ding et al. (2014) and Nikolakis et al. (2018), that proposes a heuristic for the assignment and sequencing of assembly operations to avoid safety hazards. The focus is to design a tool that evaluates the assignment alternatives for each operation according to a utility function composed of many criteria. Recently, Casalino et al. (2019) developed a model and a scheduler algorithm to simulate and optimize an HRT working cell, considering the factor of h uman uncertainty. The scheduler performs an exhaustive search in the reachability graph to prioritize the next task for the robot. They use a prediction algorithm to identify patterns in human activities and adapt the robot schedule accordingly.

In the case of a deterministic scheduling, Gombolay et al. (2018) propose an algorithm to multi -robot scheduling, which incorporates the preferences of a human supervisor. The existence of a human worker imposes some spatial constraints to support safety distance regulations. The objective is to minimize the difference to a previous schedule and spatial interfaces between the robots. But the algorithm does not schedule human tasks.

Cyclic scheduling with HRTs is also the focus of some works. Banziger et al. (2020) describe a genetic algorithm to address the assignment and sequencing of tasks in an HRTs workplace. Solutions obtained are evaluated by a simulation tool designed for that purpose and validated in a real manufacturing environment. The objective is the minimization of completion time, walking distances and waiting time. The environment consists of workstations with a single robot in collaboration with one or more human operators. Precedence constraints and minimum safety distances are taken into consideration. The setting is justified by the fact that robotic manipulators are nowadays widely used in assembly and the introduction of humans improve efficiency in the execution of specific manual tasks.

The International Federation of Robotics provides a classification on the different types of HRTs interaction (IFR, 2018). They describe five scenarios where humans and robots that operate in the same working cell. The first one is actually not collaborative, as it refers to fenced robots. The other four are summarized in the table.

HRTs Type	Coexistence	Synchronised Collaboration	Cooperation	Responsive Collaboration
Description	No fence but no shared workspace.	Operators share a workspace, but do not work simultaneously on the same component.	Human worker and robot work simultaneously on the same product or component.	Robot responds in real-time to movement of the worker

Classification of HRC provided by IFR (2018).

In the Coexistence scenario, there is no fence, but humans and robots operate in their own workspace (there is no shared area in the work-station). Synchronized Collaboration refers to cells where the operators share the workspace, but they always work in different components, performing sequential and synchronized movements. A closer interaction occurs in Cooperation, where both operators humans and robots - may work at the same time on the same components, performing collaborative tasks. Lastly, Responsive Collaboration is the highest level of interaction, where humans and robots not only share workspace and components, but the robot is able to react in real-time to the movements of a human worker.

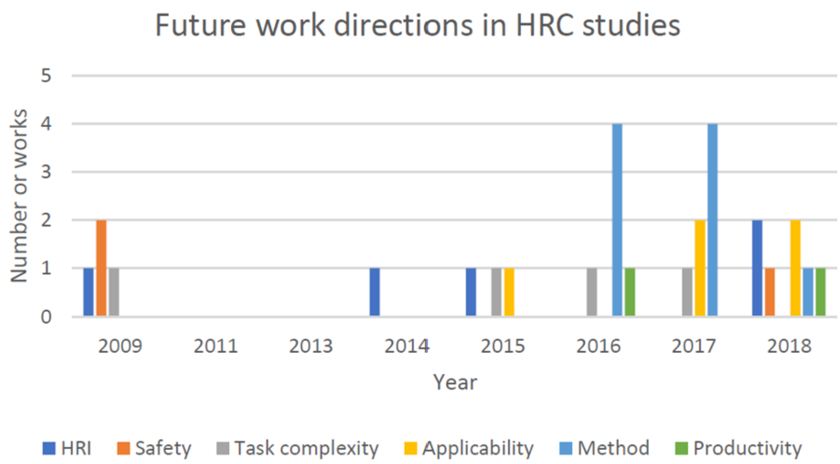
Although the last two scenarios are the most advanced and should grow in the long term, most of the current applications of HRTs are Coexistence and Synchronised Collaboration. This is due to the extensive technological challenges present in the other two scenarios (IFR, 2018). Moreover, the transition to Cooperation involves analyzing some performance trade-offs, primarily related to the impact in productivity provided by the collaborative tasks.

In classical Parallel Machine Scheduling, the environment is composed of a set of resources that work in parallel, and jobs require a single operation from one of the resources (Pinedo, 2008). Multiprocessor Task Scheduling (MTS) is a generalization of Parallel Machine Scheduling where a single job may be executed simultaneously by a set of resources in parallel (Drozdowski, 2009). Different variants of MTS problems are described in the literature. If all resources are identical, each job may require a specific number of resources (rigid tasks) or a given amount of processing time from resources (malleable tasks). Otherwise, in non-identical resources, jobs may require a specific set of resources (single mode) or accept different combinations of re-sources (multiple modes).

The first work to deal with Multiprocessor Task Scheduling is Weglarz et al. (1986). The authors studied the computational complexity of scheduling rigid tasks in the special case of unit processing times. They presented two polynomial-time algorithms with complexity O(n) for non-preemptive scheduling of tasks that require a fixed number of k processors.

In the Multimode (or General) Multiprocessor Task Scheduling Problem, each job has a set of possible modes. Each mode has a specific processing time and a subset of machines (Chen and Lee, 1999).

The problem is shown to be NP-hard by demonstrating that the particular case with three machines is strongly NP-hard (Błazewicz et al., 1992).
The scheduling literature presents several well-studied problems with similar characteristics of the MMTSP. The existence of machine eligibility constraints is usually referred to as Multi-purpose Machine Scheduling. In Brucker et al. (1997), the authors discuss the complexity of Parallel Machine and shop scheduling problems with such characteristic.
Another generalization of the MMTSP is the Resource Sharing and Scheduling Problem, that also handles a set of multimode jobs. Differently from the MMTSP, during the execution of job j by a set of resources R, the resources in R may be dedicated to j in different periods of time.
So, we saw how historically, researchers oriented their studies toward the increase of HRI relevance in their work, also with a focus on higher safety requirements and more complex tasks. In recent years, the scope of future work has expanded, with researchers focusing on more complex methods that improve the performance of their systems—whether this is by applying their method to different application fields or more complex tasks. This is likely due to the prevalence of new cobots and sensing methodologies coming onto the market, maturing algorithms, and experience in designing collaborative workcells.



Future work topics from HRC studies.

In particular, future direction focuses on having better understanding of the scene—whether this is what the operator intends to do, what is happening in the environment, or the status of the task. Researchers propose solving this by using more sensors and advanced algorithms, and fusing this information in a way that is easy to use and intuitive for the operator to understand. These systems will inherently lead to better safety, as unexpected motions will be minimized, leading consequently to more trust and uptake. We can expect that many of these advances can come from other areas of robotics research, such as learning by demonstration through hand-guiding or simulation techniques that make it easy to teach a robot a task, and advances in computer vision and machine learning for object recognition and semantic mapping. Other reviews, identify similar trends, namely those of improved modeling and understanding, better task planning, and adaptive learning. It will be very interesting to see how this technology is incorporated into the industrial setting to take full advantage of the mechanics and control of cobots and the HRI methodologies of task collaboration.

Is important to understand also, how the current market is facing the changes introduced by the new paradigm in manufacturing. The overall collaborative robot market is estimated to grow from 710 million USD in 2018 to 12,303 million USD by 2025 at a compounded annual growth rate (CAGR) of 50.31% during the forecasted period. However, the International Federation of Robotics (IFR), acknowledging an increase in the robot adoption with over 66% of new sales in 2016, expects that market adoption may proceed at a somewhat slower pace over the forecasted timeframe. However they suggest that the fall in robot prices has led to a growing market for cobots, especially considering that small- and medium-sized enterprises (SMEs), which represent almost 70% of the global number of manufacturers and could not afford robotic applications due to the high capital costs, are now adopting cobots, as they require less expertise and lower installation expenses.

Finally, a particular segment of cobots is taking over the others. When presented with different payloads capacities, the ones with up to 5 kg payload capacity were preferred; indeed, they held the largest market size in 2017, and a similar trend is expected to continue from 2018 to 2025. This preference of the market towards lightweight robots, which are safer but do not present the high speed and power typically connected with industrial robots, restrains the HRC possibilities in the current manufacturing scenario. However, the important factor to consider is that with proper regulation, the current market will possibly show a different response regarding the strict separation dividing heavy-duty tasks and HRC methods.

Acceptance of Human-Robot Interaction

Research indicates that humans perceive and value robots differently than other technologies such as ICT. Smarr points out that due to the uniqueness of the robots, acceptance patterns from other domains may not be applicable to the HRI field. On the one hand, robots are not an incremental type of technology, but a radical technology. On the other hand, robots have several unique characteristics: unlike other technologies, robots can act and move autonomously, interact with the physical world around them, and provide innovative forms of communication. In addition, humans tend to expect more social skills and intelligence from a robot than from other technologies. This is due to the tendency to attribute human qualities to the robot. Young et al. they also report that the physical and social presence of robots causes people to attribute arbitrariness to them. This results in an interaction that is essentially different from the interaction with other technologies, and people evaluate the uniqueness of this interaction as a function of the differences it has compared to the others.

There are several studies that claim to investigate the acceptance of HRI in the workplace and beyond. There are more investigations dealing with assistive and healthcare robots than there are with industrial robots, which shows the need for more studies in the industrial sector. In the field of assistive HRI, most models take into account factors such as, perceived enjoyment, confidence, anxiety, perceived sociability, ethical factors, and concerns about being stigmatized. Beer et al. they tried to summarize the factors that influence the acceptance of HRI according to previous studies and found three main categories: functionality, including for example the level of autonomy; social capacity, which refers to emotional expression and social intelligence; and, finally, shape and appearance. In terms of acceptance, these factors can all be characterized as factors related to objects, that is, factors that relate to the design of technology. Smarr addressed the one-sided focus on robot-related factors from other studies by developing a more holistic model of assistive robot acceptance. In addition, he identified several aspects that affect perceived utility, for example, robot confidence and ease of use, for example, robot anxiety. In general, research reveals that the acceptance of assistive robots depends crucially on the characteristics of the task. While robots that perform cleaning tasks are approved, most people don't want robots to perform more intimate tasks, especially in the case of older individuals.

Much of the research in the field of industrial HRI also focuses on the relationship between humans and robots. These studies mainly investigate factors related to objects, such as the movement and appearance of the robot, the mechanisms of interaction and the design of the workspace. Their results show that these factors are important, because they help people understand and predict the behavior of the robot, which is essential to trust it and feel safe when interacting with it. There are, however, studies that look at HRC acceptance from a broader perspective, taking into account factors related to topic and context. Often, studies from the field of ICT acceptance, again serve as a starting point. The automation acceptance model (AAM) theoretically derived from Ghazizadeh et al. it is based not only on ICT research, but also on the results of cognitive engineering research, which indicates that TAM is not able to explain the acceptance of technology in mandatory environments. Thus, the model also includes compatibility between technology and tasks, the contribution of trust and external variables such as user and task characteristics, as well as organizational influences. It should be noted, however, that generic automated systems and robotic systems tend to differ in some places, which is why these insights may not all be transferable.

A broad model on the acceptance of human-robot cooperation in production systems, which was empirically derived, was presented by Bröhl et al. Although it was an obligatory context, and they therefore did not examine attitudinal acceptance but focused on the intentions of use and behavior of use. Their model combines TAM, TAM2, TAM3 variables and additional factors, such as perceived security, legal and ethical considerations (e.g., fear of data security, and job loss).

Henderson conducted an exploratory study on mixed methods for the acceptance of industrial robots in manufacturing. It also focused on factors underlying to robot design, such as robot experience, workplace culture, and the availability of training offerings. In addition, he also found that the features of the task play an important role.

A study that focused primarily on the obstacles and organizational enablers for a successful implementation of HRI was presented by Charalambous et al. The results reveal the importance of context-related factors for HRI acceptance. For example, communication and workforce empowerment were found to be enablers, while poor understanding of work procedures and poor organization of resources turned out to be barriers.

So, the outcomes that can be drawn from this analysis indicate that the use of collaborative robots at work is not necessarily an indication of a positive attitude towards HRC. Commitment to the implementation process seems to be a better indicator. It was also pointed out that workers' attitude towards HRC depends significantly on whether they perceive HRC as a threat or as an opportunity. This seems to be influenced not only by rational considerations about the risks and benefits of HRC, but also by individual and sometimes irrational feelings. The results also suggest that acceptance of the change process associated with the introduction of HRC is at least as important as acceptance of the technology itself. Therefore, it is concluded that a safe and well-designed robotic system is a necessary but not sufficient condition for the acceptance of HRC. Researchers and companies should consider the acceptance of HRC not only as a technological issue but also as a cultural one. They could benefit from the integration of knowledge from different research areas, including social and economic psychology, especially organizational change. In addition, robots should be treated differently than other technologies, such as ITCs, as employees are likely to perceive robots as a more drastic change.

Requirements for a collaborative workspace for human and robot

The requirements analysis presented aims to design a collaborative workspace, in which both the man and the robot perform assembly or production tasks in a common work area. The goal is to abolish the rigid separation of work spaces and the temporal alternation of the work process between man and robot. Humans and robots should instead work collaboratively on the same product at the same time. In case of consecutive actions, the components must be delivered by the robot to humans and vice versa. In doing so, we also have the purpose of direct interaction, i.e., one subject takes over the object directly from the other. The workplace must be aligned for skilled workers of all age groups, including in particular older workers. Automated control of the production process should be as flexible as possible in order to be competitive in the globalized world economy with regard to a growing variety of products.

The requirements were identified according to Franke's approach regarding two aspects. First, they are classified into technical and functional requirements, human-related requirements, and regulatory requirements. Secondly, requirements relating to the life stages of the product, such as production, distribution, use and reuse, were collected. The table below applies Franke's product life cycle to the specific workplace case for human-robot cooperation under consideration.

Product life cycle phase		Meaning in the context of the human-robot workspace
manufacturing	planning, development, construction	planning and construction of the workplace for human-robot cooperation; comparison of available technologies
	preparation, manufacturing of components	preparation of the location of the workplace; order or manufacturing of components
	assembly	assembly of workplace; disassembly of workplace
distribution	transport	transport of the workplace to another operating place
	storage	storage of the workplace in case of disuse for a longer time
	sale	aspects for industrial sale
utilization	operation, downtime	operation of the workplace; planned or unplanned downtimes in case of pauses or maintenance
	maintenance	periodic maintenance of individual components
	repair	unplanned repair of individual components
reuse	recycling	reuse of used components; rebuild of workplace; extension of workplace by new components

Product life-cycle according to HRC.

Manufacturing Phase

At the beginning of the production stage, the workplace must be planned and designed. Technicians and do not have to be involved at this stage, in order to identify and meet all requirements in light of the general concept. Technical feasibility, as well as higher-level concepts, such as the possibilities of training the worker, must be considered. Therefore, it is advantageous to provide a digital model of the workplace. Using a CAD model all components can be planned in detail and with little effort, compared to their space needs. In addition, the model serves as an abstract visualization of the workplace at the next stage of the product cycle. Various standards and norms provide help in the design of an ergonomic workplace. DIN EN ISO 14738 and VDI 3657 specify the ergonomic and anthropometric requirements for the person working. Since humans and robots are invited to work collaboratively in the workplace, standards related to the safety of human-machine interaction must be considered equally. ISO 13854, DIN EN ISO 13855 and DIN EN ISO 13857 indicate the safety distances and specify the arrangement of the safety devices. Finally, EN 953 and DIN EN ISO 14119 describe the requirements of protective devices and their locking devices. With regard to human-robot cooperation, DIN EN ISO 10218-1 lists the dangers of robotic workplaces and specifies construction requirements. However, this standard was not established to introduce direct human-robot cooperation. The new ISO/TS 15066 includes further indications and measures to ensure functional human-robot cooperation and thus allows to keep alive the coexistence and interchange of work between the two classes of operators. It outlines, among other things, the recommended power and speed limits for collaborative robotic systems intended for operation in close proximity to humans.

Once the workplace is organized, the individual components must be compared with the currently available technologies. Designers need to decide which components can be purchased and which ones need to be developed by external experts. In order to maximize the flexibility and usability of the workplace, it should be possible to assemble and disassemble the workplace non-destructively and without special tools. In order to make the workplace modular and scalable, adaptable to new requirements that may arise in the future. In addition, it is necessary to consider the compatibility and integration of any existing components, with the tools and devices that are required by introducing robot collaborators in the workplace.

Distribution Phase

The distribution phase includes the transport of the workplace (as a final "product"), if it is not manufactured and assembled at the place of final operation or if it has to be moved to another place in the event that the production of the company is reorganized in the future. Therefore, it is advisable to design a modular workplace, which is decomposable and can therefore be easily transported without any fixed support system. The dimensions of each component of the workplace must meet local restrictions, for example, if the component is to be transported through "usual" interior doors. The labelling of hazardous components and force application points can prevent injury during transport.

Utilization Phase

Most of the requirements can be derived from the use phase. As for the robot, the focus is on its technical characteristics and capabilities in case of human-robot cooperation. The type of tasks that can be taken on by the robot depends, among other things, on its accuracy and repeatability. In general, there is a choice between standard industrial robots or lightweight robots. While industrial robots usually need to be equipped with additional safety protections to be suitable for human-robot cooperation, lightweight robots often come with built-in sensors but withstand limited payloads. In addition, power supply can be a crucial decision-making criterion, if high-voltage current for industrial robots is not available.

Regardless of the type of robot, the size of the workplace must be chosen from the dynamic forces of the robot in case of movement with the maximum possible payload, as well as the additional man-made forces. The working height must be adjustable by the individual worker, so that people of different heights are able to work ergonomically in the same workplace. The change in the working height also allows you to switch between sitting and standing during the working day, obtaining a lower level of deformation according to the state of the art. The appliances, boxes and utensils necessary for man to perform the assembly task must be ergonomically aligned with regard to the space at hand both sitting and standing. The weight of heavy tools must be reduced by means of rope hoists and the working area must be illuminated without flickering. Actuators and control panels must be designed in accordance with ergonomic standards and must provide sufficient information on the current state of the system and the state of cooperation. In addition, it is especially important to consider the time points of activation and deactivation of the robot. In an emergency, the man must have the possibility to interrupt the movement of the robot. It is therefore necessary to provide for emergency stops in appropriate places.

Direct human-robot cooperation leads to new challenges compared to standard industrial robotic applications. The physical integrity of the working person must never be endangered. As already mentioned, there are adequate standards and norms, as well as those recently introduced. The European Machinery Directive 2006/42/EC and the corresponding standards DIN EN ISO 12100, DIN EN ISO 10218 and DIN EN ISO 13849-1 describe detailed procedures for assessing the risk of a workplace and its individual components. In line with this, the robot's control unit must meet safety integrity level 3 and performance level "d". Missala proposes further detailed levels of safety integrity in the case of human-robot cooperation. Accidental collisions between humans and robots must be avoided and the maximum strength of the robot must be limited (as per ISO/TS 15066). In addition, the transported objects and tools must be fixed in the event of a power outage and no accidental activation of the robot must occur during idle times. Likewise, the system must be protected against accidental misuse by the human being.

Currently, DIN EN ISO 10218-1 requires immediate shutdown and some downtime while humans and robots are in the same workspace. The robot can only be operated in manual mode with a maximum speed of 250 mm/s. To dynamically control the speed requires an adequate and specific human, which can be established, for example, by means of cameras or laser scanners. PrEN/TS 62046, DIN EN ISO 13856-1 and DIN EN ISO 61496-1 describe different techniques for visual contact and non-contact human localization. To indicate to the worker a certain intention of the robot or an imminent situation of cooperation, it is possible to install optical and acoustic signals. In this way, positive and negative signals, e.g. acknowledgments and warnings, should be easily distinguishable. In addition, human-robot cooperation would benefit if the robot were able to react to the human's voice and gesture signals. However, this type of communication and the interpretation of these signals must also meet reliability and security level 3.

In addition to the technical requirements, cognitive-ergonomic requirements must also be taken into account. This includes the behavior of the robot's automatic control program that should comply with the operator's expectations. Designing behavior in a transparent way increases trust in the technical system and makes actions more predictable, which is of greater importance especially in the case of human-robot cooperation. This can be achieved, for example, by selecting an appropriate mounting order or introducing anthropomorphic trajectories for the robot. An automated system should also be able to provide detailed information to examine a possible incident.

For maintenance and repair cases, a detailed manual must be provided that describes all components and their functionality. However, the maintenance effort should be minimized.

Reuse Phase

In the context of an intelligent use of available resources and continuous interoperability between them, the workplace reuse phase is interpreted as the extensibility of current instruments towards the needs of future technologies. New assembly tasks may require a reorganization of workplace components. In addition, new components such as new safety devices may be installed in the future. To meet this flexibility, not only hardware components, but also software systems should be based on standardized interfaces, so as to ensure their operability and yield even with new requirements.

Preliminary definition and Assumptions

Given the problems of planning and assignment of tasks examined so far, in the event that human operators and industrial robots are able to operate in the same workspace and on the same product, it is necessary to define precise hypotheses in order to develop a common model of cooperation. It happens, in fact, that usually the models of task planning, for men and robots are treated separately. The following assumptions have been made to allow the definition of a common model:

1. The method is intended for the initial design phase, known as rough planning, which includes activities such as determining the resources to be used, generating a rough estimate of costs and determining the approximate layout of the facilities. Therefore, the exact motion plans of robots or detailed actions to be performed by humans are not addressed. These are part of a detailed planning phase, which goes beyond the scope of what is discussed and addressed here. The tools developed are aimed at providing a quick solution to the problem of combined assignment of layouts and tasks in the case of collaborative cells of humans and robots. The intervention of the human planner is still required at multiple stages of the workflow, since the experience and reasoning skills of any algorithm are still far from those of humans.
2. The list of all cell equipment is provided as input. The application of this hypothesis is based on the fact that not all types of existing equipment are accessible via a single computer, and also on the fact that the tool should take into account the actual resources available at end-user facilities. It should also be noted that the optimal set of equipment strongly depends on both the allocation of resources and the layout of the cells.
3. The scope of the process planning activity is limited to a single workstation, where multiple resources (human and robot) can operate. The same procedure can be applied to each individual workstation to arrive at an action plan at the level of the entire production line. Another peculiarity of the method is the fact that it currently uses all available, user-defined resources. This means that the solutions obtained will consider all humans and robots made available during layout planning. Human operators and robots that have unsuitable skill criteria for the purpose will not be considered.
4. The method considers multiple types of tasks, including assembly, collection, loading, and any other user-defined tasks, as long as there are adequate resources dedicated to this type of task. As for the definition of tasks to be used in planning, the method

distinguishes the following:

   a. Assembly activities that can be automatically derived from CAD models through software tools,
   b. User-defined activities (e.g., picking, inspection, etc.) that can be entered directly by the user in an XML file format.

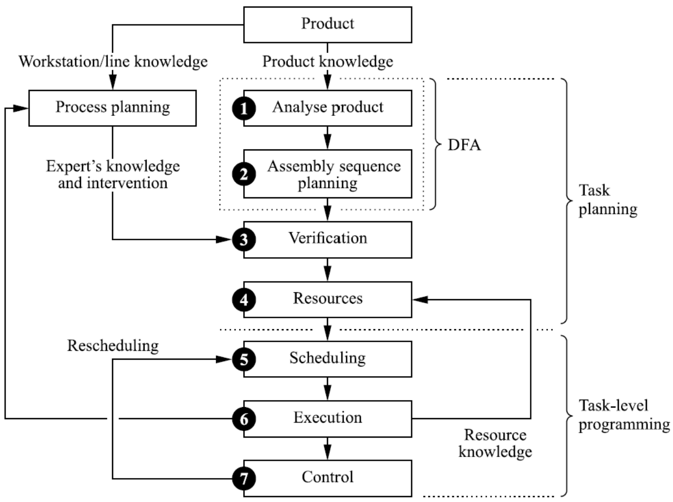
5. The developed method and tool are able to manage and assign tasks to the resources in use, e.g. humans and robots. However, other types of assets or equipment that do not perform a task, e.g. devices, storage places, stationary equipment etc. may be included in the process of arranging the layout. These resources can be linked to the start/end position of a part thus influencing the ergonomics of the workplace. In addition to this particular task, these resources are considered as obstacles to be avoided in the movement by man / robot. In addition, the model under analysis cannot consider the simultaneous execution of tasks by multiple resources employed in the same task.
6. The method shall consider the use of a basic part to which all other components are mounted. The user has the task of defining this basic part at the beginning of the process, while the location of all other elements is determined by the method in question.

The method under consideration is applicable to several cases where hybrid environments can be traced back to employment situations including: shared tasks and workspace, common tasks and workspaces, and common tasks in a separate workspace. The common denominator in such applications is the need to automate tasks that are not appropriate for humans due to problems of ergonomics, effort or in case of lack of precision, required strength. The latest reports indicate that collaborative applications of robots and humans must meet a sharply increasing demand, favored by recent investments in the field of industrial robotics. The four industrial areas that should be on the front of important investments for robotics are: computers and electronic products; electrical equipment, household appliances and components; transport equipment and machinery. At least 85% of production activities in these industries are automatable, involving the assembly and maintenance of machines that are highly repetitive.

In this perspective, the usefulness of a study in this area comes from different industrial sectors in which the paradigm of human-robot collaboration can be potentially useful. You can provide several examples where hybrid collaboration systems have been implemented to address production challenges. Similar applications have been identified in the aeronautical, consumer goods, equipment and pharmaceutical industries. The physical configuration of the cell that sees the use of human resources can be combined with the automated counterpart. Through virtual processing of existing cell environments, through programming tools it is possible to generate collaborative cell layouts. The layout varies in terms of embedded robots (standard 6-degree-of-freedom arms, double-arm robots, etc.) and in terms of product type (size, weight, conveyor or stationary movement, etc.). Thus, the scope can be extended to model any assembly application where partial robotization can be considered. The proposed tool would be particularly valuable for any system integrator who wants to consider the possibility of hybrid production systems in his first conceptual design activities.

Methodology

Assembly Planning Overview



High-level overview of the proposed approach to planning and sheduling shared tasks.

The proposed work begins with the analysis of CAD product models and the extraction of assembly characteristics from it. This process generates a number of assembly features using a variety of parameters, such as part geometry and kinematic constraints. Then, assembly characteristics are fed into the assembly sequence planning where possible assembly sequences are generated and evaluated based on a set of criteria. The best sequence is selected and the final task sequence is generated based on user input. This sequence of tasks is used by the scheduler to produce an appropriate allocation of tasks to resources. Task allocation is then sent to execution and control modules, where task allocation (rescheduling) can be requested dynamically based on changes in the shopfloor environment.

Layout model

For the formulation of the optimization problem, the definition of the available shop-floor space is first carried out, as well as the creation of constraints (e.g., location of resources or parts that are not allowed to be altered by the model). What comes next is the discretization of the shop-floor space through the definition of the base unit charged to the user. We will therefore have the representation of the shop-floor space and the organization of the possible positions of the robot resources on the discrete area. The degree of discretization (dependent on the size of the base unit defined by the operator) can be modified by the user in order to change the level of detail of the layout generation and thus, reducing the computational power and time required.

The location and orientation of all parts/resources can be derived sequentially based on the resource/part of the requested area and the available free space. All equipment assets have a bounding box that represents their footprint on the shop-floor space, as well as an indication regarding their relative reachability. We will thus have indication for each robot of the space in use of shop-floor, and in relation to this and the initial position of the human operator, instructions regarding its reachability. A constraint imposed by this modeling is the fact that the reachability of the robot is usually circle-shaped, because it operates a modeling of three-dimensional space, while the discretization of shop-floor space is usually represented and reduced through two-dimensional space. A higher resolution of the discretization can provide better results by better approximating a circular area, however the accurate representation through 3D simulation, on the other hand, requires a greater use in terms of computing resources and time required.

Meeting layout constraints means that the resource or part has been placed within the available area designated for the corresponding workstation, and that the corresponding workstation does not involve overlapping with any grid location that is already occupied by another item or resource or part. The check is performed each time a component is added against the positions of all the elements already inserted in the model. The analysis assumes that any part of the discretized shop-floor space is not available even if it is only partially covered by a component.

The location criteria enforce the requirement that each resource (robots and humans) should have at least one adequate part, placed in the shop-floor space (and therefore, its associated task) within their area of reachability, and that human operator should not be completely closed off from other parties and resources. At this point, the faithful reconstruction of the real space of operation was obtained. Through the layout generated by the shop-floor environment analyzed it is possible to consider the positioning of any resource on the X-Y plane and possibly, the kinetic rotations of manipulation of a care robot around a possible Z axis.

Data entry and task extraction from assembly CAD

In order for the Task Planner to provide the user with the desired simplicity of the program and reduce the amount of input data required, it can extract different properties of CAD files of the assembly that will later be used for the assignment of tasks. Therefore, whenever the user requests a new production plan, he is initially required to enter the respective 3D assembly file. At the next stage, the characteristics of the product and the part are extracted from their CAD.

Some of these characteristics derive directly from the geometry (e.g., length or surface) while others are calculated on the basis of the mass and properties of the material. These characteristics must be used, at a later stage, for the definition of the suitability of a type of resource (robot or human) for the manipulation of this object and involve the following elements:

- Part Weight: Part weight calculated based on the weight, density and volume of material products, measured by CAD software.
- Part dimensions: overall dimensions of the piece used for the evaluation of the surface/volume of the parts and manipulability. Measured by verifying the largest area projection of the piece on each plane.
- Part flexibility: The conformity of the part in changing its shape under its own weight or external forces. While the first two characteristics can be extracted from the CAD model, the flexibility of the part must be entered by the user as a Boolean variable.

Following the extraction of the part and the characteristics of the product, the assembly sequence for the assembly work is extracted. To simplify the model, it is assumed that its assembly starts from a basic component, and all other parts are installed on it. This allows to significantly reduce the time required for the generation of the sequence of tasks to be implemented, among all possible combinations. User intervention is measured to select this basic component.

The automatic extraction tool provides the sequence of tasks for assembly with the use of a one -by-one mapping between parts and activities. In the event that multiple sequences can be calculated by the tool, the user is responsible for selecting the final one to be used. If extra tasks are needed that cannot be automatically extracted from CAD files (e.g. picking or inspection) they can be entered manually by the operator.

Resource suitability assessment

Going to deepen what are the capabilities and limits of the resources used in the manufacture, in the context of the shared space of shop-floor, it is necessary to specify how the assessment of suitability and the subsequent assignment of tasks takes place in relation to the peculiar characteristics of the two types of resources used, the human and the robotic. To achieve optimal processing times and the most accurate use of resources possible, it is necessary to evaluate the planning times, and consequently apply changes to existing resources, through the definition of their suitability for each of the tasks in the generated assembly sequence. All resources have certain characteristics that must be identified and declared in the planning phase; such characteristics will allow resources to be differentiated from each other. All the characteristics of the resources are entered by the user and can therefore be modified as needed.

Some of the features will be used in order to define, at an early stage, whether a resource can perform a specific task and to determine which of the possible alternatives can produce the best results in terms of criteria set by the user.

The suitability assessment ensures that only resources that meet the characteristics of the part and the general job requirements are candidates for the assignment. The evaluation shall be based on the following criteria:

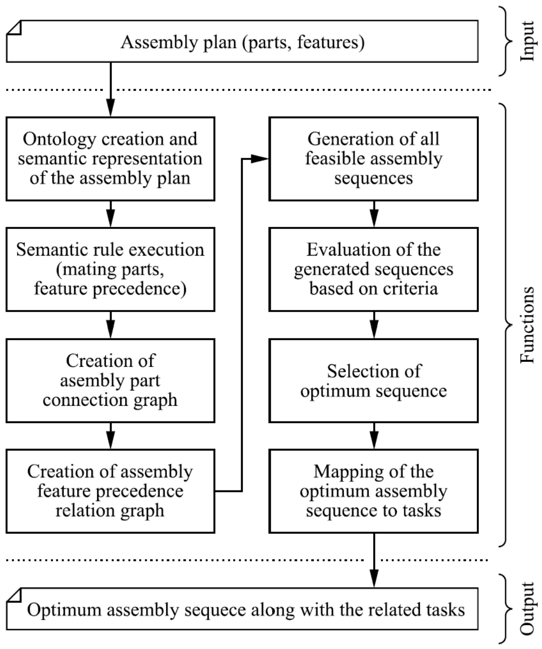
- Human operators must not handle parts weighing more than 11 kg, as indicated by the ergonomic analysis. This limit can be adapted to each application by the user. The weight limit does not apply to robotic resources as it depends on the payload of the robot, which will be taken into account during the final assignment of tasks.
  The height of the human being will also have to be taken into account. This is in immediate correlation with his arm width. Fixed a value of average height for men and women, it is possible to estimate a corresponding value of opening arms. A component that has dimensions smaller than the pre-established minimum value is to be considered relatively easy to manipulate by the human operator. Stability and manipulability, for parts with dimensions greater than the pre-established minimum value, but lower than the upper limit of operational capacity, shall be established on the basis of the weight of the part and its other dimensions.
- Flexibility of use is used to ensure that only humans are selected for handling elastic parts, since robots lack dexterity. This variable is Boolean and therefore can only take a true or false value. Therefore, when a part is selected to be used flexibly, any task that includes its manipulation will be passed directly to human operators. At this point, the user can intervene to modify the suitability according to his experience, or any other parameter that the program is not able to take into account. The sequence diagram will therefore be enriched with the different alternative resources for each task. This diagram will be used for the generation of allocation plans in the following sections, where it will be crucial to have a clear overview of resources, uses and related resource-use relationships.

Feature-based Task Planning

An assembly feature contains information concerning the connection of two or more assembly parts. Regarding the association of components in an assembly plan, each assembly task is associated with a specific workstation, resource and feature, and each feature is subsequently associated with one or more assembly parts.

An organic assembly model is created and used to temporarily store and manage the information of the assembly plant. The model consists of five main classes, which refer to assembly tasks, parts, features, resources and workstations respectively. The feature class contains a subclass, which concerns simple features. The simple assembly features supported by the current development are the positioning, inserting and screwing features. Features can be composed of more than one simple feature. Each class of the model of has some specific semantic properties that describe it. Assembly tasks, parts, assembly features, resources and workstations that are imported are declared as entities in the assembly model, and information about them is assigned to them by semantic properties. Then, by reasoning about the assembly model, or by executing semantic rules, the properties of the entities are examined, properties such as which class they belong to, and, in this way, the entities are classified into the classes of the assembly model.

As a first step, the algorithm imports the assembly plan, including assembly tasks, parts, features, resources and workstations. Then, the organic assembly model is created, which is used to manage the assembly entities, and semantic rules are used to extract the connections of the assembly parts. A linked graph is created, which presents these connections. Precedence features are also extracted during the execution of the semantic rules, and another linked directed graph is created, declaring the precedence relationships of the assembly features. Then, a graph search algorithm is run several times on the assembly feature graph and generates possible assembly sequences. Subsequently, the generated assembly sequences are evaluated and sorted according to various criteria. At the end, the optimal assembly sequence is exported with a list of tasks that corresponds to the assembly sequence. The main flow chart of the developed algorithm is presented in the figure.

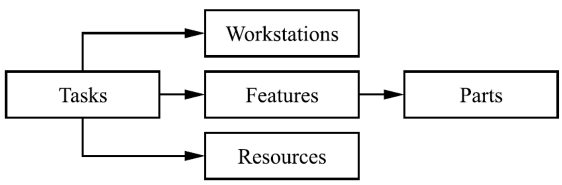


Main flow-chart of the algorithm.

The algorithm imports the assembly parts of the product with their assembly characteristics. An assembly function contains information about connecting two or more assembly parts. For example, an assembly feature can be "Screwing Part A to Part B." The entire assembly plan consists of the following components:

- Assembly tasks
- Assembly parts
- Features
- Resources
- Jobs

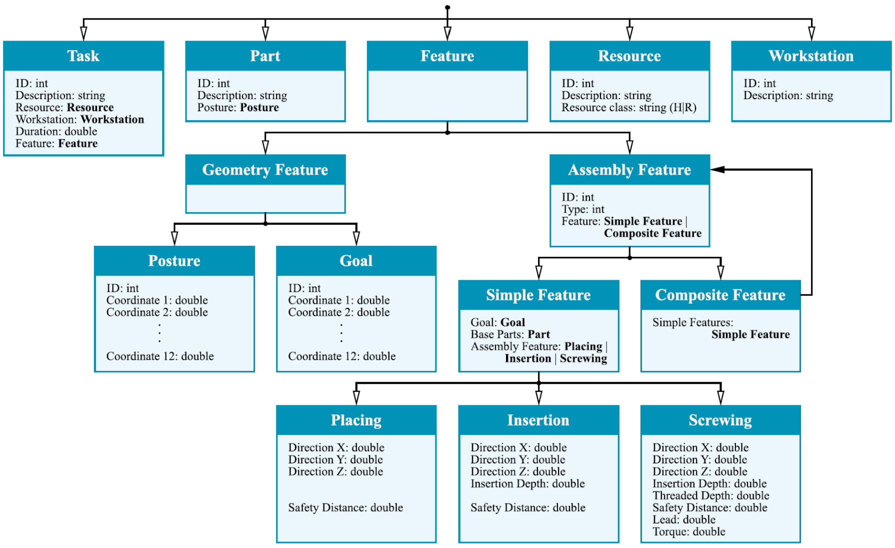
As for the association of assembly plane components, each assembly task is associated with a specific workstation, resource, and feature, and each feature is subsequently associated with one or more assembly parts. The reports of the components of the assembly plan are presented in the figure. Assembly plan information is retrieved from an existing legacy system.



Association of assembly plan components.

The next step of the algorithm is the creation of a collection model, which is used to temporarily store and manage assembly plan information. The model consists of five main classes. The class of characteristics contains two subclasses, one concerns the geometric characteristics of the parts, and the other concerns the assembly characteristics of the tasks. Geometric features define the posture or destination of parts in space. Assembly characteristics define how two or more parts are connected and can be divided into two subclasses, the class of simple characteristics and the class of compound characteristics.

The representation of the classes and properties of the organic collection model is shown as an Entity Relationship Diagram (ERD) in the figure. Each box represents a set class with its corresponding semantic properties. Property values set in bold declare that this property correlates entities in this class with other entities in the class in bold.



Entity Relationship Diagram (ERD).

After the classification of the individuals of the whole and through the use of semantic rules, the pairing of assembly parts and characteristics that precede the extraction of relations takes place. To extract the connections of the assembly parts, any simple feature information is processed.

After finding all the connections between the parts, the connection between them can be represented by an undirected connected graph, where the vertices will represent the assembly parts and the edges the connections between the parts. The last step is to create a list of parts, assembly characteristics and classes of assembly characteristics.

1	2	4	3	3
IF (x is a Simple Feature) AND (a is Base Part of x) AND (b is Moved Part of x) → THEN connect a and b	–	–	–	–

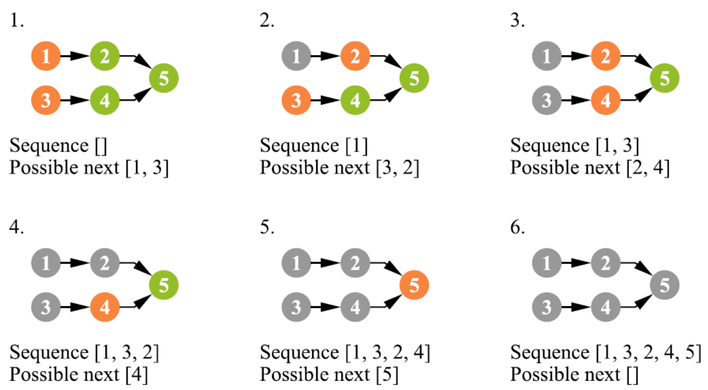
Assembly part matching rule.

It should be noted that the feature-based approach to task scheduling automates the procedure up to a certain point and takes into account only the available information. After the first batch of suggested assembly sequences generation, manual entry by an experienced engineer is required. In addition, the same approach is also followed in the subsequent stage of task planning. The process is automated up to a certain point and then manual entry and confirmation are necessary to proceed to the final stage concerning the planning of activities. Semantic properties of simple characteristic class elements such as base parts, moving parts, and assembly characteristics are intended to declare component parts and how they are connected. By creating a semantic rule that connects the basic parts and moving parts of a simple feature, the connections of all parts can actually be found. The rule that matches assembly parts is presented in the table.

Part	Name	Feature	Feature name	Class
1	Part 1	1	Placing throttle	Placing
		2	Screwing flange	Screwing
		3	–	Screwing
2	Part 2	4	–	Screwing
		1	–	–
		2	–	–

Assembly features and classes.

A search algorithm is therefore implemented that works through the graphs of the precedence relationships of the assembly characteristics, to identify the totality of the possible assembly sequences for the assembly of the product. The procedure for generating a possible assembly sequence is presented in the figure.



Alternative assembly-feature-based sequences.

The vertices of the graphs represent the characteristics and the connecting edges oriented the precedence relations. The characteristics that can be entered into the sequencing are shown in orange and the characteristics that have already been sequenced in gray.

First, the algorithm finds all the possible origins of the graph, in other words, vertices that have no incoming edges. These characteristics state that the parts they connect can be joined together at any time independently of the other parts. In this example, there are two roots, characteristics 1 and 3, and the algorithm randomly selects function 1 as the first function to perform.

At the next stage, features are sought that can follow function 1 in an assembly sequence. In the example, these are characteristic 3 (another origin of the graph) and characteristic 2 (which must be preceded by characteristic 1). Next, element 3 is randomly selected from possible subsequent functions. The procedure is carried out until all the features have been analyzed. In this example, function 5 will always be the last in the sequence of functions, as it can only be started after all other assembly operations have been completed.

When all possible sequences have been generated, they are finally evaluated using the following criteria for identifying the most appropriate choice:

N_{SS}: Number of independent stable subsets

N_{PO}: Number of parts reorients during assembly

N_{TC}: Number of tool changes required during assembly

U_{CT}: Consecutive Use of the Tool

Consecutive use of the tool is defined as:

$$U_{\mathrm{CT}} \stackrel{\mathrm{def}}{=} N_{\mathrm{MC}}(1 - P_{\mathrm{LF}} - P_{\mathrm{LC}}),$$

where N_{MC} is the maximum number of consecutive assembly elements processed using the same tool in an alternate assembly sequence, P_{LF} is the location of the last assembly element in the sequence, and P_{LC} is the location of the last consecutive assembly element.

Using the above criteria in a user-weighted approach, the assembly sequence self-assessment indicator, IASAE, expressed in %, is generated as follows:

$$I_{\mathrm{ASAE}} = ((w_1 \cdot N_{\mathrm{SS}} + w_2 \cdot U_{\mathrm{CT}}) - (w_3 \cdot N_{\mathrm{PO}} + w_4 \cdot N_{\mathrm{TC}})) \cdot 100,$$

where w_i indicates the weight of each criterion selected by the tool user or assembly engineer.

Through this phase, alternative assembly sequences are generated and classified for the assembly of a specific product. The highest in the ranking is suggested to the assembly engineer or user as the most appropriate one. This approach can be used iteratively across multiple parts or products to achieve a series of better and better level assembly sequences for each part or product.

Following the above approach, the assembly engineer will be able to define, in a short time, the optimal approach for the assembly of one or more products, but not for their production. This would require knowledge of the specific workstation/line where the operations are performed. Since the approach, up to this point, has not included any knowledge of the specific workstation or assembly line, the user must refine the appropriate sequence of assembly operations by modifying or changing the suggested sequence, or by selecting an alternative sequence. As soon as this process is completed, a list of tasks has been generated that can be assigned to resources on the shop floor.

In addition, it should also be said that this step is semi-automated and requires user input, the expert can calibrate the solution for sequences that do not follow the normal assembly workflow.

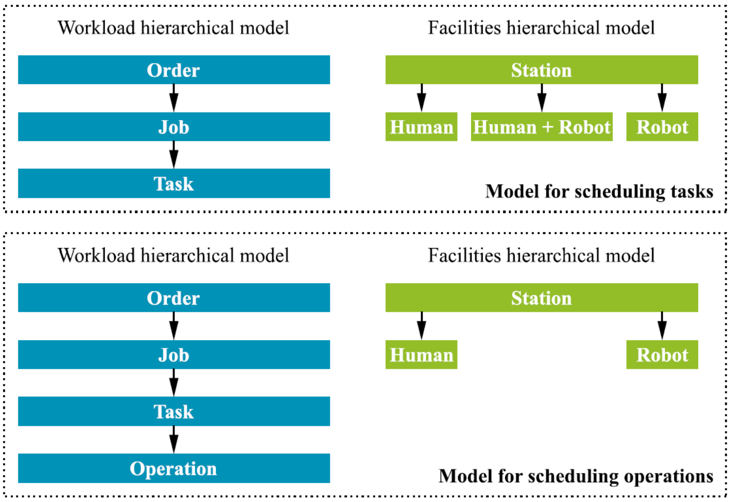
The assembly sequence planning core is also supported by a user interface that is responsible for viewing the results, manually editing the solution, and persisting the final solution in a database to support task scheduling.

Task Scheduling for Human-Robot Collaboration

The planning core is responsible for making assignments of tasks related to the production of a specific and already analyzed product, to the resources of a line or workstation, available and able to perform it. The scheduling procedure requires defining a model that can be used to assign tasks to resources, a decision algorithm to decide which task should be assigned to which resource, and for defining a start point that kicks off the schedule, or a decision point for the algorithm.

A factory can contain multiple departments where parts are assembled. A department can include one or more stations. Each department involves many resources, for example, human operators or / and robots. Similarly, the workload is divided into parts, so as to manage it in specific and different places, used for different tasks, so as to follow what happens for the separation of the corresponding plant levels.

To facilitate human-robot collaboration in a workshop environment, the human operator and the robot could be considered resources capable of exchanging and/or sharing tasks. As a result, a task could be assigned to one or both as represented in the figure.

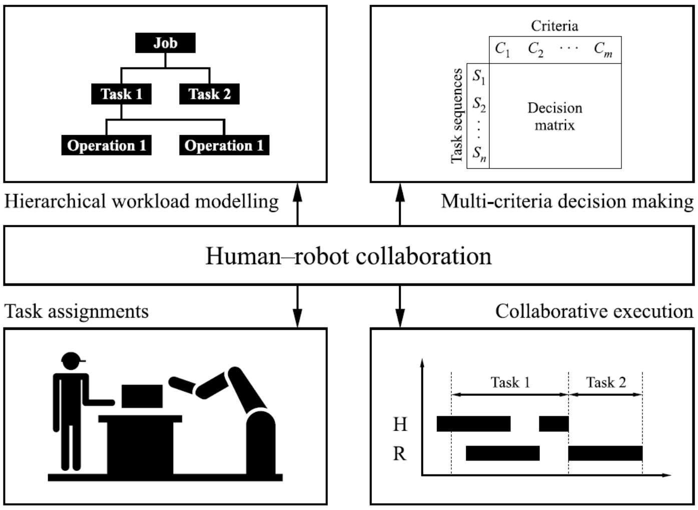


Task and operation models for scheduling HRC tasks.

A task can be shared both in time and space. Sharing over time refers to the consecutive work of a human being and a robot, at a specific time, for the fulfillment of the assigned task. Sharing space, on the other hand, means that one part of the task will be done by one operator, while the rest can be completed by another. A shared task in space can include serial, parallel, or mixed execution of smaller task segments. In both cases, it must be assumed that a task describes a combination of smaller sub-tasks, called operations.

The task assignment procedure (shown in the figure below) is carried out at a decision point by a decision-making framework, through the following stages:

- Description of possible assignments of tasks/operations to resources.
- Selection of criteria for assigning tasks/operations to resources.
- Evaluation of the alternatives generated according to the selected criteria.
- Selection of the alternative with the highest score. After marking all the alternatives in the previous step, the highest one in the ranking is selected as the most suitable to meet the current goals.



Human-Robot scheduling concept.

It is assumed that there is at least one resource suitable for fulfilling the given task. The suitability of resources is decided on the basis of human capabilities (e.g., flexibility, problem-solving, complex perception, manipulation) and the capabilities of the robot (repeatability, efficiency, accuracy, high load capacity, etc.). In addition, for the suitability algorithm, the availability of resources and their ability to manipulate tools/grippers is considered. Input to the decision-making framework includes resources, tasks, the ability to combine task and resource, priority constraints for the task, task duration, and task start and end time.

```
<WORKCENTERS>ID,NAME
<RESOURCES>ID,NAME
<HIGH_LEVEL_TASKS>ID,NAME
<TASKS>ID,NAME
<TASK_PRECEDENCE_CONSTRAINTS>
  <PRE_CONDITION>TASK id
  <POST_CONDITION>TASK id
<RESOURCE_AVAILABILITY>TRUE/FALSE
<TASK_RESOURCE_SUITABILITY>TRUE/FALSE
<START_TIME_OF_TASK>YEAR,MONTH,DAY,HOUR,MINUTES,SECONDS
<END_TIME_OF_TASK>YEAR,MONTH,DAY,HOUR,MINUTES,SECONDS
<DURATION_TIME_OF_TASK>SECONDS
```

Task scheduling input.

The decision-making framework selects the resources that will be allocated to the execution of a task based on the suitability of the resources.

The alternative solutions selected through the decision-making framework are evaluated on the basis of multiple criteria to select a good solution in a short time. The selection of criteria is based on the requirements and specifications of the user. There is no restriction on the type and number of criteria that can be selected. Some of the criteria applied are summarized below:

Total weight of the parts lifted: the criterion refers to the sum of the weight of all the parts raised by human resources. It is estimated by the following relationship:

$$W_H = \sum_{i=1}^{k} m \cdot w_p,$$

where:

w_P the weight of a part relieved by a human resource,

m the iteration n of a part raised by a human resource,

k the total number of parts raised by a human resource.

Total duration of task execution/per time cycle: This criterion is estimated as the sum of the time to complete tasks n assigned to a resource. The following relationship is used:

$$T_H = \sum_{i=1}^{n} T_c^i,$$

where:

T_c^i completion time of task i assigned to a resource,

n total number of tasks assigned to a resource.

Production or completion speed: The R_P production speed (expressed in parts/hours) is inversely proportional to the T_C cycle time of a process (expressed in minutes) and is estimated through the relation:

$$R_P \approx \frac{60}{T_C}.$$

This policy is used to define a new cycle time for scheduling a shared task so that the new solution will have a timeless cycle or equal to the estimated cycle time.

Operating cost: The criterion is estimated as the sum of the operating costs of each resource for each task. Two distinct formulas are used to estimate the cost of human resources and robots.

$$C_{OH} = \frac{S_D}{T_W} \cdot T_c^i \qquad C_{OR} = C_E \cdot T_c^i \qquad C_O = \sum_{i=1}^{k} C_i,$$

where:

C_{OH}, COR operating costs for humans and robots, respectively,

S_D daily wage of the human labor force,

T_W working time of human labour,

C_E cost factor for robots,

C_i is the total cost of ownership for activities for robots and humans separately,

C_O total cost of ownership per time cycle.

The result of the scheduling method includes the task, the resource assigned for the task, the time factors (start date, month, year, hour, minutes, seconds) and the duration of the task (ms).

```
<TASK>ID
<RESOURCE>ID
<YEAR>YEAR
<MONTH>MONTH
<DAY>DAY
<HOURS>HOUR
<MINUTES>MINUTES
<SECONDS>SECONDS
<DURATION_IN_MILLISECONDS>MSECONDS
```

Task scheduling output.

At the beginning, a roadmap is generated and the tasks are assigned to the resources after the evaluation procedure described in the previous section. The same roadmap is repeated as many times as necessary to fulfill production orders.

During the run time, unexpected events may occur, or changes may be required to meet production goals, for example, the number of products set for an 8-hour shift. In the event of such events, the system should be flexible enough to adapt to the newly introduced parameters.

As a result, in the event of such an event, a reprogramming of the remaining tasks is performed according to a predetermined set of rules and constraints. In this case, depending on the nature and stopping point of the task, the manufacturing process can adapt and continue its execution, reassigning several operations to a different resource.

Programming, as a result of the decision algorithm, occurs after an initial activation event defined by the user before the start of production. This event is the initial decision point for the algorithm. To enable the generation of a new program taking into account the new production constraints introduced, a new decision point must be created for the decision-making algorithm that reflects the event that occurred. Next, a new program is generated and the activities are reassigned to the shop floor operators.

In addition, the algorithm takes into account the status of the resources in the shop-floor at the time of generating each new decision point. For example, a robot may malfunction or a human resource may have moved away from its workstation. In such cases, such resources shall be excluded from the allocation of tasks. This information is obtained through the status and location tracking infrastructure installed on the shop floor.

The planning core is supported by a user interface component that is used to display task assignments to resources using a Gantt chart.

Alternative Generation Model

The case of hybrid systems requires a different approach to the planning process, due to the fact that the spatial layout can prevent resources from performing a task and therefore, forcibly conditions the assignment of tasks. This happens because if the position of the resources relative to the parts / products is already defined, in most cases, a task planner would be forced, due to constraints of reachability, or for reasons of efficient duration, to produce a particular plan accordingly, or alternatively, would be forced to abandon the initial layout designed by the designer.

Starting from a completely robotic or completely manual solution, you can't expect to get satisfactory results just by going to modify it. This is due to the fact that a predefined layout is optimized for the peculiarities of production equipment and human skills. If, on the other hand, a combination of robots and humans is used, the definition of the layout of the station must be carried out through the examination of the various assignments of alternative tasks. Therefore, a more general approach to the problem of planning is needed, which can combine the needs arising from the joint use of human operators and robots.

Since the specific method aims to serve as a decision support tool for the preliminary design phase, it must be intuitive to the user and in accordance with the way humans today design workplaces. Current practice involves engineers putting all available components and resources within a CAD system and then experimenting with their placement. During this process, they must take into account any location constraints (equipment already installed, shop-floor peculiarities, access to consumer items, etc.) and then try to decide on the best possible positioning. The peculiarity therefore lies in the fact that currently only robots are accustomed to performing all the tasks and therefore, there is no doubt about the resource to which the task must be assigned. Task assignments are then predetermined and the problem is reduced to deciding where to place parts/resources in order to meet the constraints of reachability. With the introduction of humans and their ability to move freely in the shop-floor space, decision-making options change considerably.

The layout itself affects the suitability of humans for a given task. In order for this method to be able to evaluate each assignment in full knowledge of the facts, the position of the parties/resources must be known in advance. Therefore, the algorithm must first generate several layouts (among those possible) and then will have to perform the assignments, which can then be evaluated through the assigned criteria.

The alternative method would be to select the assignments first and then decide on the placement of the resources. Potentially, this could lead to an efficient search for the organizational tree to pursue, since the decisions with the lowest branching factor would be those made first (fail-first principle). Therefore, depending on the focus that is required of the analysis, it will be possible to focus more on the formulation of the problem and its correct modeling or otherwise, discuss the possible practices of optimization of computational effort.

Criteria for training and evaluation of alternatives

For the successful creation of a production plan for a cooperative assembly station, some specific rules and particular constraints must be established in such a way as to effectively differentiate resources and thus allow the creation of the final allocation to the planning algorithm, taking into account as many system variables as possible. To this end, a multi-criteria evaluation method is usually applied for the creation of the production plan. The criteria that most characterize the different capacities for human and robot resources are:

Robot Reach: This is an expression of the robot's ability to reach the necessary parts. Although the robot's workspace is primarily a 3D sphere, the discretization approach for layout creation usually takes advantage of a two-dimensional approximation of space. In any case, it is usual to consider the rectangle value corresponding to the maximum extension capacity of the arm. The rectangle ensures that all points within the rectangle are reachable by the robot.

Force criterion: The force required to manipulate the part participating in the specific operation. It expresses the ease of the human operator in manipulating the part used in the specific operation. The criterion of resistance, the limit of human strength and the weight of the part to be manipulated must be indicated. During the evaluation of the case under consideration and the possibility of interchangeability of the task with the robot, the resistance criterion is combined with the payload of the robot and is expressed as a payload number supported, according to the specifications of the robot.

Robot payload: The weight of the part to be manipulated is crossed with the payload of existing robots. This criterion establishes the preference for using a robot with a payload close to the weight of the part, but not less. This logic allows the program not only to express a preference in choosing a robot that has a payload closer to the weight of the workpiece, but also in the selection of a human operator for a lightweight part.

Ergonomic criteria: Indicate the limits and specific characteristics for operators, relying on studies on the ergonomics of workplaces with regard to the human operator and the specifications of use indicated with regard to the robot operator. We will have, the ergonomic criterion, the weight of the part, the permissible weight limit, and the respective are the multipliers of position, relative distance, asymmetric angle, frequency / duration of lifting and coupling.

Cost: The cost criterion is also important to include in order to have a clear indication of the economic implications of alternative projects in the workplace. Since task planning can result in different saturation levels for resources, the cost of operation was taken into account. This is also indicative of the energy and consumables used in the choice to pursue the realization of the task through the use of one resource over another. It must therefore be examined for resources that constitute possible alternatives. The resource where this indicator is minimized will be chosen.

Cost of investment: The criterion is calculated as the total cost for the acquisition and installment of any additional resources. It will include the investment cost of the entire station, the number of different resources and the type of resources to be acquired, and the unit investment cost of a resource.

Shop-floor space: The space occupied by all resources. Its value must be minimized while meeting the rest of the criteria.

Time saturation: This is the saturation level of a resource, that is, the percentage of time that this resource is used. This variable is intended to have the highest possible value because in this way the downtime of the robots is minimized. The saturation level of the human operator is not taken into account as it is accepted that the human operator may perform other tasks during his period of inactivity.

Fatigue: the level of physical fatigue of the human operator based on the time in which he/she must perform the operations.

Handling time: the total time of handling/assembly/work. Its calculation is based on the assumption that most of the time required for the handling of a part is the time it takes to be transported to the basic part. For the first part, the robot must move towards the part and after collecting it, towards the basic part. For all the resulting parts, the robot moves from the base part to each new part and vice versa.

Multiple decision-making criteria

The design of the assembly line is subject to a number of criteria, which in some cases may be contradictory. In order to be able to identify the solutions that best reflect the desired criteria and to optimize the planning of the most suitable alternative, a decision-making mechanism or criterion responsible for classifying the possible alternatives and choosing the best one for the task in question must be established. An array is used that contains the different project alternatives as row values and criteria calculated as columns. Normalization is performed for criteria that the operator believes should be maximized or minimized:

$$\hat{C}_{ij} = \frac{C_{ij} - C_j^{min}}{C_j^{max} - C_j^{min}} \qquad \hat{C}_{ij} = \frac{C_j^{max} - C_{ij}}{C_j^{max} - C_j^{min}}$$

Where:

- C_{ij} = value of consequence of the alternative i with respect to criterion j.

- C_{ij} = normalized value of C_{ij}.

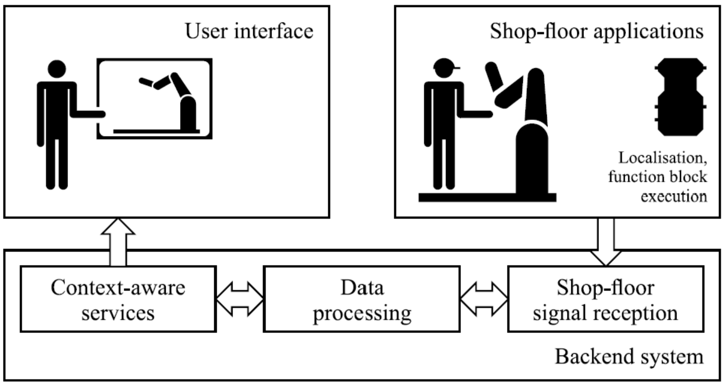
The choice of the alternative that best combines the desired attributes is based on the total score (utility value) of each alternative, calculated as the sum of the products obtained by multiplying the values of the normalized criteria with a weight factor assigned to each criterion. The utility value is calculated as follows:

$$U_i = \sum_{j=1}^{n} w_c \hat{C}_{ij}$$

where, w_c is the weight factor of the criterion. Alternatives with higher utility value are more preferable as they better meet user-defined criteria. The branch with the highest average utility factor is selected as a result and you can proceed with the research by moving on to the next decision-making horizon. When the planner has completed all assignments, the alternative with the highest utility factor, calculated from the average of his respective activities, is presented to the user.

System Implementation

The system of planning and programming tasks is implemented according to a distributed approach, shown in the figure. The implementation of the overall system consists of the development of three main components such as the shop-floor components, the back-end system and the user interface.

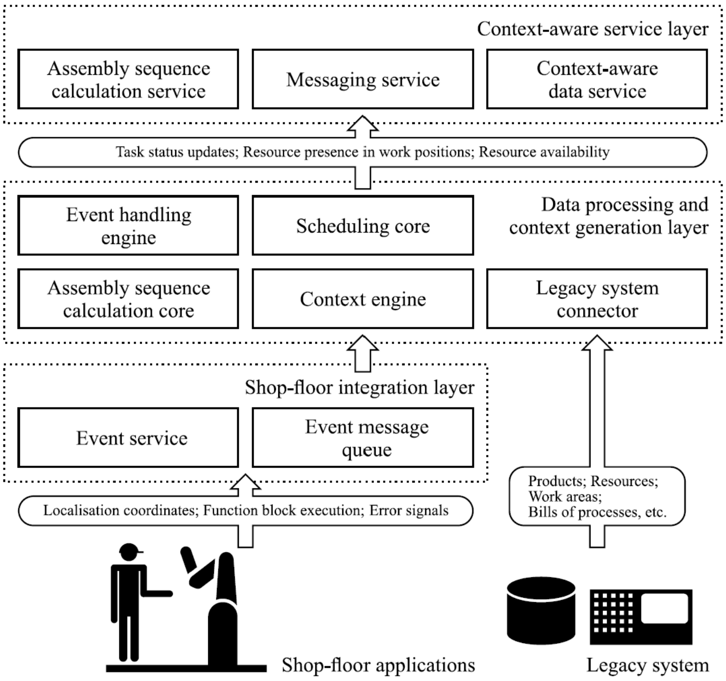


System conceptual design.

Shop-floor components consist of various software applications used on the shop floor. These applications perform various functions such as task execution management and resource localization. Since these applications control the workflow and have very specific functions in the organization of the processes and activities used, the need to interface with them has an influence on the design of the system.

The *back-end system* is the central component of the system and is often developed as a web application through which to interface with the software integrated into the shop-floor. In particular, the system interfaces with shop-floor applications to intercept events from shop-floor applications, then processes the information received to generate significant information for the user to be viewed through the user interface component. In addition, it can also support data processing for workflow that takes place entirely in the context of the user interface, such as calculating assembly sequences used for human-robot collaboration planning.

The development of the back-end system follows a multi-layered architecture as shown in the next figure.



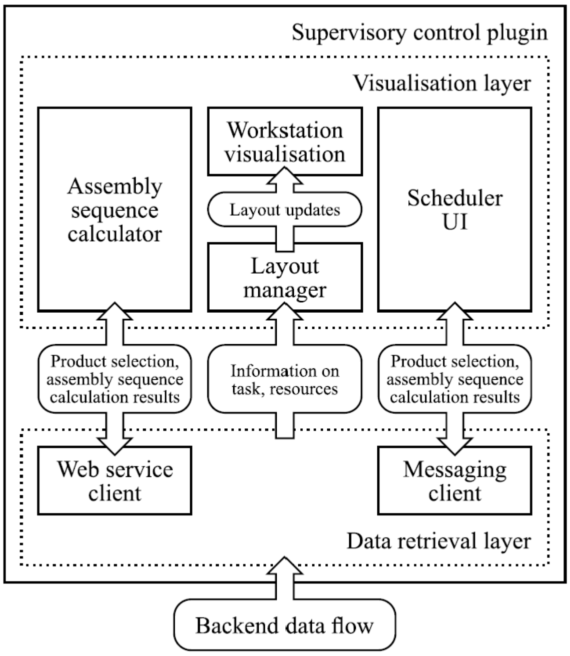
Back-end layered architecture.

The three levels that make up the backend are the context function service layer, the data processing and context generation layer, and the shop-floor integration layer.

The shop-floor integration layer is responsible for receiving signals from the components used in the shop-floor.

The data processing and context generation layer consists of various components, starting with the event management engine that is responsible for interpreting and extrapolating the events that take place on the shop-floor, in order to obtain useful information. For example, location coordinates are interpreted as the presence of resources in the workstation. The context engine is responsible for populating the contextual model, ensuring a representation of the current state of the shop-floor, with information from the event management engine. For example, the context engine has information about each worker's position, his or her respective task, and the progress of the production plan. The assembly sequence calculation core is responsible for processing an XML representation of assembly characteristics and identifying the most appropriate assembly sequence using different criteria. The programming core is responsible for calculating the schedule of performing tasks based on information on the quantities to be produced, product codes and available resources.

The context function service layer is responsible for declaring events and context information to system clients (for example, the user interface). For this purpose, two mechanisms are employed. The first mechanism is constituted in order to fulfill a type of operation typically based on demand (on demand). The second is a notification service that forwards events from the event management engine to all registered customers and therefore interested in receiving information directly.

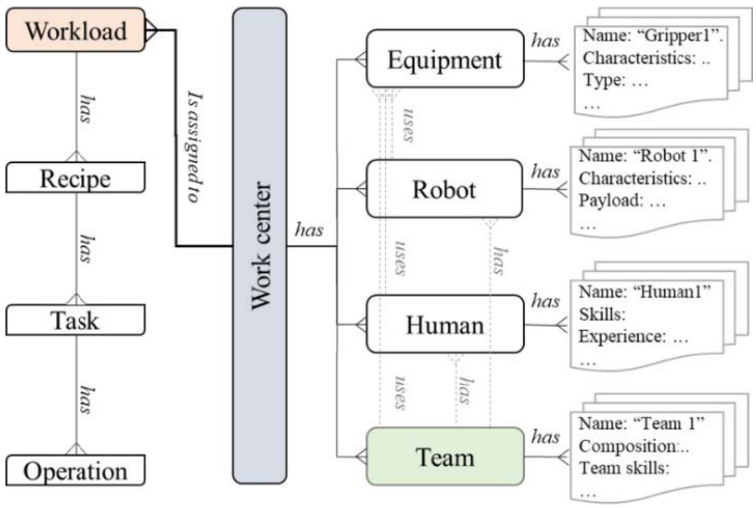


User interface overview.

The *user interface* of the system has internal structure as shown in the figure above. The user interface consists of two levels. The data pickup layer is responsible for retrieving data from back-end services and also for logging and receiving events from the back-end messaging service. Instead, the display layer is responsible for showing the appropriate information and control elements to the user. These elements are used to control the calculation of assembly sequences, for task planning and for viewing the status of shop-floor workstations.

Use Case Approach

A generalized model to jointly represent human resources and robots was created (in the figure), as the basis of the scheduling method. HR resources are structured as individual resources (human or robot) or as HR teams (e.g., human-robot, human-human etc.). Each resource can be linked to certain tools for performing a specific task. In addition, the link to a tool can be extended to include different "objects", such as devices, or specific characteristics of the resource, such as the age of an operator. The tasks are grouped into recipes, with different recipes making up the workload, which is the goal of production in the scenario examined. This could relate to work to be done in one or more workplaces or on an entire production line. In the lower level of the workload model (pictured), some operations make up a task. The purpose of the lower workload model is to break down a task into a basic operating unit that can be run from one of the two resources, in the appropriate format, and if both resources have the ability to perform it, as a "move" operation.



Resources and workload model.

For a given task, there may be one or more resources adequate for its execution. The eligibility of resources shall be decided on the basis of the capacities of the resources. These include among others for humans, experience, physical characteristics, and others, while for the robot, speed, accuracy, payload capacity, etc. In addition, the availability of resources and their ability to handle tools/grippers are considered together with more complex aspects such as non-value-added operations and/or risks not related to ergonomics.

<WORKCENTERS>ID, NAME
<RESOURCES>ID, NAME
<WORKLOAD>ID, NAME
<HIGH LEVEL TASKS>ID, NAME
<TASKS> ID, NAME
<TASK PRECEDENCE CONSTRAINTS>
<PRE_CONDITION> TASK id
<POST_CONDITION> TASK id
<RESOURCE AVAILABILITY>TRUE/FALSE
<TASK-RESOURCE SUITABILITY>TRUE/FALSE
<START TIME OF TASK>DAY, MONTH, YEAR, HOUR, MINUTES, SECOND
<END TIME OF TASK>DAY, MONTH, YEAR, HOUR, MINUTES, SECOND
<DURATION_TIME_OF_TASK>SECONDS

Shared HR task scheduling input.

The decision-making framework receives as input the operational resources, the list of tasks, the task-resource suitability, the possible constraints of precedence, the duration of the tasks as well as the time of starting and completing a task in execution (figure above). The last sets of values are provided during execution time through Function Block events. Function Blocks can be executed both by the robotic controller, including commands to be executed to complete the robot's tasks, and by mobile devices assigned to human operators. This allows for a re-evaluation of programming criteria and alternative schedules to improve the assignment of running tasks. After evaluation and correlation of inputs by the algorithm, the result is the assignment of a task to a resource, based on the suitability of all available resources.

During the decision-making process, more than one result is generated, since there may be more than one suitable resource for a given task. Workarounds are evaluated according to different criteria to select a more suitable solution in a short time. The selection of criteria is based on the requirements and specifications of the user. The solution to be chosen is determined by assigning weights to the criteria evaluated according to the characteristics of the case. For example, in one case the reduction of cycle time may be of greater importance, while in another case the minimization of energy consumption may be of greater importance. There is no restriction on the type and number of criteria that can be selected. Some applied criteria for scheduling and reprogramming shared tasks of human resources are presented below.

1. *Total weight, WH, of the parts lifted in kilograms*: the criterion refers to the sum of the weight of all parts lifted by human resources. It is estimated by the following relationship:

$$W_H = \sum_{i=1}^{k} m * w_p$$

Where:

• w_p: the weight of a part that is lifted by a human resource;

• m: the iteration n of a part that is raised by a human resource;

• k: the total number of parts that are lifted by a human resource.

2. *Total duration of tasks performed by man per time cycle, TH, in seconds*: this criterion is estimated as the sum of the time of completion of tasks n assigned to a human resource in a specific production cycle.

$$T_H = \sum_{i=1}^{n} T_c^i$$

Where:

• T_c^i: time of execution of a task i assigned to a human resource;

• n: the total number of tasks assigned to a human resource.

3. *Production or completion rate, PR*: the production rate (parts/hours) is inversely proportional to the cycle time of a process and is estimated through the relationship:

$$Production\ rate\ (\frac{parts}{hour}) = \frac{60\ (\text{min})}{cycle\_time(min)}$$

This policy will be used to define a new cycle time for shared task scheduling so that the new solution has a cycle time less than or equal to the estimated cycle time.

4. *Operating cost, CB, in monetary units*: the criterion is estimated as the sum of the operating cost of each resource for each task. Two distinct formulas are used to estimate the cost of human resources and robots.

$$OC_H = \frac{Daily\ salary}{Working\ Time} \times T_c^i \qquad OC_R = E \times C_E \times T_c^i \qquad OC = \sum_{i=1}^{k} c_i$$

Where:

- OC_H, OC_R: operating costs for humans and robots respectively;
- E: average energy consumption of the robot (kWh);
- C_E: cost of 1 kWh for the energy consumption of the robot;
- OC: total cost of operation per time cycle;
- c_i: total cost of ownership per task for robots and humans separately.

The final stage of the decision-making framework is the evaluation of alternative solutions. This includes normalization, criteria weighing, and final classification. The weighing process includes the selection of weighting factors for each criterion, while the result of the evaluation of the criteria multiplied by the weights selected for each alternative is called the "utility" value. This value should be maximized or minimized, depending on the nature of the implemented policy.

```
<TASK> ID
<RESOURCE> ID
<DAY>DAY
<MONTH>MONTH
<YEAR>YEAR
<HOUR>HOUR
<MINUTES>MINUTES
<SECONDS>SECONDS
<DURATION_IN_MILLISECONDS>MSECONDS
```

Shared HR task scheduling output.

The result of the scheduling method includes the task, the resource assigned for the task, time factors (start day, month, year, hour minute, second) and task duration (ms) (figure above).

The advantage of an approach of this nature is twofold. On the one hand, task planning and online rescheduling are possible not only in separate HR tasks, but also in shared tasks that allow simultaneous modeling of teams composed of humans and robots. Generalized modeling of resources and workload can be used in different concepts of human-robot collaboration and extended to include additional information. On the other hand, the multi-criterion evaluation also allows the customization of the method according to the different specifications and requirements.

Use Case of Choice

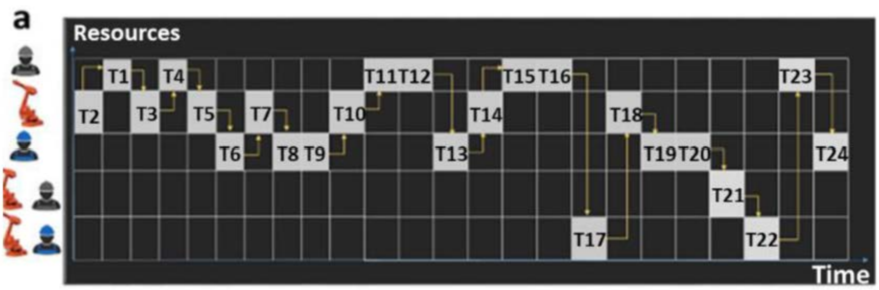
The method discussed so far has been applied to a particular case of the automotive industry that sees the assembly of a turbocharger. The available resources consist of two humans and a robot, while the workload consists of 24 tasks.

The suitability of tasks and resources is assessed as described in the problem approach section. The list of task identifiers with the respective suitability of resources is presented in Table 1. The screwing activity is of a type suitable not only for human or robotic resources, but also for composite HR teams. Table 1 also shows the duration of the task for the human, robot and HR teams.

Task ID	Precedence relations	Task type	Resource type	Task duration (sec)		
				Human	Robot	HR team
1		Pick and place	H or R	6	12	
2		Pick and place	H or R	4.7	9	
3	2	Pick and place	H or R	16.6	18	
4	1,3	Sensing	H or R	8.1	10	
5	4	Pick and place	H or R	3.9	7	
6	5	Pick and place	H or R	1.7	3	
7	6	Pick and place	H or R	7.9	11	
8	7	Screwing	H or R	18	21	
9	8	Screwing	H or R	19	23	
10	9	Pick and place	H or R	5.3	9	
11	10	Pick and place	H or R	2.4	4	
12	11	Pick and place	H or R	1.7	5	
13	12	Pick and place	H or R	2.7	6	
14	13	Pick and place	H or R	3.3	8	
15	14	Pick and place	H or R	8.5	10	
16	15	Screwing	H or R or H-R	8.8	15	9
17	16	Screwing	H or R or H-R	13.5	25	15
18	17	Pick and place	H or R	9.5	12	
19	18	Pick and place	H or R	1.9	4	
20	19	Pick and place	H or R	2.4	3	
21	3	Screwing	H or R or H-R	7.2	8	7.5
22	21	Screwing	H or R or H-R	12.3	15	12.5
23	22	Pick and place	H or R	17.7	20	
24	23	Sensing	H or R	2.6	4	

Table 1. Turbocharger assembly. Tasks, resources suitability and tasks durations.

The planning result based on the data in Table 1 is displayed in Fig. a. Separate tasks are performed by human1, human2 or robot, while shared tasks are performed by teams of human1 -robot or human2-robot.



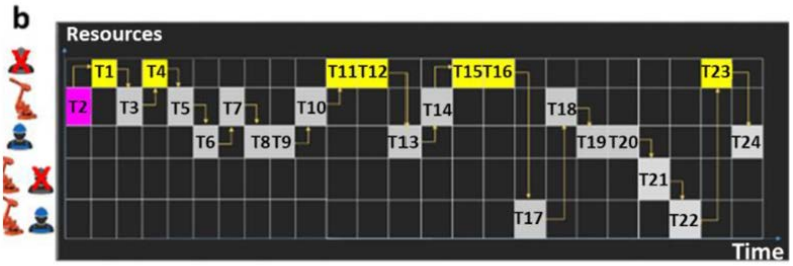
a) HR task scheduling result.

An example of the utility values for 10 planning workarounds is presented in Table 2. Among these workarounds, alternative number 8 was selected by the planning tool, such as the one with the maximum utility value.

No of Alternatives	W_H	T_H	PR	OC	Utility
Alternative 1	13.287	205.2	7.544	16	0.163
Alternative 2	12.594	204.7	7.587	8	0.169
Alternative 3	13.337	202.5	7.778	10	0.167
Alternative 4	12.979	215.8	6.682	10	0.168
Alternative 5	13.100	200.6	7.946	10	0.167
Alternative 6	12.641	200.9	7.919	12	0.166
Alternative 7	3.088	153.9	13.392	4	0.322
Alternative 8	2.385	188.1	9.139	3	0.351
Alternative 9	3.116	176.0	10.455	4	0.327
Alternative 10	13.287	205.2	7.544	16	0.163

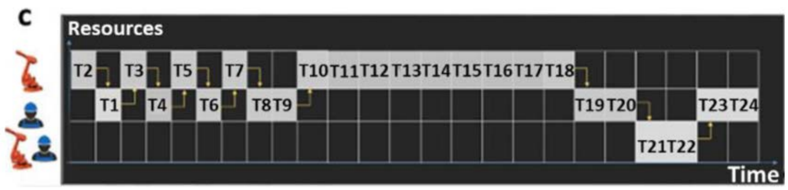
Table 2. Example of criteria values for 10 HR task scheduling alternatives.

During the execution of task 2, human 1 is not available in the station, and the result of the initial programming should change. The availability of the resource is determined by a monitoring system belonging to shop-floor applications, which updates the asset model with the current location information. The decision-making tool evaluates the updated information through the event management component which, based on a logic based on specific rules, triggers the generation of a new schedule with the updated inputs. This reprogramming is applied considering as available resources only the second human, the robot and an HR team (Fig.b). Because Task 2 has not completed, the Reprogramming Tool will consider the list of tasks from Task 2 through Task 24.



b) Unexpected event where Human 1 is not available.

The result of the reprogramming is presented in Fig. c. After carrying out a multi-criteria assessment, the decision-making framework assigned the overall workload for turbocharger assembly to the three available resources.



c) HR task re-scheduling result.

Based on the results obtained here, it can be argued that the highest utility function is achieved when the human operator is less involved in tasks that require heavy lifting, thereby minimizing the corresponding operating cost. In the present case, in fact, the robot compensates for the additional effort required to complete the operation.

Conclusion and outlook

This document presented a method for planning shared HR activities to support the transition that the manufacturing industry is experiencing in recent times. High-level activities are considered for planning between separate (human or robot) or shared (HR teams) activities available in a common workspace. The suitability of resources for a task is based on the combination of capabilities between humans and robots. An important issue for reprogramming in case of unforeseen situations is the constant monitoring of the HR collaborative work cell. Human activities and feedback on the execution of the robot's activities allow you to actively monitor the tasks in place and the current allocation of resources. In this way it is possible to reschedule the current activity, allowing a valid planning of HR activities in a short period of time. The integration with robotic modules to allow the execution of shared human and robot tasks, as well as the coordination that this hybrid dynamic allows, are also advantages of such an interaction.

The procedure for the generalized modeling of separate and shared human activities and resources was shown. This allowed the evaluation of multiple alternative solutions in a short time, taking into account the criteria related to existing requirements and specifications. With reprogramming, you can account for incidents when performing tasks. Reprogramming is based on the evaluation of the events generated during the collaboration of human-machine resources in the workplace and allows the execution of the tasks assigned by human operators or robots.

The advantage of such a method is to simultaneously address both the layout and the problems of assigning tasks, under a common research problem. The direct benefits of the hybrid approach to the production system include reduced planning time for joint assembly activities, efficient spatial utilization, and assignment of a task to humans and robots. This makes it possible to consider the particularities of human resources and robotic equipment and to merge them into a common production system.

Possible avenues have been proposed for the definition of selection criteria suitable for the assignment of tasks between human operators and robots, but research in this direction is still ongoing. The representation of information for humans, robots and HR teams is also an important issue for this field of research as the different interpretative and relational skills of the two types of operators must be evaluated. It is also necessary that the communication between one type and another takes place in the most effective and safe way possible, perhaps through the use of visual and acoustic signaling systems. Integration through special sensors and communication through feedback are valid proposals and certainly to be considered for the construction of hybrid work environments. Integration with existing production execution systems (MES) will also be a challenge, and will have to lead to the coexistence of more or less recent resources with those of recent invoice. This thoughtful integration will allow for easy integration of HR collaboration concepts into hybrid workspaces by assigning and reassigning tasks in HR resources.

It has been seen that a simulation based on worktop and layout data can be used to model complex dependencies between objects such as tools, parts, containers, and products on assembly lines. The integration of a physical model of a human worker and a robot in the simulation allows the accurate prediction of total production times. This also shows that times based on preliminary forecasts can be used for accurate prediction of assembly steps and then adapted as a basis for simulation and optimization of hybrid workplaces. Standardized times will be adapted for robotic skills, since robots have different capabilities than human workers. For a more accurate prediction of distances, the position of the worker and the direction of approach for the different tasks must be included in the initial simulation where the organization of the shop-floor structure space is planned.

The analysis was aimed specifically at the early stages of design, to provide a layout and preliminary planning that can be further detailed in the later stages. The first phases of design, however, proved to be crucial in the choice of the path to be pursued with regard to the aspect of the resources used and the assignment to them. It was clear from the outset that the best way to obtain a valid and sparing assembly result in terms of resources, was to achieve the goal of cooperation between resources, so as to use them to the best of their abilities and peculiarities. The desired effectiveness has been guaranteed and, for the entire duration of the planned work, the safety of the human resources employed.

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