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Operations management issues in design and control of hybrid human-robot collaborative manufacturing systems: a survey

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Abstract

A manufacturing system able to perform a high variety of tasks requires different types of resources. Fully automated systems using robots possess high speed, accuracy, tirelessness, and force, but they are expensive. On the other hand, human workers are intelligent, creative, flexible, and able to work with different tools in different situations. A combination of these resources forms a human-machine/robot (hybrid) system, where humans and robots perform a variety of tasks (manual, automated, and hybrid tasks) in a shared workspace. Contrarily to the existing surveys, this study is dedicated to operations management problems (focusing on the applications and features) for human and machine/robot collaborative systems in manufacturing. This research is divided into two types of interactions between human and automated components in manufacturing and assembly systems: dual resource constrained (DRC) and human-robot collaboration (HRC) optimization problems. Moreover, different characteristics of the workforce and machines/robots such as heterogeneity, homogeneity, and ergonomics are introduced. Finally, this paper identifies the optimization challenges and problems for hybrid systems. The existing literature on HRC focuses mainly on the robotic point of view and not on the operations management and optimization aspects. Therefore, the future research directions include the design of models and methods to optimize HRC systems in terms of ergonomics, safety, and throughput. In addition, studying flexibility and reconfigurability in hybrid systems is one of the main research avenues for future research.

Keywords: Collaborative robot (cobot), Reconfigurability, Ergonomics, Human-robot collaboration (HRC), Dual resource constrained (DRC), Operations management, Optimization.

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1. Introduction

Automation of manufacturing systems is an ongoing trend in the industrial sector. At the same time, for many industries, the transition to a fully automated system remains an unsurmountable challenge. However, Industry 4.0 fosters the adoption of collaborative robots (cobots). Indeed, the recent advances in artificial intelligence and sensor devices gave rise to this new type of robots able to collaborate with humans and to perform a wide variety of tasks (Olsen & Tomlin, 2020).

These cobots (e.g., dual-arm assembly robot) lead to a manufacturing system, where humans and robots work side by side. Such system is called human/robot collaborative (HRC) system. Several studies report the benefits of HRC systems in terms of throughput, product quality, ergonomics, safety, and flexibility (Michalos et al., 2014; Tsarouchi et al., 2016; Sadik & Urban, 2017b). Nevertheless, these robots are expensive, and their introduction in manufacturing systems requires significant efforts.

The present paper aims to identify the challenges and industrial requirements of human/robot manufacturing systems from operations management perspectives. Surprisingly, HRC systems did not catch the attention of the operations management community yet. The closest topic concerns dual resource constrained (DRC) systems. In DRC systems, there are fewer workers than machines, and workers operate a machine to perform a task (Yue et al., 2008), whereas in HRC systems, humans and cobots either cooperate to perform a task or work separately on different tasks (Krüger et al., 2009). Based on the recent literature on DRC and HRC systems, several operations management research avenues to improve the efficiency of HRC systems are identified.

From mathematical and computer modeling perspectives, the robot's characteristics appear similar to those of human operators, and this could explain the lack of operations management literature on HRC systems. In other words, both humans and robots are considered as resources with a specific set of skills. However, robots and humans have different characteristics (Tsarouchi et al.,

2016). Robots possess high speed, accuracy, tirelessness, and force, but they are quite expensive. On the other hand, human workers are intelligent, creative, flexible, and able to work with different tools in different situations. These different characteristics lead to the definition of specific operations management problems for HRC systems, such as the design of hybrid workstations combining efficiently the human and robot skills, scheduling problems that account for ergonomics, the design of reconfigurable HRC systems where workers and cobots move from one station to another to rebalance the line when needed.

The rest of this paper is organized as follows. Section 2 presents the previous literature reviews on HRC and DRC systems, and it introduces the scope of our survey. Section 3 discusses the issues associated with the management of HRC systems, namely, resource skills, ergonomics, and flexibility. Section 4 surveys the literature on DRC and HRC systems, whereas Section 5 discusses the future research directions for the efficient design and management of HRC systems. The paper ends with a summary of the main conclusions.

2. Previous review papers and our review direction

This section presents existing review papers related to our work. More precisely, we give the list of reviews, state of the arts, and surveys on the topics of HRC and DRC systems. To highlight the contribution of our work, we briefly mention the topic covered in each paper in Tables 1 and 2.

Table 1 reports the existing surveys on HRC systems. This topic is popular since seven reviews appeared in the last five years. In fact, HRC systems lead to a wide range of research challenges (human-robot communication, development of cognitive systems), but only Tsarouchi et al., (2016) consider task planning and scheduling. However, (Tsarouchi et al., 2016) is dedicated to mechanical engineering and robotics audience, since the authors give a robotic perspective on planning in HRC systems since they focus on the interaction between the planning system and its environment, the software architecture to implement the planning system within cobots, and the robot programming methodology. Compared to their review, the present paper will benefit the operations management and control community since it aims to identify the main operations research and optimization issues associated with the rise of HRC systems.

Table 1. Previous surveys on HRC systems

Paper	Concept
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Stecke & Aronson (1985)	Models and solution approaches dedicated to human-machine systems.
Haque & Armstrong (2007)	Extension of (Stecke & Aronson, 1985), focusing on the human-machine interface models.
Bauer et al. (2008)	Design, applications and communication types between partners in HRC systems.
Goodrich & Schultz (2008)	Trends, areas, and challenging problems related to human-robot interactions.
Green et al. (2008)	Design of HRC systems, and the importance of Augmented Reality to improve HRC systems.
Chandrasekaran & Conrad (2015)	Applications of HRC systems in education, industry, entertainment, health, military.
Tsarouchi et al. (2016)	Human-robot task planning, scheduling, and coordination in manufacturing systems (robotic point of view).
Robla-Gómez et al. (2017)	Design of a safe HRC system in an intelligent manufacturing environment.
Wang et al. (2017)	Applications and classification of HRC assembly systems.
Lesota et al. (2017)	Various methods to improve safety in HRC systems.
Liu & Wang (2018)	Different technologies and algorithms for gesture recognition as an interface between humans and robots in HRC systems.
Villani et al. (2018)	Challenges and applications of HRC in manufacturing systems.
Ajoudani et al. (2018)	Intermediate interfaces, robots' interaction modalities, and stability in HRC systems.
El Zaatari et al. (2019)	Different types of communication between humans and robots in HRC systems.
Matheson et al. (2019)	Different types of interaction between humans and robots in HRC systems.

Table 2 presents the existing surveys on DRC systems. The most recent review is (Xu et al., 2011). The present work extends (Xu et al., 2011) with the main findings after 2011, but most importantly, our survey seeks to identify how the literature on DRC systems must be extended to cover the application of HRC systems.

Table 2. Previous surveys on DRC systems

Paper	Concept
Treleven (1989)	Characteristics of models and methodologies in (DRC) system with flexibility of cross-trained workers.
Hottenstein & Bowman (1998)	Simulation studies on (DRC) systems.
Xu et al. (2011)	Different methodologies for scheduling problems related to Dual Resource Constrained (DRC) systems.
Thürer (2018)	A systematic review of some operations research problems; such as worker assignment and production planning problems; in DRC systems.
Dhiflaoui et al. (2018)	A classification of job shop and flexible job shop scheduling problems in a DRC environment.

The analysis of existing review papers shows a gap in the literature. Despite the growing amount of review papers and classifications related to the technologies and interfaces in HRC systems, there exist no vision of the operations management issues in HRC systems. On the other hand, the surveys on operations management problems in DRC systems (such as scheduling, workforce assignment, and production planning problems) do not consider the different interaction modes of the cobots. Consequently, the present paper starts with a review of existing works in DRC systems

(a well-known topic from the operations management community) before to provide a survey of the HRC literature. More precisely, this paper first presents the main issues related to hybrid automated/manual production, namely: resource skills, safety and ergonomics, and flexibility. Then, a survey of the literature on DRC and HRC systems is provided. Finally, we discuss the possible future research directions in terms of operations management problems. This classification is shown in Figure 1.

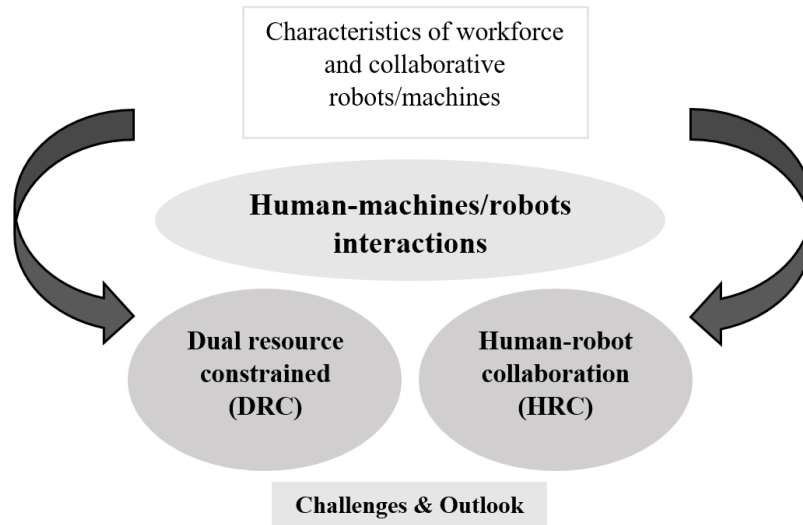


Fig. 1. Main focuses of the current survey

3. Characteristics of workforce and machine/robot

This section presents the main elements to consider when managing a manufacturing system with humans and robots. First, an efficient system must carefully manage and combine the skills of both humans and robots. Second, the introduction of cobots can enhance the ergonomics of the systems. For instance, the cobot can perform or assist the workers to perform painful or dangerous tasks. However, in novel HRC systems, robots and workers operate in a fenceless environment, and this introduces some safety concerns for the workers. Finally, the cobots are fast to set up, easy to program, and mobile. These characteristics give cobots an advantage in flexible assembly lines since they can easily be re-deployed among stations. Consequently, a well-designed HRC system must lead to a high level of flexibility and reconfigurability. This section successively describes these three features (resource skills, ergonomics, and resource flexibility).

3.1 Resource skills

Industrial components (e.g., workforce, machines, and robots) possess different skills, and thus they can perform different tasks. This led to the classification of workforce assignment problems in two categories: homogeneous workers or heterogeneous workers. In a manufacturing system with *homogeneous* workers, all resources are the same with respect to their skills, physical abilities, labor costs, or any other characteristics. Consequently, each worker can perform all the tasks. On the contrary, in a system with a *heterogeneous* workforce, workers have different skills or skill levels, which creates resource-task assignment restrictions. Typically, in workforce planning problems with heterogeneous resources, each operator is associated with a skill set (Wittrock, 1992), and an assignment is feasible if the assigned task is covered by the operator's skill. These skill-sets may be identical, non-identical or in some cases overlapping from one resource to another.

Homogeneity has the same definition and application for machines and robots (Ikemoto et al., 2005; Kim & Lee, 1998; Jones et al., 2006). However, the problems with heterogeneous resources become more complex when workstations include humans and machines/robots at the same time since the processing of a task requires to join the skills of robots and operators. This setting is typically encountered in DRC problems with workforce heterogeneity (Malhotra & Kher, 1994; Felan & Fry, 2001; Bokhorst, et al., 2004; Thürer et al., 2019). Note that DRC problems are not limited to heterogeneous workforce, and homogeneous workforce is also considered (Frye, 1974; Malhotra et al., 1993).

In practice, workforce skills change with time, because of learning and forgetting effects. In addition, companies can control the skill-sets of the workforce through cross-training strategies. Workforce homogeneity or heterogeneity hardly depends on the task proficiencies. Note that cross-training, learning and forgetting effects are defined for both heterogeneous and homogeneous workforce. Learning and forgetting effects are the same for all workers of a homogeneous workforce, while for a heterogeneous workforce they can be different from a worker to another. There are several studies concerning the impact of cross-training strategies on both heterogeneous and homogeneous workforce (Kher & Malhotra, 1994; Shafer et al., 2001; Süer & Tummaluri, 2008; Kim & Nembhard, 2010).

Heterogeneous workforce planning can be viewed as a selection of equipment alternatives for workstations, where different equipments result in different productivity and cost. In other words, the equipment selection problem is equivalent to a worker selection problem, where workers with different qualifications in terms of production speed or quality are available and are paid according to their qualifications (Akagi et al., 1983; Wilson, 1986). Assembly line balancing models with equipment alternatives are addressed by (Bukchin & Tzur, 2000; Bukchin & Rubinovitz, 2003), see also the survey by Battaïa and Dolgui (2013).

3.2 Ergonomics and safety

Ergonomics concerns the interaction between humans and their work environment. It seeks to improve the work conditions, improve workers' well-being, decrease human errors, and improve the system's performance (Bridger, 2008). A low ergonomic level leads to injuries, absenteeism, fatigue and other negative effects that reduce the system's productivity. Human-robot manufacturing systems require a special attention to ergonomics (Marvel et al., 2014). For instance, when a human and a robot perform a task jointly, some injuries may happen due to collision between the human and the robot, or because of the force and pressure the robot transfers to the object (Marvel et al., 2014). Moreover, the improvement of ergonomics is different in a fully manual system and in a human-robot system because some painful tasks can be assigned to the robots in HRC systems. In manufacturing systems, there exist multiple metrics to evaluate ergonomics, such as collisions and injuries (Wang et al., 2013; Schmidt & Wang, 2014), pressure and loading of the workforce (Marvel et al., 2014; Peternel et al., 2017; Wansoo et al., 2019), workforce fatigue and errors (Peternel et al., 2018), and workforce stress (Pearce et al., 2018).

Classical measures to improve the ergonomics include the design of user interfaces to increase the compatibility between tasks and workers; the design of a safe and appropriate work environment; the affectation of tasks based on the resource compatibility and resource characteristics; and the improvement of the work condition in terms of psychological and social needs (Bridger, 2008). In addition, cobots are often introduced on the shop floor for ergonomic reasons since they reduce the physical and cognitive loading of employees.

3.3 Resource flexibility

Flexibility is defined as the capacity of a manufacturing system to change into a variety of states and functions in order to respond to changing requirements with a little penalty of time, cost, or performance (De Toni & Tonchia, 1998). On the other hand, reconfigurability is the capability to quickly provide a customized flexibility via equipment modularity when needed to meet market requirements. This kind of customized flexibility, in comparison with general flexibility, is specifically addressed for the production of a part family (Koren, et al., 1999).

Figure 2 shows the evolutions of the automation level in manufacturing systems and their impact on the characteristics of the system (ElMaraghy, 2005). Manufacturing systems evolved from mass manufacturing systems to flexible manufacturing systems (FMSs), and more recently, to reconfigurable manufacturing systems (RMSs) (Koren, et al., 1999). Concurrently, technological progress modified manufacturing systems from fully manual toward almost fully and hard automated, then to flexible, and subsequently to hybrid automated systems. The implementation of fully automated systems converted manual systems into hard automated systems with automated transfer lines. Later, the need for flexibility led to flexible automated systems (e.g., CNC machines in a flexible manufacturing system (FMS)). Finally, the need for reconfigurability fosters the integration of humans and robots in a hybrid automated manufacturing system.

The design of flexible or reconfigurable automated systems is a hard task. The development of computer numerical control (CNC) machines helped to tackle this challenge with flexible automation into the manufacturing systems (e.g. FMSs). The recent advances in robotics led to the creation of machines able to process a large variety of tasks, and these new robots will further extend the flexibility of automated manufacturing systems. Nevertheless, human workers remain the most flexible component of a manufacturing system. In the mass customization area, manufacturing systems must rely on the human to attain the desired flexibility level (ElMaraghy, 2005).

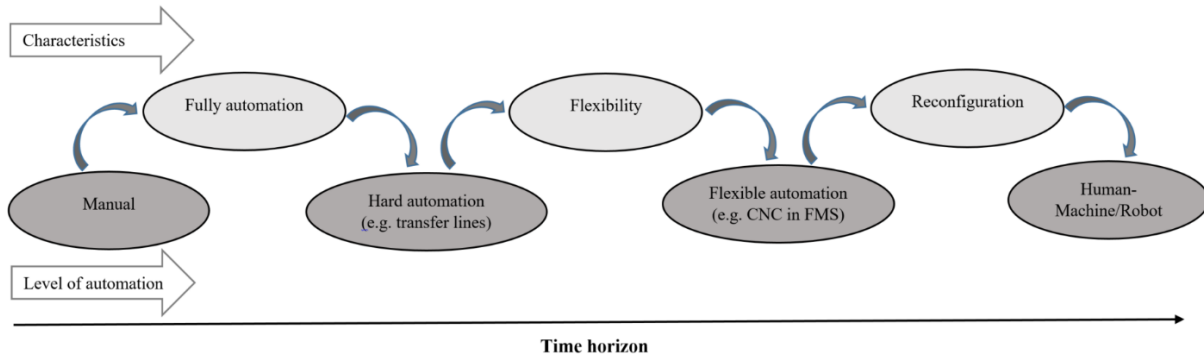


Fig 2. Relationship between human/automated resources and the evolution of manufacturing system

The adoption of robots in manufacturing systems creates new operations management challenges. For instance, robots and workers have different capacities, and this affects the allocation of the resources in the system and the (re-)assignment of tasks to the workforce/robots. Besides, ergonomics and risk assessments are of critical importance in HRC manufacturing systems. Consequently, the model to design, plan, and schedule the operations must account for ergonomics and safety constraints. Finally, hybrid human-robot systems can be very flexible and reconfigurable if designed appropriately. The next section presents how the existing literature accounts for these characteristics.

4. Human and machine/robot interactions

In this section, two main hybrid manufacturing systems are discussed: dual resource constrained (DRC) and human-robot collaboration (HRC). The description of a DRC system is very close to a hybrid system, requiring both humans and machines to perform manufacturing tasks. A DRC system corresponds to a manufacturing system, in which the number of machines exceeds the number of workers, and collaboration between workers and machines is an essential condition needed to complete the tasks. DRC system is a well-known topic in operations management literature. HRC systems depict a production environment, which has different types of interaction between humans and robots.

4.1 Dual resource constrained (DRC) system

DRC scheduling problems occur when the production process is constrained by capacities and limitations of both workers and machines. This problem consists in assignment of workers to

machines and sequencing tasks on the machines. The resulting schedule accounts for the skill-levels, characteristics, availability, and capacity of the workforce and machines.

DRC scheduling problem can be formally described as follows (Gong et al., 2018). A shop contains m machines (M_1, M_2, \dots, M_m) and w workers (W_1, W_2, \dots, W_w). A set of j jobs (J_1, J_2, \dots, J_j) has the same or different subset of task sequences t (T_1, T_2, \dots, T_t). These jobs have either the same or different precedence relationships between tasks. The tasks must be assigned to the appropriate machines, while workers must be assigned to the machines to perform the tasks. The main constraints in this problem concern the capacity and availability of resources: machines and workers.

A crucial characteristic of DRC problems is the heterogeneity or homogeneity of the resources (especially workers). In addition, the skill-level of workforce and machines impacts the flexibility of the system, since skilled workers can move to multiple stations to perform different operations. Workers' cross-training enhances the flexibility of a DRC system. For instance, Park (1991) and Park & Bobrowski (1989) justified that flexibility of a DRC system can be improved by using both heterogeneous and homogeneous workforce. Kher & Fry (2001) considered different levels of flexibility for workforce (from no flexibility to fully flexibility). They showed that workforce flexibility improves the delivery performance of a DRC system for both vital and normal priority customers. Finally, note that learning and forgetting effects impact the flexibility of the system (Kher, 2000a).

Before year 2000, various issues on dual resource-constrained (DRC) systems have been studied, such as resource flexibility in job shops (Bobrowski & Park, 1993; Fry et al., 1995), workforce flexibility and learning effect (Malhotra et al., 1993), workforce flexibility in cellular manufacturing systems (CMS) (Morris & Tersine, 1994), and workforce assignment in job shop scheduling problems (Liao & Lin, 1998; ElMaraghy et al., 1999). These publications were already analyzed in the survey (Xu et al., 2011). In Table 3, only the papers on DRC related problems published after 2000 are listed. These studies are sorted based on their objectives, such as performance analysis, minimization of the workforce idleness, tardiness, makespan, and production cost. For each paper, Table 3 indicates the considered production environment (job shop, open shop, etc), characteristics of the problem (workforce heterogeneity, learning/forgetting, flexibility, and performance parameters), objective and solution approach.

Table 3. Studies on dual resource constrained (DRC) systems (after 2000)

Paper	Problem	Characteristics, parameters & data	Objective	Methodology
Suresh & Gaalman (2000) ; Jensen (2000)	Evaluation of the impact of workforce flexibility	Homogeneity of resources, setup, lot sizes, level of cross-training, tardiness	Performance analysis	Simulation
Kher (2000a,b)	Evaluation of the impact of workforce assignment and flexibility	Homogeneity of resources, cross-training workforce, learning and forgetting effect, inventory level, customer service level	Performance analysis	Simulation
Kher & Fry (2001)	Evaluation of the impact of workforce flexibility and assignment	Homogeneity of resources, flexibility of workforce, customer delivery service	Performance analysis	Simulation
Bokhorst, et al. (2004)	Evaluation of the impact of workforce assignment rules	Heterogeneity, cross-training workforce	Performance analysis	Simulation
Suresh & Slomp (2005)	Scheduling problem in CMS	Homogeneity, cross-training workforce, setup, lot sizes, level of cross-training	Performance analysis	Simulation
Yue et al. (2008)	Parallel job shop scheduling problem	Heterogeneity, cross-training workforce, learning and forgetting effect, cross-training level of workforce	Performance analysis	Simulation
Uzun Araz & Salum (2010)	Scheduling problem	Heterogeneity, mean flow time	Performance analysis	Simulation, artificial neural networks and fuzzy inference system
Thürer et al. (2019)	Workforce assignment problem in job shop	Heterogeneity, cross-training workforce	Minimize the workforce idleness	Simulation
Felan & Fry (2001)	Evaluation of the impact of workforce flexibility	Heterogeneity, cross-training workforce, learning effect	Minimize the tardiness and production cost	Simulation
Kannan & Jensen (2004)	Workforce assignment in CMS	Homogeneity, learning effect	Minimize the mean flow time and tardiness	Simulation
Paksi & Ma'ruf (2016)	Job shop scheduling problem	Heterogeneity	Minimize the tardiness	Genetic algorithm
Renna et al. (2020)	Flexible job shop scheduling and workforce assignment problem	Homogeneity	Minimize tardiness, workload on machines, work in process.	Game theory and simulation
Yang et al. (2019)	Flexible job shop scheduling problem	Heterogeneity	Minimize lateness, makespan, and maximum workload deviation on machines	Heuristic algorithm

Andrade-Pineda et al. (2019)	Flexible job shop scheduling problem	Homogeneity	Minimize the makespan and tardiness	Heuristic algorithm
Lei & Guo (2015)	Flexible job shop scheduling problem	Heterogeneity	Minimize the makespan interval and carbon footprint	Dynamic neighbourhood search, variable neighbourhood search, genetic algorithm
Tao et al. (2007)	Job shop scheduling problem	Heterogeneity	Minimize the makespan	Petri nets, genetic algorithm, simulated annealing
Lei & Guo (2014)	Flexible job shop scheduling problem	Homogeneity	Minimize the makespan	Variable neighbourhood search, genetic algorithm
Lei & Guo (2015)	Flexible job shop scheduling problem	Heterogeneity	Minimize the makespan interval and carbon footprint	Dynamic neighbourhood search, variable neighbourhood search, genetic algorithm
Faccio et al. (2015)	Job shop scheduling problem	Homogeneity	Minimize the makespan	Simulated annealing
Liu & Wang (2016)	Scheduling problem in CMS	Heterogeneity	Minimize the makespan	Hybrid simulated annealing
Menci et al. (2016)	Job shop scheduling problem	Heterogeneity	Minimize the makespan	Genetic algorithm
Zhang et al. (2017)	Flexible job shop scheduling problem	Homogeneity, resource flexibility	Minimize the makespan	Particle swarm optimization, simulated annealing
Wu et al. (2018)	Flexible job shop scheduling problem	Homogeneity, learning effect	Minimize the makespan	Hybrid genetic algorithm and variable neighborhood search
Xixing & Yi (2018)	Flexible job shop scheduling problem	Homogeneity	Minimize the makespan, total equipment loading, and production cost	Multi-objective evolutionary algorithm based on decomposition
Li et al. (2016)	Job shop scheduling problem	Heterogeneity	Minimize the makespan, the resource operation and inventory costs	Genetic algorithm
Zhong et al. (2017)	Resource planning and scheduling in flexible job shop system	Homogeneity	Minimize the completion time, number of workers, production cost, equipment loading	Non-Dominated Sorting Genetic Algorithm II
Satoglu & Suresh (2009)	Design of DRC in CMS	Heterogeneity, cross-training workforce	Minimize the machine purchasing costs, cross-training	Integer goal programming

			costs, hiring costs, firing cost	
Fan et al. (2010)	Cell formation problem in CMS	Heterogeneity	Total intercellular part and workforce movement	Genetic algorithm
Li et al. (2011)	Job shop scheduling problem	Heterogeneity	Minimize the production cost	Hybrid ant colony optimization and simulated annealing
Hamed et al. (2012)	Cell formation problem in CMS	Heterogeneity, cross-training workforce	Twelve goals; such as shortage, resource cost, etc	Linear programming, multi-objective tabu search

Until 2011, many studies on DRC problems were relied on simulations (Xu et al., 2011). Then, as shown in Table 3, a large number of publications were related to the use of metaheuristic approaches. Most of them have studied scheduling issues. The table show that multiple objectives were considered, and not only the makespan. Nevertheless, other crucial discrete optimization problems such as combinatorial design, task/resource assigning and planning, assembly line balancing, etc. were not enough investigated, and could be considered for future research. A few researchers have also studied the human factors and ergonomics in DRC systems (Jaber & Neumann, 2010; Sammarco et al., 2014; Botti et al., 2017).

4.2 Human-robot collaboration (HRC) system

A HRC system refers to a common workspace, where robots and workforce collaborate to jointly process a product (Simões et al., 2019). Such robots, able to collaborate with workers, are called cobots. HRC systems offer an alternative to fully manual workstations, and it results in workstations gathering the strengths of both humans and robots. Typically, manufacturers introduce cobots in their production system to improve the level of safety, ergonomics, quality, flexibility, and reconfigurability (Krüger et al., 2009; Krüger et al., 2011; Koppenborg et al., 2017; Elprama et al., 2017; Hoecherl et al., 2018; Simões et al., 2019).

Multiple companies already adopted HRC systems either completely or partially. For instance, cobots work around the workforce and take over dangerous tasks in the BMW production plant presented in (Michalos et al., 2018a). El Makrini et al. (2018) studied an HRC system in an Audi assembly plant, where cobots cooperate with workers and assist them when it is needed. Interestingly, in these large automobile companies, workers express a high willingness to work with the cobots (Elprama et al., 2016).

4.2.1 Collaboration

Table 4 presents possible communication modes between humans and cobots (Michalos et al., 2018a; Bauer et al., 2008; El Zaatari et al., 2019), whereas Table 5 presents different interaction modes (coexistence, synchronization, cooperation, and collaboration) (Matheson et al., 2019).

Table 4. Human-cobot communication modes

Communication mode	Description	Example
Direct physical interaction	Worker's body contact with a cobot or a job in process in order to perform a task	When a cobot lifts a heavy item, a worker positions the item in the appropriate position to perform an assembly task
Remote contactless interaction	Interfaces (e.g. voice, cameras, and gesture recognition software) are used to make contact between human and cobot	Using a voice command in order to move cobot's arms.
Teleoperation	Workers can directly drive a cobot using an interface	A worker can move a movable cobot with a joystick
Message exchange	The information is exchanged using digital signals transmitted through physical buttons	Using programming modules to operate cobots

Table 5. Different ways of interaction in human-cobot systems

Way of interaction		Description	Example
(Matheson et al., 2019)	(El Zaatari et al., 2019)		
Coexistence	Independent	Both a worker and a cobot are in the same place, but there is no interaction between them, and they perform two different tasks on two different items	An automated and a manual task are performed independently
Synchronized	Sequential	A worker and a cobot work in the same place, but not at the same time; two tasks are performed in sequence on the same item	An automated task is performed by a cobot, and then a worker can move or pack the items stored in the station
Cooperation	Simultaneous	A worker and a cobot work in the same place at the same time, but they perform two separate tasks; two different tasks on the common item at the same time	An automated and a manual task are performed in parallel
Collaboration	Supportive	A worker and a cobot perform a common task together; one hybrid task on the single item cooperatively	A hybrid task is performed by both a

			worker and a cobot at the same time
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The different ways of interaction between humans and cobots can be selected based on the task to be executed. Each way of interaction constrains operations management problems in its proper manner. Precisely, coexistence/independent interaction can be viewed as a two-sided assembly line constrained by different skill-sets of humans and cobots. Synchronized/Sequential interaction can be constrained by assigning and sequencing humans and robots on the line with respect to the precedence relationship between manual and automated tasks. Cooperation/Simultaneous and collaboration/supportive interactions refer to the concept of DRC systems. Since a task is performed simultaneously by a worker and a cobot, the risks of injury and process quality deterioration must be taken into account. Some specific technologies enhancing collaboration between humans and cobots, such as cameras, human-machine interfaces, and sensors, represent an interesting feature for future studies.

4.2.2 Resource skills

More generally, Figure 3 shows the strengths of humans and robots, and the collaboration between humans and robots, which creates workstations with a mixture of these advantages. Humans have learning and cognitive skills to enhance their ability for performing various tasks. Intelligence and creativeness makes them the most flexible resource in manufacturing systems. On the other hand, robots are able to perform a much higher volume of tasks manufacturing tasks thanks to their force, tirelessness, speed, accuracy, and repeatability. These features are the main advantages of humans and robots, whose combination leads to a higher level of productivity, ergonomics, safety, flexibility, and reconfigurability.

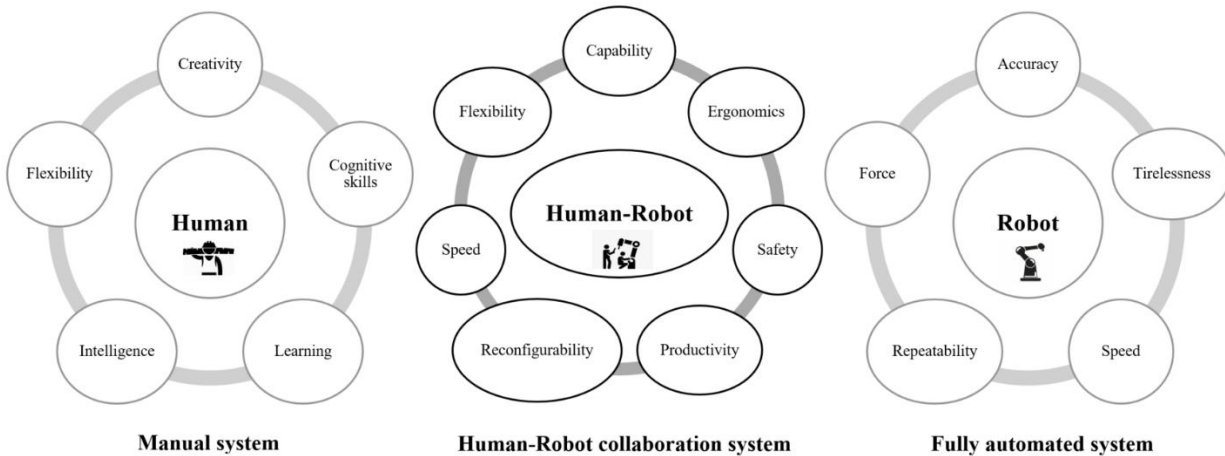


Fig. 3. Main characteristics of the three manufacturing systems: manual, fully automated, and human-robot (hybrid)

Several studies show the advantage of combining robots and humans in a workstation. Compared to a fully manual station, HRC stations lead to a better safety, productivity, and quality in flexible assembly lines (Rahman & Wang, 2015, 2018), and in cellular manufacturing systems (Tan et al., 2009; Kato et al., 2010; Hu et al., 2013). For instance, Fast-Berglund, et al. (2016) showed a significant positive impact of cobots in assembly lines on the cost, physical space, and time, compared to the manual system. Fager et al. (2019) compared a fully manual mixed-model assembly line with cobot supported system and revealed a lesser cycle time variation for the latter.

4.2.3 Ergonomics

Workforce ergonomics is the main concern in the design of an HRC system (Botti et al., 2017). Usually, manufacturers seek to assign tiresome or dangerous tasks (e.g., tasks requiring twisting or lateral forces) to robots (Argote et al., 1983; Akella et al., 1999). The existing approaches to improve ergonomics seek to reduce the muscle fatigue (Peternel et al., 2018), decrease the workforce overloading (Kim et al., 2017; Peternel et al., 2017; Wansoo et al., 2019), ensure comfortable workforce posture (Busch et al., 2017, 2018), minimize the workers' physical strain (Pearce et al., 2018).

There exist offline (Marvel et al., 2014) and online (Magrini et al., 2020) methods to improve the ergonomics of a HRC system. Online optimization methods mean that every parameter is recorded and monitored during the tasks' execution, otherwise they are considered as offline. There are only

a few studies using offline optimization methods, which are mostly used to assess parameters as a part of online methods (Marvel et al., 2014). The online approaches monitor the tasks execution and suggest improvements. For instance, Peternel et al. (2018) proposed an online optimization method, using a machine learning technique, which estimated muscle efforts in different conditions and searched for a task assignment with the smallest level of muscle fatigue. Kim et al. (2017) gave another online approach to minimize workforce overloading when a robot accompanies the processing of tasks. The optimization process is performed to adjust the robot trajectories facilitating the work of a human operator. The authors consider several elements to discover the optimal workforce configuration, such as worker's stability, shared workspaces, and task constraints. Later, Kim et al. (2018) presented a vibrotactile feedback interface, which estimates the force of overloading on the worker's body, informs the equipped worker in case of overloading and guides him/her to a better loading condition.

4.2.4 Safety

Contrarily to classical production environments, HRC systems require robots to operate in a fenceless environment, and this creates safety concerns for the workers. Albeit the near-passivity of cobots increases the level of safety compared to classical robots (Akella et al., 1999), it does not guarantee the complete safety. There is still possibility of various dangers and injuries (Marvel et al., 2014). To prevent injuries, there exist tools able to detect dangerous situations and send a warning to workers. Several danger prediction technics exist, such as monitoring and detecting collisions (Wang et al., 2013; Schmidt & Wang, 2014), human motions in an assembly line (Liu & Wang, 2017; Coupeté et al., 2019; Unhelkar et al., 2018; Marin et al., 2018; Gopinathan et al., 2018), workers' presence and intentions (Koch et al., 2017).

Safety issues can also be improved with offline approaches. For instance, Marvel et al. (2014) performed an offline risk assessment of each task in the primary design steps. This risk assessment accounts for tooling (functionality and features of the tools), task's execution time, contact duration, required forces and pressures.

4.2.5 Productivity

The productivity of a manufacturing system is related to several measures such as the throughput (that is the number of units produced per period), the resources consumption for a given output,

the number of defective items produced, etc. Researchers confirm the hypothesis that power, velocity, predictability, repeatability, and precision of robots in combination with human intelligence, creativeness and skills increase the productivity of assembly lines (Michalos et al., 2014; Ore et al., 2015; Akella et al., 1999; Sadik & Urban, 2017b; Kinugawa et al., 2016). As cobots handle some tasks, adding a cobot to a fully manual line reduces the takt time, and thus increases the throughput. In addition, robots usually perform tasks faster than humans, while producing less defective items.

Fager et al. (2019) proposed a mathematical modelling approach to compare the cycle time of a manual and cobot-supported material supply for a mixed-model assembly line (MMAL). The value of cycle time in case of cobot-supported supply proved to be more stable, which helps companies to better plan the workload and decrease the inventory level. HRC systems also reduce the number of defective items related to human errors, thanks to the precision and repeatability of cobots (Morioka & Sakakibara, 2010).

Several studies show that HRC systems improve performance of various production environments, such as flexible manufacturing system (Rahman & Wang, 2015, 2018), reconfigurable manufacturing system (Sadik & Urban, 2017b), agile manufacturing system (Sadik & Urban, 2017a), and simple assembly line (Paula 1997; Tsarouchi et al., 2017).

Most of these studies have not proposed mathematical programming models related to a specific type of operations management problems. They proposed either an algorithmic or simulation approach to demonstrate productivity improvement in HRC environment. For example, Ore et al. (2015) developed a simulation software to provide outputs concerning processing times and biomechanical load on workforce in an assembly line. Rahman et al. (2015) proposed some algorithms to evaluate the performance of a HRC with affection-based motion control of the robot.

4.2.6 Operations management in HRC systems

Operations management seeks to improve the productivity and responsiveness of a company. Since cobots used in HRC systems are expensive, their number should be as small as possible, and they must be used at maximum or near maximum capacity. Ghosh & Helander (1986) already discussed task allocation problems in such systems. They proposed a systematic approach using analysis of human-robot interaction to find a good task allocation to humans and cobots in an HRC system.

The introduced approach includes an inventory of common manual and automated tasks, resources needed to execute these tasks, design of products to be produced, and analysis of different tasks allocation to humans and cobots based on their capability. Some researchers have only recently begun to study HRC systems in the context of operations management (Darvish et al., 2018; Bogner et al., 2018; Michalos et al., 2018b). The related topics include system's design (Chen et al., 2011; Michalos et al., 2018b), line balancing (Weckenborg et al., 2019), scheduling (Bogner et al., 2018; Casalino et al., 2019), resource allocation (Takata & Hirano, 2011), and task planning and assignment (Chen et al., 2013; Hu & Chen, 2017; Darvish et al., 2018).

There exist methods for the design of HRC systems in cellular manufacturing systems (Tan et al., 2009, 2010), flexible assembly lines (Rahman & Wang, 2015, 2018), and cellular manufacturing systems (Kato et al., 2010; Hu et al., 2013). The typical methods to tackle operations management problems in HRC systems include linear/non-linear programming (Hu & Chen, 2017; Bogner et al., 2018), (mixed-)integer programming (Weckenborg et al., 2019), heuristics (Bogner et al., 2018) metaheuristics algorithms (Chen et al., 2013; Weckenborg et al., 2019), multi-criteria evaluation approach (Michalos et al., 2018b), and simulation models (Darvish et al., 2018; Bänziger et al., 2018).

The HRC production environment creates specific constraints for an operations management problem. For instance, the presence of both humans and cobots in the line affects the sequencing of tasks and products (Bogner et al., 2018), and the tasks assignment must account for processing times, skills, physical and mental conditions, geometrical dimensions. HRC systems often require online task assignments to humans and cobots based on their current states (Darvish et al., 2018) and characteristics (Chen et al., 2013). Precisely, Darvish et al. (2018) proposed an online task planning technique using simulation to predict robot's behaviors, then assign tasks dynamically. This research aimed to minimize the total cooperation cost between humans and robots. Mainly, the objective functions correspond to the time and cost; such as makespan (Bogner et al., 2018), cycle time (Casalino et al., 2019; Weckenborg et al., 2019), and production cost (Takata & Hirano, 2011; Chen et al., 2013; Hu & Chen, 2017).

4.2.7 Flexibility and reconfigurability

The flexibility of a manufacturing system depends on its resources. Humans and cobots have complementary skills. Humans represent the most flexible resource thanks to their learning, training, and cognitive skills. Cobots are adapted to repetitive work, they are more precise and can handle heavy parts without fatigue. Consequently, the human-robot interaction increases the flexibility of manufacturing systems. For instance, Rahman & Wang (2015, 2018) showed the improvement of productivity and quality in automotive, aerospace, and electronic industries using flexible assembly lines with cobots.

The HRC system is also a potent concept able to enhance the reconfigurability of manufacturing systems (Chryssolouris, 2013). Hybrid reconfigurable systems design have been studied in the context of virtual prototyping and digital manufacturing (Andrisano et al., 2012; Pellicciari et al., 2012). With hybrid stations instead of fully automated or manual stations, reconfigurations of a production line are possible through movements of all or some of the workers and mobile robots (Wansoo et al., 2019). These movements adjust human and robot skills and capacities to the required production task. Consequently, manufacturers can reconfigure a hybrid line whenever needed. For instance, to face production picks, the cobots can assist humans, while workers may help cobots to perform a certain task (Calitz et al., 2017). Sadik & Urban (2017c) introduce HRC systems as a strategy for reconfigurability, which is a fresh and interesting point of view for future research. Sadik & Urban (2017b) proposed an approach to solve a flow shop scheduling problem in a reconfigurable manufacturing system with one robot, one worker, and a buffer between the robot and the worker. To dynamically assign the resources and tasks, the authors extended the Johnson scheduling algorithm. Their approach uses historical data to predict the processing time of a job and assigns operations based on these predictions. Kim et al., (2017) propose an approach to configure the workforce, which accounts for the human stability, shared workspaces, and task constraints. Kim et al. (2019) developed an HRC framework for production/assembly systems, which is designed to improve their reconfigurability. In this framework, the cobot simultaneously adapts to user states in the workspace (e.g. pose, overloading torques, manipulating hand, positional variations) and task conditions. Table 6 reports the existing literature on HRC systems in manufacturing systems for each specific issue of HRC (e.g., ergonomics and safety).

Table 6. List of papers related to each type of HRC system challenges

Objective	Papers
Ergonomics & Safety	Argote et al., (1983), Akella et al. (1999), Tan et al. (2009), Tan et al. (2010), Kato et al. (2010), Hu et al. (2013), Wang et al. (2013), Schmidt & Wang (2014), Michalos et al. (2014), Lenz & Knoll (2014), Marvel et al. (2014); Ore et al. (2015); Rahman & Wang (2015), Elprama et al. (2016), Pini et al. (2016), Bobka et al. (2016), Botti et al. (2017), Kim et al. (2017), Liu & Wang (2017), Busch et al. (2017), Peternel et al. (2017), Koch et al. (2017), Rahman & Wang (2018), Busch et al. (2018), Coupeté et al. (2019), Unhelkar et al. (2018), Marin et al. (2018), Gopinathan et al. (2018), Peternel et al. (2018), Kim et al. (2018), Van de Perre et al. (2018), Michalos et al. (2018b); Maurice et al. (2019), Wansoo et al. (2019), Nikolakis et al. (2019); El Makrini et al. (2019), Magrini et al. (2020)
Productivity	Argote et al., (1983), Akella et al., (1999), Lien & Rasch (2001) Productive Tan et al., (2010), Kato et al., (2010), Morioka & Sakakibara (2010), Weidner et al., (2013), Hu et al., (2013), Michalos et al., (2014), Rahman & Wang (2015), Kinugawa et al., (2016), Sadik & Urban (2017b), El Makrini et al., (2018), Peternel et al., (2018), Rahman & Wang (2018), Coupeté et al., (2019), Unhelkar et al., (2018), Salmi et al., (2018), Michalos et al., (2018b), Casalino et al., (2019)
Completion time	Akella et al., (1999), Fast-Berglund et al., (2016), Pearce et al., (2018), Bogner et al., (2018), Michalos et al., (2018b), Fager et al., (2019)
Flexibility	Lien & Rasch (2001), Surdilovic et al., (2010), Lenz & Knoll (2014), Ore et al., (2015), Rahman & Wang (2015), Sadik & Urban (2017b), Makris et al., (2017), Rahman & Wang (2018), Salmi et al., (2018), Bänziger et al., (2018), Wansoo et al., (2019), Nikolakis et al., (2019)
Reconfigurability	Andrisano et al., (2012), Pellicciari et al., (2012), Chryssolouris, (2013), Sadik & Urban (2017b), Sadik & Urban (2017c), Kim et al., (2017), Kim et al., (2018), Maurice et al., (2019), Kim et al., (2019)

This section is a tentative of cross fertilization of the concepts of dual resource constrained and human-robot collaborative systems. It presents a literature review of DRC systems' studies in the field of operations management. It also provides a survey on related features and problems in HRC systems. The studies on DRC systems are classified using such characteristics as resource heterogeneity/homogeneity, learning and forgetting, resource flexibility, etc. The survey on HRC systems is based on classification of studies using the following challenges: collaboration, resource skills, ergonomics, safety, productivity, relation to operations management, flexibility and reconfigurability.

5. Discussions and Outlook

Our survey shows a growing amount of research on HRC systems in the last few years. This interest is related to the large benefits of HRC systems for manufacturers, such as ergonomics, safety, productivity, and flexibility. Different aspects of HRC systems draw particular attention of research communities: robotics, artificial intelligence, communication, software architecture. At the same time, operations management literature on HRC systems remains scarce and the scope of studied issues is small. For instance, most studies on scheduling for HRC systems seek to minimize the makespan, whereas other criteria are rarely considered. Three research directions in operations management regarding HRC systems are identified.

The first research direction concerns the extension of DRC problems to account for different cobot interaction modes. This extension includes the definition of manual, automated, and hybrid tasks. Humans perform manual tasks, cobots perform automated tasks, and hybrid tasks require both human and cobot at the same time. These different task types create complex precedence constraints. The inclusion of HRC features into a DRC scheduling problem would lead to the creation of hybrid workstations with the required skill sets. As exposed in Section 4, HRC systems are composed of stations with a wide range of skills, and the design of the right station requires the use of advanced optimization approaches. These approaches can be designed based on the DRC literature.

The second research avenue suggests including ergonomic constraints in DRC problems. As ergonomics improvement is a major motivation for the introduction of cobots, there is a considerable literature on ergonomics for HRC systems. On the contrary, very few studies exist on ergonomics in DRC problems (Jaber & Neumann 2010; Sammarco et al. 2014; Botti et al. 2017). However, a careful assignment of tasks to workstations can improve the ergonomics in such systems. With regard to the first research direction, ergonomics corresponds to manual and hybrid stations, mostly. This could be seen as a constraint, especially, when the types of stations are decision variables. Moreover, methods, technologies and interfaces developed in the literature for HRC systems can be included in operations management methods.

The third research perspective calls for deeper study of reconfigurability issue of HRC systems. As exposed in Section 4, HRC systems are usually characterized by a high level of flexibility and

reconfigurability. However, it comes at a cost. The design of HRC systems with the right level of flexibility requires advanced optimization methods. As shown in Table 6, only few studies address the reconfigurability issues of HRC systems. Since robots are expensive, reconfigurability of the system may decrease the cost, because mobile robots and workers can move among stations instead of adding a new robot. Furthermore, variety of collaborative robots applications like picking and placing, screw driving, inspection, assembly tasks, in addition to their quick and easy set-up, and mobility (Weckenborg et al., 2019), makes their use in reconfigurable manufacturing systems very attractive. Thus, there is a need to develop design methods aiming to enhance the system's reconfigurability. Such methods can leverage on the assembly line balancing literature, and may include stochastic or robust optimization techniques to account for different product sequences, changes in customer demands, and other uncertainties.

In all these research directions, further studies might be done by defining new optimization functions and/or solution techniques. For example, a function for trading off between either the number of fully manual, automated, and hybrid stations or the number of resources (workforce and robots) in these stations. On the other hand, integrating technologies used in HRC systems with optimization methods creates certain challenges in terms of operation management techniques. The development of exact methods and/or heuristics should take into account the specificity of proposed technologies or features in HRC systems and may be inspired from (combined with) some techniques used in the control theory.

6. Conclusion

Performing a huge variety of the tasks in manufacturing systems require different types of resources. On the other hand, the reduction of product lifecycles, frequently changing demand and enhanced customization urge industrial companies to employ manufacturing systems with a high level of flexibility and reconfigurability. There exist a huge body of literature on flexibility, system reconfiguration and machine tools reconfiguration. The present paper focuses on the challenges of the interaction between humans and machines/collaborative robots in order to discover potential contributions of operations management methods aimed to improve hybrid systems.

The interaction between humans and machines/collaborative robots appears in two manufacturing system types: dual resource constrained system (workers use machines/robots) and human-robot

collaboration system (workers and robots collaborate). In the beginning, the main characteristics of human-machine/robot (hybrid) manufacturing systems such as heterogeneity, homogeneity, ergonomics and safety are given. Then, optimization models in terms of design, scheduling, resource planning and assignment in DRC systems are mentioned. The summary of studies on HRC systems, making emphasis on the related challenges are provided as well. Finally, a short discussion on the main points of the proposed survey and future research avenues are proposed.

According to our survey, reconfigurability is one of the interesting challenges of human-robot systems which has not been sufficiently taken into account in the literature. In addition to the reconfigurability, there are other challenges such as ergonomics, safety, time, flexibility, and productivity. Studying operations management problems taking into account these challenges is an interesting research perspective.

This paper also discovers several other interesting avenues for future research. The literature analysis revealed a small amount of operations management studies of HRC systems. Such challenges as reconfigurability, flexibility, time and cost reduction can be included in a comprehensive study of a HRC system. For instance, the trade-off between workforce and cobots is a hot research topic, in which the number of workforce and cobots must be balanced so that the total cost is minimized. On the other hand, all these features can be included in scheduling and resource planning of DRC systems, aimed to optimize other objectives in addition to the makespan such as reconfiguration cost, number of resources, workload smoothness for human operators etc.

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