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Abstract

This paper provides a literature review and an analysis of the studies related to workforce reconfiguration strategies as a part of workforce planning for various production environments. The survey demonstrates that these strategies play a crucial role in the resilience and flexibility of manufacturing systems since they help industrial companies to quickly adapt to frequent changes in demand both in terms of volume and product mix. Five strategies are considered: the use of *utility*, *temporary*, *walking*, *cross-trained* workers, and *bucket brigades*. They are analyzed in the context of mixed and multi-model manual assembly lines, dedicated, cellular, flexible, and reconfigurable manufacturing systems. The review shows that most of the researches on these reconfiguration strategies focus on multi- or mixed-model assembly lines. At the same time, few studies consider workers team reconfiguration in flexible and reconfigurable manufacturing systems. Finally, this paper reveals several promising research directions in workforce reconfiguration planning, namely, the use of both machine and workforce reconfigurations, consideration of the ergonomic aspects, the combination of multiple workforce reconfiguration strategies, the study of workforce reconfiguration in human-robot collaborative systems, and the use of new technologies in human-machine industrial environments.

Keywords: Workforce planning, Workforce assignment, Flexibility, Reconfiguration strategies, Manufacturing systems.

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1. Introduction

Industrial companies are facing an increasing uncertainty in the future market demand, abrupt changes in customer needs, large product variety, and short product life cycles. Thereby, manufacturing companies switch from mass production to mass customization and individualization to be more adjustable and adaptable in terms of production capacity and functionality. This allows companies to quickly react to the changes in market and technology, and launch new products frequently. The achievement of this goal depends on reconfigurability, adaptability and flexibility of manufacturing systems. A new concept of reconfigurable manufacturing system was proposed by Koren et al. (1999), where resources can be rearranged, and replaced quickly to change the production capacity. Human workers, as a type of manufacturing resources, can easily be moved, added, or removed, which increase the reconfiguration capability of production systems. Therefore, human workers can play an important role in reconfiguration of manufacturing systems, and it is crucial for companies to investigate how human workers can be seen as a factor of reconfigurability.

There is a growing amount of literature on the reconfiguration of machines and equipment. In contrast, workforce reconfiguration is not enough analyzed. Nevertheless, humans are flexible by nature, and they represent an opportunity to enhance the flexibility of manufacturing systems. Unlike machines, which cannot perform a task beyond the scope of their predestination (at least to a certain degree), human workers are creative and able to operate with different tools and equipment. Moreover, a worker can handle a non-standard situation, where an automated resource would fail. Thus, the workers increase the flexibility and adaptability of manufacturing systems.

This review explains which are possible strategies of workforce reconfiguration, how workforce reconfiguration and respective workforce planning help to make manufacturing systems more adaptive and resilient. The paper analyzes the five following workforce reconfiguration strategies: the use of *utility*, *temporary or walking workers*, *bucket brigades*, and *cross-trained workers*. Workforce planning problems are analyzed in various environments, such as dedicated manufacturing systems, mixed and multi-model manual assembly lines, cellular manufacturing systems, flexible manufacturing systems, and reconfigurable manufacturing systems.

Note that the present work is a follower of the conference paper (Dolgui, et al., 2019) where the literature on the workforce reconfiguration strategies is analyzed for mixed-model assembly lines. Here, the previous analysis is improved and extended to all types of manufacturing systems.

Studies on workforce planning in manufacturing systems were initiated by Akagi et al. (1983) and Shttjb (1984). Most of the following studies were done in the context of production scheduling problems. Several articles provided the states of the art on the existing advances in workforce planning research. The main topics of these review papers, sorted in the chronological order, are summarized in Table 1.

Table 1. Previous reviews on workforce reconfiguration strategies and workforce planning

Paper	Main topic
Baker (1976)	Workforce allocation in cyclical scheduling problems
Stecke & Aronson (1985)	Classification of models and methods related to the worker/machine interference problems
Treleven (1989)	Characteristics of dual resource constrained (DRC) systems with flexibility of cross-trained workers
Hottenstein & Bowman (1998)	Simulation studies on DRC systems with flexibility of cross-trained workers

Bratcu & Dolgui (2005)	Modelling approaches for bucket brigades
Bidanda et al. (2005)	Human-related problems in cellular manufacturing systems
Xu et al. (2011)	Applications of DRC systems
Quader (2013)	Applications and possible extensions of bucket brigades
Van Den Bergh et al. (2013)	Personnel scheduling problems
Ammar et al. (2013)	Workforce assignment issues in manufacturing systems
Qin et al. (2015)	Workforce flexibility methods in operations management problems
De Bruecker et al. (2015)	Workforce planning problems taking into account skills of the workers
Bouajaja & Dridi (2017)	Applications of workforce allocation problems

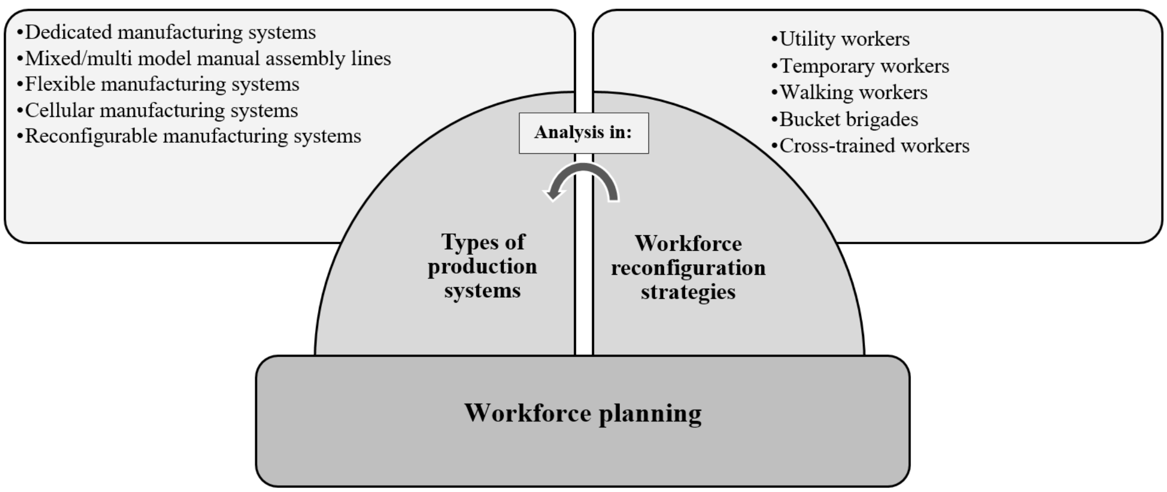

Figure 1. Framework of the paper.

This paper has two main objectives. First, unlike the previous reviews, this paper focuses on the impact of the workforce on the manufacturing system's reconfigurability, and second, revealing promising directions for future research in workforce planning in the context of reconfigurable manufacturing systems to increase their flexibility and efficiency. We mainly focus on the publications that appeared after 2005.

(Qin et al., 2015) is the closest study to the present state of the art. There, the authors describe workforce flexibility instruments in terms of working time, and strategies such as overtime, flexible workdays, annualized hours, working time accounts, floaters (utility workers), cross-training, teamwork and temporary workers irrespectively of the manufacturing configuration. In this paper, instead, we concentrate on the applications of these and other workforce reconfiguration strategies in various production environments.

The rest of this paper is organized as follows. Section 2 presents workforce planning in the manufacturing context and describes the main types of manufacturing systems. Section 3 reviews the literature related to the five workforce reconfigurability strategies that aim to enhance the adaptability and resilience of a manufacturing system. Section 4 provides the analysis of workforce reconfiguration strategies in different manufacturing systems and reveals promising research directions. Section 5 concludes the paper and future research directions.

2. Workforce planning and manufacturing systems

This section contains two subsections. The first presents workforce planning problems in the manufacturing context. The second describes the main existing types of manufacturing systems. The goal of this section is to have a better understanding of workforce planning, present its typical objectives and constraints, and describe different manufacturing systems workforce reconfiguration strategies.

2.1. Workforce planning in manufacturing

In the manufacturing context, workforce planning consists in determining the workforce capacity and assigning workers to the tasks. Workforce planning problems vary significantly depending on the nature of the items to produce, the type of the manufacturing system, the decisions to be made, and the optimization criteria.

Traditionally, a task is an indivisible amount of work to be performed on a product item. While mass production led to the design of production lines, which repetitively manufacture large series of the same item, mass customization drives towards multi-item manufacturing systems. When multiple items are produced, their sequences can be finite or infinite, repetitive or not, fully or partially specified.

In most studies, a single worker performs each task, and the task processing time is fixed. However, some studies consider that the processing time of a task depends on the quantity and characteristics of the assigned resources including workforce (Battaïa et al., 2015). These resource-dependent processing times can be deterministic, stochastic or uncertain due to, for example, the resources unavailability or production failures.

The shop floor's structure has a critical impact on workforce planning. In the classical flow shop setting, all tasks have the same routing from the first workstation to the last. However, in more complicated manufacturing systems, called job shops, tasks have different processing routes through the workstations. Some systems are constrained to process a single task per station, whereas others can perform several tasks sequentially or in parallel. In addition, industrial resources can induce various constraints on the task's allocation, such as space and time constraints. Finally, the timespan between two consecutive items moved from one station to the next one is a crucial characteristic of a manufacturing system. In a paced system, these moves follow the same time step, called cycle or takt time, for all stations. An essential characteristic of a paced production system is that the stations have no buffer to stock the incoming or outgoing products. In un-paced systems, buffers with a limited capacity are set between the stations.

Workforce planning is often combined with design, planning, and scheduling of a whole manufacturing system. In most cases, the physical layout and the composition of the processing and transporting equipment are decided before the workforce planning. However, several works have considered the case where the equipment is selected along with the workforce planning.

An optimization criterion is chosen depending on the need of the decision maker. The typical criteria related to the workforce are minimization of the labor costs, the number of workers in each production cycle, the ergonomic risks, the maximum workload, the workers' traveling distance, and maximization of the work variability and smoothness of the workload. Workforce planning aims to optimize efficiency criteria in different manufacturing systems: minimization of the cycle time, a function of the product completion times (usually in the case of the non-repetitive production), the equipment costs, the cost of the additional resources, maximization of the number of completed products per time unit. Sometimes, these criteria are replaced with the constraints limiting their values.

Note that, contrarily to the service industries, the workers in a manufacturing system follow regular shifts, and the workforce planning decisions usually do not account for the same work constraints and regulations.

2.2. Types of manufacturing systems

A manufacturing system can be characterized by the variability of manufactured products (Dolgui and Proth, 2010). In general, a system can be either dedicated to a single product type, in which case it is called a dedicated manufacturing system, or it can be designed to produce multiple product types. Besides, manufacturing systems vary with regard to their layout and the level of the flexibility. The literature on manufacturing systems that can handle various products can be categorized into publications on cellular, flexible, and reconfigurable manufacturing systems.

Dedicated manufacturing system (DMS). A DMS is a mass production system because it focusses on a high volume and low variety of products. Thereby, a DMS is characterized by relatively low costs and high throughput. Some examples are the transfer lines in automotive industry for machining cylinder blocks (Dolgui et al., 2009; Dolgui & Ihnatsenka, 2009). The fixed structure of a DMS does not allow to increase the product variety or the throughput. The only way to enhance the flexibility of a DMS is to use several DMSs in parallel, where each DMS handles a specific product type (e.g., Özcan, 2018). A DMS can be reconfigured for new products, but it is costly and time consuming (Makssoud et al., 2014; 2020).

Flexible manufacturing system (FMS). An FMS can be efficient in situations where new products are introduced frequently, and companies are shifting from low-mix high-volume to low-volume high-mix production, thus, require more flexibility. A high level of flexibility such that the new product requirements are adapted easily and quickly lead to the high initial investment for an FMS. An FMS is equipped with computer numerical control (CNC) machines connected by an automatic material handling system, where the numerical control is easily changed to process different tasks (Elmaraghy, 2005).

Reconfigurable manufacturing system (RMS). The concept of an RMS, introduced by (Koren, et al., 1999) is based on physical reconfiguration of equipment and other resources. Such system is able to adjust to different products of a product family. It is less costly than an FMS and offer a trade-off between the high throughput of a DMS and the universality of an FMS. An RMS is composed of the components such as workforce, machines, tools and material handling devices that can be easily added, removed or replaced. This system permits two levels of reconfiguration: (1) the system level, which changes connections between the components, (2) the components level, which changes the functionality of a component. Thanks to its ability to change the components, the RMS reduces setups and is able to change and adjust the production capacity and functionalities. (Bortolini, et al., 2018) give a comprehensive review on RMS research trends. They link reconfigurable manufacturing with Industry 4.0 technologies.

Note that FMS and RMS flexibilities are based on different concepts. An FMS is able to change its functionality without changing its physical configuration (except for tools), whereas an RMS is able to change its functionality by changing its physical configuration, modules and pieces of equipment. Both abilities are assumed to be cost effective.

Cellular manufacturing system (CMS). A CMS is an implementation of the Group Technology principles (Rajamani et al., 1990; Singh, 1993; Askin, 2013). A CMS comprises multiple cells, where each cell consists of a set of machines. Each cell is dedicated to the production of a given part family, where each family contains some parts with similar manufacturing requirements. Usually, the machine layout of the same cell is U-shaped to facilitate movements of the worker assigned to stations of the opposite sides of the cell.

While an FMS is highly flexible, but they have a limited capacity. A DMS is highly productive, but not flexible. Besides, a CMS can be considered as a compromise by using several dedicated cells instead of a sole DMS. However, their applicability is limited by the necessity of a rather predictable demand and a long lifecycle of the manufactured products (Benjaafar et al., 2002). An

FMS does not have such constraints, but it is also costly, less productive and more complex. An RMS is less costly than an FMS, and it provides a customized flexibility when compared to the general flexibility existing in an FMS (Elmaraghy, 2005). In other words, an RMS creates the capacity and functionality that is needed, when it is needed. Thereby, in terms of capacity and functionality, an RMS may be placed between a DMS and an FMS (Mehrabi et al., 2000).

Assembly line. A lot of researches are dedicated to assembly line balancing and configuration problems, see the review papers of (Rekiek et al., 2002; Boysen et al., 2008; Battaïa & Dolgui, 2013). Assembly lines represent a subclass of manufacturing systems, whose specificity consists in their flow shop nature and repetitive production. Assembly lines can be DMS, FMS, CMS or RMS. However, in terms of variety of products assembled on the line, assembly lines are commonly classified as dedicated, multi- or mixed-model lines (Bellgran & Säfsten, 2009). Often manual assembly lines are studied. On multi-model manual assembly lines products of the same type are manufactured in batches, allowing a high level of productivity to the expense of low reactivity in product type changes. On mixed-model assembly lines (MMAL), products of different types can be produced in an arbitrary order, which increases the level of flexibility compared to the multi-model assembly lines. Dedicated assembly lines have the same properties as a DMS. They are designed to assemble a single product type with high throughput.

3. Workforce reconfiguration strategies

This section presents a classification of workforce reconfiguration strategies. The proposed classification of workforce reconfiguration strategies is based on the concept of reconfiguration of manufacturing systems (Koren et al., 1999; Mehrabi et al., 2000). A manufacturing system is called reconfigurable if it can modify its specific process capabilities, and subsequently adjust the production capacity to quickly respond to changes in the market demand. In a RMS, it is easy to add, remove, or interchange the components. In other words, the reconfiguration creates the capacity and functionality, which is needed, when it is needed.

The following subsections are dedicated to five workforce reconfiguration strategies studied in the literature. For every research paper related to a workforce reconfiguration strategy, we mention the studied problem's criterion, the type of the manufacturing system and the solution approach. The aim of this section is to know for which manufacturing systems workforce reconfiguration strategies were already studied in literature and for which this is still an open issue.

3.1. Utility workers

A task which cannot be executed completely within the workstation's takt time is called a utility work. It may create problems such as line stoppages, increased stocks of unfinished goods between stations, insufficient productivity and, as a result, unsatisfied demand. Utility workers assist permanent workers to complete such tasks. The problems are in designing algorithms to assign utility workers to the tasks. Most of them are scheduling problems. An assignment of utility workers to utility work can be considered as a reconfiguration of a manufacturing system as the allocation of workforce resources may vary from one cycle to another or from one product sequence to another. Table 2 presents the classification of the major studies related to the concept of utility workers, in which MMAL stands for mixed-model manual assembly lines.

Table 2. Articles related to utility workers

Paper	Minimization of	Type of the system	Solution approach
Hyun et al. (1998)	Utility work and setup cost	Straight MMAL	Genetic algorithm
Celano et al. (2004)	Total stoppage time	U-shape MMAL	Genetic algorithm
Yoo et al. (2005)	Weighted sum of line stops and idle time	Straight MMAL	Simulated annealing and Tabu search

Boysen et al. (2011)	Number of overload situations	Straight MMAL	Exact and heuristics
Cevikcan & Durmusoglu (2011)	Total utility work and utility worker transfers	Straight MMAL	Meta-heuristics and local search
Li & Gao (2014)	Total regular and overtime labor costs	Straight MMAL	Heuristic and branch-and-bound-and-remember algorithm
Cortez & Costa (2015)	Utility work needed	Straight MMAL	Mixed integer programming and heuristics
Faccio et al. (2016)	Number of workers and work overload	Straight MMAL	Hierarchical approach
Aroui et al. (2017)	Total work overload	Straight MMAL	Mixed integer linear programming, simulated annealing, genetic algorithm

In these studies, a utility work mostly leads to line stoppages and increased workload. The studied problems are related to product sequencing (Yoo et al., 2005; Boysen et al., 2011; Cevikcan & Durmusoglu, 2011; Cortez & Costa, 2015), line balancing (Li & Gao, 2014) and both sequencing and balancing (Faccio et al., 2016). One can notice that all these studies consider an MMAL. This is expected since assembly lines rely mainly on manual operations. Besides, product differentiation is often done in the assembly step, and assembly lines must be reconfigurable. The solution methods, which are mostly composed of heuristics and meta-heuristics, reflect, on one hand, the complexity of the studied problems and, on the hand, emphasize the importance of solution times.

These studies present various ideas of how utility workers may assist regular workers: sequentially, in parallel or replacing a regular worker completely. In (Celano et al., 2004), if a task is not completed on time, a utility worker intervenes and assists the regular worker in completing the task. Boysen et al. (2011) study the case where utility workers do not help, but rather replace regular workers to finish the task. Regular workers, in turn, start processing the next part. Utility workers that operate in parallel or after regular workers in the same cycle are called "jolly workers" (Faccio et al., 2016). A kind of utility workers is considered in (Aroui et al., 2017), where some workers work besides regular workers to minimize the overloading. Line balancing with a demand changing from shift to shift, both in terms of volume and product mix, is considered in (Li & Gao, 2014). (Cortez & Costa, 2015) study a case, where heterogeneous regular workers are assisted by utility workers able to perform any task.

3.2. Temporary workers

Temporary workers can be used to help permanent workers. As the temporary workers are in most cases, less skillful than regular workers, they usually perform only a specific subset of tasks. Temporary workers improve the adaptability and, therefore, responsiveness of a manufacturing system in case of a high seasonal or uncertain demand (De Bruecker et al., 2015; Corominas et al., 2008; Francas et al., 2011). Table 3 summarizes the recent literature, which concentrates on the use of temporary workers and corresponding optimization problems.

Table 3. Studies concentrating on temporary workers

Paper	Criteria	Type of the system	Solution approach
Stratman et al. (2004)	Minimization of the total cost	Straight MMAL	Discrete event simulation
Techawiboonwong et al. (2006)	Minimization of workforce-related and inventory costs	Straight MMAL	Mixed integer programming
Corominas et al. (2008)	Minimization of the number of temporary workers	Straight single-model assembly line	Integer linear programming
Widyadana (2009)	Minimization of the number of temporary workers and the cycle time	U-shape single-model assembly line	Goal programming
Francas et al. (2011)	Maximization of the difference of expected second-stage profits and first-stage investment costs	Straight multi-model assembly line	Two-stage stochastic model
Manavizadeh et al. (2013)	Minimization of the total weighted idle time, workload imbalance, uneven distribution of idle time	U-shape MMAL	Simulated annealing
Buyukkaramikli et al. (2013)	Minimization of the flexible crew cost	Parallel single-model assembly line	Transient behaviour analysis of multi-server queues
Kim et al. (2018)	Minimization of the total operating and workers cost, the cycle time, and work overload	Straight MMAL	Integer and mixed integer linear programming and hybrid genetic algorithm

Several researchers proposed solutions to workforce assignment problems where temporary and permanent workers have different skill levels (Stratman et al., 2004; Techawiboonwong et al., 2006; Corominas et al., 2008; Manavizadeh et al., 2013; Kim et al., 2018). For example, in (Stratman et al., 2004) it was showed that allocating skilled permanent workers upstream of the production process leads to a better cost efficiency. In (Buyukkaramikli et al., 2013), the authors compared the hiring of temporary and permanent workers in a make-to-order production system. The cost incurred for a temporary crew is higher than the one for a permanent crew. However, it decreases as the length of the hiring period increases. The results showed that the highest cost reduction is achieved when the cost of a flexible crew equals the cost of a permanent crew.

In terms of the layout, Widyadana et al. (2009) studied a MMAL balancing problem with permanent and temporary workers, and they show that a U-shape line provides better results compared to a straight line.

3.3. Walking workers

Walking workers are not fixed to a given workplace and may follow the processed product until its last task. Upon completion, they return upstream to start processing a new product unit (Al-Zuheri et al., 2014). Several studies (Bischak, 1996; Deepak et al., 2017) showed that moving workers, whose dynamic reassignment allows increasing the workforce resource where and when needed, improve the performance of production lines and provide larger throughputs, larger resource utilization, and less work in process.

A walking worker can be skilled or unskilled, temporary or permanent. Chen et al. (2016) considered a so called "chasing-overtaking" production line, in which workers with high efficiency are allowed to overtake workers with low efficiency at workstations. The conducted simulation showed the superiority of the "chasing-overtaking" production line over traditional and bucket brigade (see Section 3.4) production lines in terms of production capacity and resource utilization.

In (Pröpster et al., 2015), workforce-related reconfigurability is expressed in two ways: drifting of workers within a station and so-called “jumpers”, i.e. workers able to intervene to any station if necessary. Table 4 presents the papers related to walking workers, classified by content/criteria, production system’s type and solution approach.

Table 4. Studies related to walking workers

Paper	Content or criteria	Type of the system	Solution approach
Nakade & Ohno (1995)	The proof of the equality between the sums of cycle times with original and reverse order of task processing	U-shape single-model assembly line	Mathematical model
Bischak (1996)	Maximization of the throughput	U-shape single-model assembly line	Simulation
Zavadlav et al. (1996)	Minimization of the number of stations	U-shape MMAL	Markovian and simulation models
Sparling & Miltenburg (1998)	Minimization of the number of stations	U-shape MMAL	Heuristic
Nakade & Ohno (1999)	Minimization of the overall cycle time and the number of workforce	U-shape single-model assembly line	Heuristic
Ahn et al. (2002)	Minimization of the total cost	Parallel single-model assembly line	Heuristic
Zhao et al. (2004)	Minimization of the total overload time	Straight MMAL	Heuristics
Süer & Dagli (2005)	Minimization of the total intra-cell manpower transfers Maximization of throughput	Cellular manufacturing system	Mathematical programming and traveling salesman approach, McNaughton’s algorithm
Ertay & Ruan (2005)	Maximization of the output to input ratio	Cellular manufacturing system	Data envelopment analysis
Bock et al. (2006)	Minimization of the total cost related to workforce and off-line repair	Straight MMAL	Heuristics, simulated annealing, and local search
Chaves et al. (2007)	Maximization of the line’s productivity	Straight single-model assembly line	Heuristic (Clustering search)
Wang et al. (2007)	Minimization of the number of workstations and the number of walking workers	Straight MMAL	Simulation
Battini et al. (2007)	Minimization of load and setup times	Straight MMAL	Heuristics
Miralles et al. (2008)	Minimization of the cycle time	Straight single-model assembly line	Branch-and-bound
Nakade & Nishiwaki (2008)	Minimization of the overall cycle time and the number of workers	U-shape single-model assembly line	Heuristic
Shewchuk (2008)	Minimization of the number of workers and maximization of the workforce utilization	U-shape single-model assembly line	Heuristic
Moreira & Costa (2009)	Minimization of the cycle time	Straight single-model assembly line	Tabu search

Simaria et al. (2009)	Minimization of the idle time and workload unbalance at stations	U-shape MMAL	Ant colony optimization and heuristics
Yaakob & Watada (2009)	Maximization of the system's efficiency	Cellular manufacturing system	Particle swarm optimization
Mahdavi et al. (2010)	Minimization of total cost (holding, backorder, machine, workers, material handling)	Dynamic Cellular manufacturing system	Branch-and-bound
Sirovetnukul & Chutima (2010)	Minimization of the number of workers	U-shape MMAL	Heuristics
Al-Zuheri et al. (2010)	Minimization of the number of workers and equipment costs	U-shape MMAL	Simulation and combinatorial optimization
Altemeier et al. (2010)	Minimization of the total cost	Straight MMAL	Decision support tool and heuristics
Francas et al. (2011)	Maximization of the difference of expected second-stage profits and first-stage investment costs	Straight multi-model assembly line	Two-stage stochastic model
Soolaki (2012)	Minimization of the cost and cells load variation	Dynamic Cellular manufacturing system	Multi-objective genetic algorithm
Nikoofarid & Aalaei (2012)	Minimization of holding and backorder costs	Dynamic Cellular manufacturing system	Branch-and-bound
Yang et al. (2013)	Minimization of the number of workstations, rebalancing cost and workload unbalance	Straight MMAL	Multi-objective genetic algorithm
Al-Zuheri et al. (2013)	Maximization of line's productivity and ergonomic performances	U-shape MMAL	Mathematical model and simulation
Wang et al. (2013)	Maximization of the performance: flexibility, efficiency, responsiveness and re-configurability	Straight MMAL	Simulation
Eğilmez et al. (2014)	Maximization of the production rate & minimization of the number of workers	Cellular manufacturing system	Hierarchical approach
Al-Zuheri et al. (2014)	Evaluation of errors in the model predictions of performance measures: production rate, walking and waiting times	U-shape MMAL	Mathematical model and simulation
Kucukkoc & Zhang (2014)	Minimization of the number of workstations	Parallel two-sided MMAL	Agent-based ant colony
Savino et al. (2014)	Maximization of workers' productive capacities and minimization of buffers levels	U-shape MMAL	Simulation
Pröpster et al. (2015)	Creation of tool for monitoring, validating line balancing results and forecasting	Straight MMAL	Simulation
Battaïa et al. (2015)	Minimization of the total number of workers	Straight MMAL	Linear programming and randomized heuristics
Chen et al. (2016)	Maximization of the production capacity	U-shape single-model assembly line	Simulation
Cevikcan (2016)	Minimization of the number of workforce and maximization of the workload smoothness	Straight Multi-model assembly line	Heuristics

Tapkan et al. (2016)	Minimization of the number of stations and workers' walking time	Parallel single-model assembly line	Bee colony and artificial bee colony
Kucukkoc & Zhang (2016)	Minimization of the weighted summation of line length and the number of workstations	Parallel two-sided MMAL	Agent-based ant colony
Jaehn & Sedding (2016)	Minimization of the makespan	Straight multi-model assembly line	Heuristics
Al-Zuheri et al. (2016)	Minimization of the total cost	U-shape MMAL	Genetic algorithm
Vairaktarakis et al. (2016)	Levelling criteria: maximization of the workforce size and minimization of the maximum workforce fluctuation	Straight MMAL	Heuristics
Aljuneidi & Bulgak (2016)	Minimization of the total cost	Dynamic Cellular manufacturing system	Integer nonlinear programming model
Liu et al. (2016)	Minimization of backorder and holding costs	Dynamic Cellular manufacturing system	Meta-heuristics
Kellegöz (2017)	Minimization of the number of workers and stations opened in the line	Straight single-model assembly line	Simulated annealing
Deepak et al. (2017)	Maximization of the resource utilization and minimization of the work in process	Straight single-model assembly line	Simulation
Stadnicka et al. (2017)	Minimization of the walking path of the workers	Straight single-model assembly line	Simulation
Sikora et al. (2017)	Minimization of the cycle time	Straight MMAL	Mixed integer linear programming
Kuo & Liu (2017)	Minimization of the number of workers	Cellular manufacturing system	Mixed integer linear programming
Feng et al. (2017)	Minimization of the total cost	Cellular manufacturing system	Particle swarm optimization
Lian et al. (2018)	Minimization of the deviations from the average workload of cells and workers' number	Cellular manufacturing system	Non-dominated sorting genetic algorithm
Baykasoğlu et al. (2018)	Minimization of machine and worker duplication costs	Cellular manufacturing system	Integer and constraint programing
Biele & Mönch (2018)	Minimization of labor and inventory costs	Straight MMAL	Random-key genetic algorithm
Dolgui et al. (2018)	Minimization of the maximum number of workers	Straight MMAL	Mixed-integer linear programming and heuristics
Gebennini et al. (2018)	Minimization of the workers' walking cost and ergonomic risks of scheduled jobs	Straight single-model assembly line	Mixed integer linear programming
Naderi et al. (2019)	Minimization of the number of workers	Five-sided MMAL	Benders' decomposition
Delorme et al. (2019)	Minimization of the maximum number of workers	Straight MMAL	Integer linear programming and dynamic programming
Méndez-Vázquez & Nembhard (2019)	Estimation of system's productivity in four scenarios related to its configuration	Cellular manufacturing system	Simulation

Mahdavi et al. (2010), and Soolaki (2012) studied workforce assignment problems in a dynamic CMS with reconfiguration, i.e., adding, removing and changing machines between cells. In these studies, workers can be removed from one cell and assigned to another cell in each time period. A similar production line configuration, in which workers can move from one station to another after completing a task in the MMAL, was considered in (Battaïa et al., 2015; Dolgui et al., 2018; Delorme et al., 2019). This movement changes the number of workers assigned to the tasks at stations, which, in turn, either increases or decreases corresponding task processing times. The objective was to find an optimal scheduling of worker moves among stations minimizing the number of workers while respecting the line takt time.

Most studies confirm that skilled walking workers improve the manufacturing system's performance and responsiveness. The reconfigurabity increases as well, as they shift productive capacity from one workplace to another in order to adapt it to the current situation in a production system.

In many researches, workers are assigned to stations based on their skill levels (Nakade & Ohno, 1999; Wang et al., 2007; Nakade & Nishiwaki, 2008; Al-Zuheri et al., 2013; Eğilmez et al., 2014; Mura & Dini, 2016; Lian et al., 2018; Méndez-Vázquez & Nembhard, 2019). Indeed, workers must be properly trained to perform multiple or complicated tasks efficiently. Learning by doing repetitive tasks usually reduces processing times, whereas long periods between two successive similar tasks lead to forgetting and increase processing times. The worker assignment taking into account learning and forgetting effects has drawn a certain attention from researchers (Anzanello & Fogliatto, 2007; Thongsanit et al., 2010; Wang et al., 2013; Liu et al., 2016).

In (Battini et al., 2007), the authors studied a semi-automated line, where workers perform tasks on a multi-turn rotation table. Sikora et al. (2017) provided some real case studies with human workers and robots, assignment restrictions, zoning constraints, tasks executed by machines and common tasks requiring at least two workers.

Bock et al. (2006) used workers' movement in a real time control of an MMAL to deal with disruptions caused by a worker's absence, material bottleneck, or machine breakdown, among others. Al-Zuheri et al. (2016) studied the impact of distances between workstations, number of stations, layout design and a workload assigning method on ergonomic measures including energy expenditure and walking time to standing position working time ratio. In (Yang et al., 2013) both tasks and workers are allowed to be reassigned to other stations when a change of the demand occurs. Battaïa et al. (2015) studied a workforce planning problem, in which workers are allowed to move between stations after finishing a task.

A combination of moving and temporary workers was considered by Francas et al. (2011). The authors proved that temporary workers always decrease the investment in regular workers. It was also shown that, in spite of a possible increase of investment on moving the regular workers due to a positive influence on labor utilization, moving workers enhance the efficiency of temporary workers. Thus, an industrial company may benefit from a right combination of temporary and moving workers.

3.4. Bucket brigades

Bartholdi & Eisenstein (1996) introduced a self-balancing approach for flow shop manufacturing systems, called "bucket brigade" (BB). A bucket brigade is an organization of workforce movement, where the number of workers is lower than the number of stations and a worker follows the part from one station to the next until he/she meets his/her successor. Once a worker meets his/her successor, the successor takes over the work on the product, and the worker moves upstream to take over the part of his/her predecessor and so on. Bartholdi & Eisenstein (1996) demonstrated that sequencing workers from the slowest to the fastest leads to a stable partition of work making the bucket brigade self-balancing.

In a survey paper, Bratcu & Dolgui (2005) pointed out the main advantage of bucket brigades, namely, their adaptability to changing operational conditions like task times, product mix, spatial configuration modifications, etc. Moreover, their relatively easy implementation reduces the design and control effort, making the corresponding reconfiguration strategy popular among practitioners.

Despite the deterministic nature of the basic bucket brigade model, it can have a chaotic behavior that negatively influences the performance of an assembly line (Bartholdi et al., 2009). Indeed, the hand-offs can be unpredictable when workers are interrupted at any time or any position of the line. In the initial model the return velocity was considered as infinite. Song et al. (2011) studied bucket brigades with limited return velocities and analyzed their impact on the line's stability and productivity. They demonstrated that bucket brigades with the same return velocity are self-balanced and that the line's productivity is directly proportional to the value of return velocity.

Lim (2011) introduced the concept of cellular bucket brigade (CBB), where the workers operate in aisles with production lines on both sides. A worker performs tasks at one side of the line moving in one direction, but when he/she reaches his/her successor, this worker executes tasks at the other side of the line, moving in the other direction. Thus, unproductive traveling times are reduced. Lim (2011) proposed simple rules for work sharing and a sufficient condition for self-balancing.

Numerical experiments showed a 30% to 50% increase in throughput compared to the traditional bucket brigade model (Lim, 2012; 2017).

Table 5 contains recent papers on bucket brigades, where BB and CBB stand for bucket brigades and cellular bucket brigades, respectively.

Table 5. Studies considering bucket brigades

Paper	Content or criteria	Type of system	Solution approach	CBB/BB
Bartholdi & Eisenstein (1996)	Modelling and performance analysis of bucket brigades	General manufacturing systems	-	BB
Bartholdi et al. (1999, 2001)	Modelling and performance analysis of bucket brigades (deterministic/stochastic)	General manufacturing systems	-	BB
Bratcu & Dolgui (2005)	A survey on bucket brigades.	Assembly lines	-	BB
Ahn & Righter (2006)	Analytical study of work sharing between stations	Straight general manufacturing systems	-	BB
Hytonen et al. (2008)	Maximization of the workers' utilization	Straight MMAL	Discrete event simulation	BB
Bartholdi et al. (2009)	Modelling and performance analysis of bucket brigades with chaotic behavior	General manufacturing systems	-	BB
Bratcu & Dolgui (2009)	Finding a sufficient condition for self-balancing. Building a simulation model for general complicated cases	Dynamic general manufacturing systems	Analysis and simulation	BB
Lim & Yang (2009)	Maximization of the throughput	General manufacturing system	Heuristic (simulation)	BB
Quintana et al. (2009)	Maximization of the machine availability and utilization	General manufacturing system	Simulation	BB
Koo (2009)	Maximization of the workers' productivity	Order picking system	Simulation	BB
Wang et al. (2009)	Minimization of in-process waiting times	U-shape MMAL	Simulation and mathematical modelling	BB
Wang et al. (2010)	Minimization of in-process waiting and traveling times	Assembly line	Mathematical modelling	BB
Song et al. (2011)	Maximization of productivity and production stability	General manufacturing system	Heuristic	BB
Villalobos et al. (2011)	Minimization of the labor turnover	Serial assembly lines with workforce learning effects	Modified work sharing	BB
Webster et al. (2012)	Maximization of the throughput	Order picking line	Discrete event simulation	BB
Lim et al. (2011)	Minimization of the unproductive travel. Simple	Generalized assembly line	Numerical simulation	CBB

	rules leading to the line's self-balancing			
Lim (2012)	Minimization of the unproductive travel. Simple rules leading to the line's self-balancing	Order picking line	Numerical simulation	CBB
Sriram et al. (2014)	Maximization of the throughput	U-shape cellular manufacturing system	Discrete event simulation	CBB
Lim & Wu (2014)	Minimization of the unproductive travel. Simple rules leading to the line's self-balancing	Generalized assembly line	Numerical simulation	CBB
Lim (2017)	Minimization of the unproductive travel. Impact of hand-off times on the CBB performance	Generalized assembly line	Numerical simulation	CBB
Zhou et al. (2017)	Minimization of the unproductive travel	Generalized assembly line	Mathematical modelling and simulation	CBB

Sriram et al. (2014) considered a bucket brigade approach in a U-shape assembly line with buffers. They proposed a new control protocol for bucket brigades. By using a discrete events simulation and an optimization model, the authors determined optimal buffer locations and buffer control levels associated with each worker maximizing the line throughput. A buffer level is the amount of excess production capacity in a production line that is included to ensure that production goals are met in the event of downtime. Lim & Wu (2014) proposed some simple cellular bucket brigade rules to coordinate workers in a U-shape assembly line with stations in which at most one worker is allowed to operate at a station. The goal was to maximize the productivity of the line. The simulation results show that the number of stations has a critical impact on the performance of a cellular bucket brigade.

3.5. Cross-trained workers

A cross-trained worker is a worker able to perform multiple tasks in various locations of a manufacturing system when needed (Ebeling & Lee, 1994). Compared to walking or bucket brigade workers, who are initially trained to perform multiple tasks and whose movement is planned, cross-trained workers are specialized on specific tasks but also trained to perform other tasks in case of an unplanned necessity. Such unplanned necessities include an ill operator, a change of product mix, or a change in the demand of specific products. Workers' cross-training improves their understanding of the whole production process and tends to increase the overall quality of the manufactured products.

A cross-trained worker's timely response to unplanned situations enhances the flexibility of a manufacturing system. On the other hand, cross-training is costly, and it can increase the production time. To mitigate these shortcomings, several strategies for efficient cross-training were introduced. In the chain cross-training strategy (Inman et al., 2004), workers are trained to execute a secondary task, and tasks are allocated to the workers in a chain. For example, worker A performs tasks 1 and 2, worker B executes tasks 2 and 3, and so on, where the latter task for each worker is the secondary task. Hopp et al. (2004) proposed two other strategies, namely, cherry-picking and skill chaining. In cherry-picking, cross-trained workers assist their colleagues in a bottleneck station to increase the system's throughput. Such strategy implies a higher investment in workers' cross-training. Skill chaining reduces cross-training costs since only workers from an adjacent station assist directly at the bottleneck station. Others assist indirectly by taking part of the work of the following or preceding station. More details on skill chaining with cross-trained workforce are presented in (Tekin et al., 2002). A summary of the studies on problems with cross-trained workers is given in Table 6.

Table 6. Studies considering cross-trained workers

Paper	Criteria	Type of system	Solution approach
Ebeling & Lee (1994)	Maximization of the total profit	Straight MMAL	Integer linear programming
Vairaktarakis & Winch (1999)	Minimization of the number of workers and cross-training cost	Straight MMAL	Branch-and-bound and heuristics

McCreery & Krajewski (1999)	Maximization of performance	U-shape MMAL	Heuristic
ElMaraghy et al. (2000)	Minimization of the mean flow time	Job shop	Genetic algorithm
Norman et al. (2002)	Maximization of the effectiveness including productivity, product quality, training costs	Cellular manufacturing system	Mixed integer programming
Campbell & Diaby (2002)	Maximization of the utility of workers in departments	General service system	Heuristic
Inman et al. (2004)	Minimization of the cost of workers	Straight single-model assembly line	Heuristic (chain cross-training)
Hopp et al. (2004)	Maximization of throughput for a fixed work-in-process and finding the necessary amount of work-in-process for the desired throughput	General manufacturing system	Heuristic (cherry picking and skill chaining)
Bokhorst et al. (2004)	Maximization of the productivity	Job shop	Simulation
Slomp et al. (2005)	Minimization of the training and operating cost	Cellular manufacturing system	Integer programing
Sennott et al. (2006)	Minimization of the total cost and maximization of the workforce utilization	General manufacturing system	Approximating sequence method
Winch et al. (2007)	Minimization of the number of workers	Straight MMAL	Branch-and-bound and heuristics
Sayin & Karabati (2007)	Maximization of the department utility (function of the labor shortage) and the total skill improvement	Generalized manufacturing or service system	Simulation, mixed-integer programming with piecewise linear approximation
Fowler et al. (2008)	Minimization of the workforce related cost	General manufacturing system	Heuristics and genetic algorithm
Yue et al. (2008)	Maximization of the system's efficiency	Job shop	Simulation
Kaku et al. (2008)	Maximization of the productivity, minimization of the inventory and stock outs	U-shape MMAL and Cellular manufacturing system	Heuristic (human-factor-based training approach) and simulation
Davis et al. (2009)	Minimization of the workload imbalance	Job shop	Simulation
Aryanezhad et al. (2009)	Minimization of the total cost including production, hiring, firing, and training costs	Dynamic cellular manufacturing system	Linear programming
Bokhorst & Gaalman (2009)	Maximization of the productivity	Job shop	Simulation
Satoglu & Suresh (2009)	Minimization of cross-training, hiring, firing, and over-assignment of workers to more than one cell	Hybrid (adapted both to high/stable and low/sporadic demand) cellular manufacturing system	Goal programming
Campbell (2011)	Maximization of the workers' utility in the departments	General service system	Two-stage stochastic approach
Easton (2011, 2014)	Minimization of the labor cost, maximization of the service level	General service system	Two-stage stochastic approach
Kim & Nembhard (2013)	Minimization of the number of workers	Parallel MMAL	Data mining technique

Xu et al. (2015)	Minimization of the total workforce-related cost and maximization of the customer satisfaction	General service system	Binary programing and non-dominated sorting genetic algorithm
Yang & Gao (2016)	Minimization of the number of skill zones (stations)	Straight MMAL	Branch-and-bound
Wu et al. (2018)	Minimization of the training cost, maximization of the workload balance	Cellular manufacturing system	Particle swarm optimization and artificial bee colony
Chu et al. (2019)	Minimization of the costs related to the workers' training, assignment, and workload imbalance	Cellular manufacturing system	Adaptive memetic differential search algorithm

The positive impact of using cross-trained workers on the production system's performance was proved in numerous studies. For example, in Sayin & Karabati (2007), the authors proposed a simulation model to analyze the impact of some parameters on the utility and skill improvement. These parameters include the number of workers, departments, demand for workers, learning speed, demand variation, etc. The authors suggest that cross-training and skill improvement lead to higher system's productivity. Davis et al. (2009) showed that an extensive cross-training improves the performance under high workload variation conditions. However, in the case of insufficient capacity of equipment in a job shop manufacturing system, additional training expenses are not justified by the marginal improvement related to cross-training. The impact of cross-trained workers' learning and forgetting effects on the performance of manufacturing systems were also investigated by (McCreery & Krajewski, 1999; Kim & Nembhard, 2013; Chu et al., 2019).

Several studies on using cross-trained workforce in dual resource constrained (DRC) production systems were conducted, for example in (Yue et al., 2008; Bokhorst & Gaalman, 2009; Bokhorst et al., 2004; Hottenstein & Bowman, 1998; Elmaraghy et al., 2000; Davis et al., 2009; Satoglu & Suresh, 2009; Xu et al., 2015). DRC system is a manufacturing system, which is not only constrained by machine capacity, but also by workforce capacity. Cross-trained workforce is also largely used in CMS (Slomp et al., 2005; Kaku et al., 2008; Aryanezhad et al., 2009; Wu et al., 2018; Chu et al., 2019).

4. Analysis of workforce reconfiguration strategies in different manufacturing systems and promising research directions

Several workforce reconfiguration strategies, helping to improve the manufacturing system's adaptability and resilience are described in the previous section. This section has two goals. The first goal is to overview the existing literature on workforce planning and assignment and to clarify the importance of workforce reconfiguration strategies for different types of manufacturing systems. The second goal is to analyze workforce reconfiguration strategies by highlighting their advantages and challenges and to provide promising research directions.

4.1. Analysis of the research on workforce reconfigurability for different types of manufacturing systems

This subsection reviews the literature on different types of manufacturing systems and certifies the relative significance of workforce reconfiguration strategies for each of them. It is interesting to see how the five workforce reconfiguration strategies, have been studied across different types of manufacturing systems: dedicated, flexible, cellular, and reconfigurable manufacturing systems. Figure 2 shows the number of articles in refereed journals per year related to each workforce reconfiguration strategy, whereas Figure 3 gives the number of papers based on both the workforce reconfiguration strategies and manufacturing system's types.

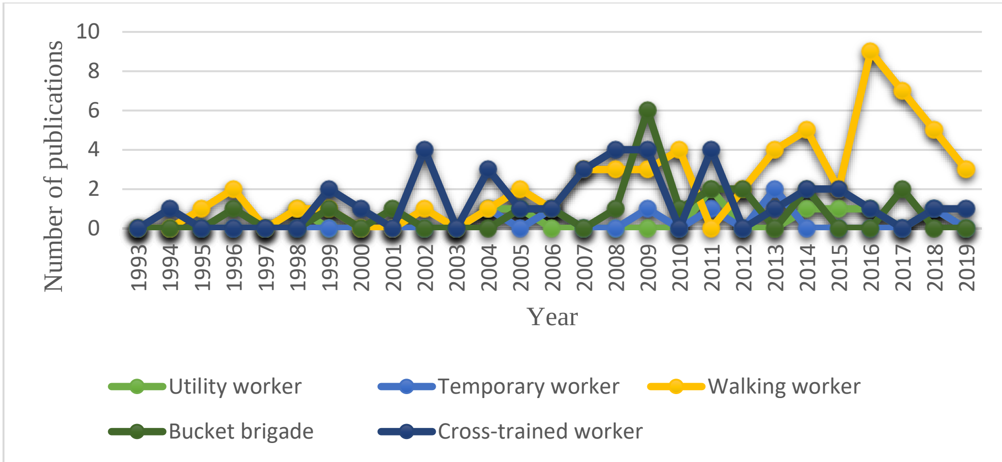

Figure 2. The number of articles per year related to each workforce reconfiguration strategy

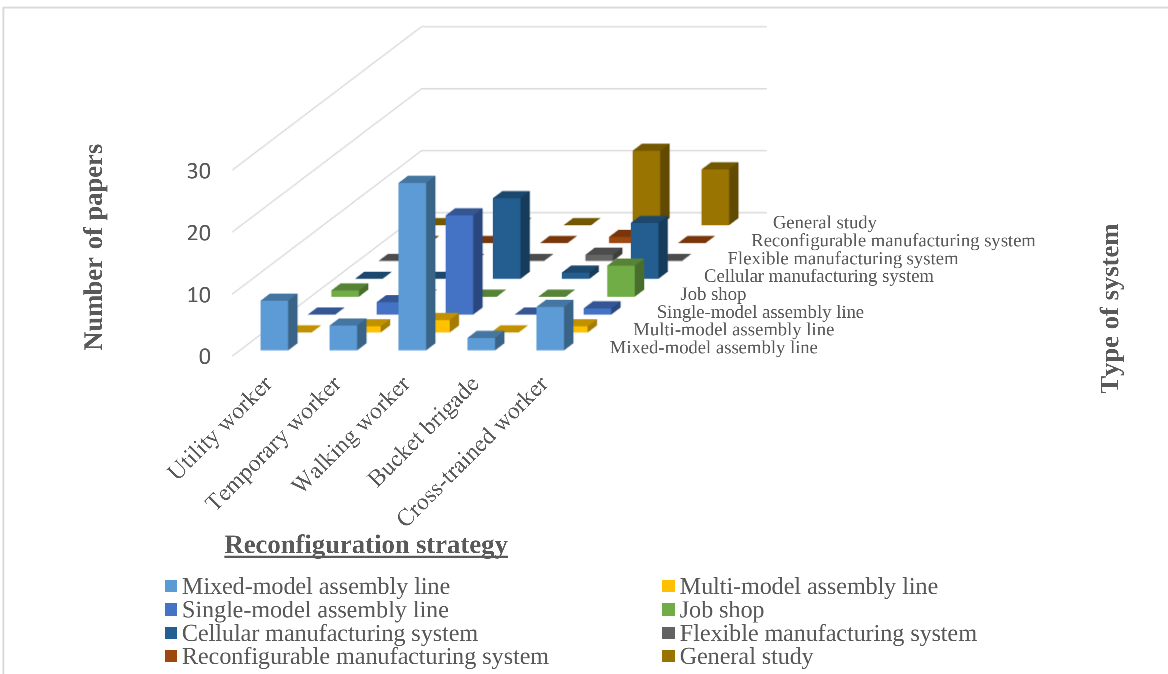

Figure 3. The number of papers based on both workforce reconfiguration strategy and manufacturing system's type

These figures indicate that most of the studies consider mixed-model manual assembly lines and emphasize the importance of utility, walking and cross-trained workers in the system's reconfigurability.

4.1.1 Dedicated Manufacturing System and Mixed- and Multi-model Assembly Lines

A large number of studies exist on workforce assignment in a DMS, see for example (Sungur & Yavuz, 2015; Lai et al., 2019). Several researchers studied workforce assignment for a single-model assembly line (Nakade & Ohno, 1999; Miralles et al., 2008; Moreira & Costa, 2009; Chaves et al., 2007; Anzanello & Fogliatto, 2007; Thongsanit et al., 2010; Mura & Dini, 2016). In contrast, due to the fact that only one product can be produced by a DMS, there are only few studies regarding workforce reconfigurability (e.g., Corominas et al., 2008; Moreira & Costa, 2009; Stadnicka et al., 2017; Gebennini et al., 2018). On the other hand, a large body of literature is dedicated to workforce assignment problems related to mixed/multi-model assembly lines (e.g., Battaïa et al., 2015; Delorme et al., 2019), since such lines are usually manual. In most cases, see Figure 2, the line's adaptability is achieved by walking workers, who, upon completion of a task, can be assigned to another task at another station. On the one hand, walking workers allow to have a necessary minimal amount of workers to accomplish the task and therefore keep the production going. On the other hand, this strategy can decrease the task's processing time and consequently increase the line's productivity. In many studies, the number of workers and workforce-related costs (e.g. cost of temporary workers' hiring, cross-training cost) are a part of the problem's criterion. In such case, the cycle time criterion is usually replaced by the corresponding constraint, limiting the value of a station time.

4.1.2. Cellular Manufacturing System

A CMS can be viewed as a collection of several assembly lines (cells), each of which is designed to process only a specific set of products. Thus, a CMS represents a mixture of flow and job shop systems. Compared to a static situation, where the demand volume and product mix are known, a multi-period problem with changing demand volume and product mix requires a CMS to be robust and adaptive. Historically, the re-assignment of machines between cells (adding, removing and swapping) was the first type of CMS's reconfiguration, see for example (Safaei et al., 2008; Papaioannou & Wilson, 2010). In a CMS involving workers, cells quite often have a U-shaped layout, allowing workers assigned to a cell to move from one station (machine) to another in a short time (Schrader & Elshennawy, 2000). In a quickly changing dynamic environment, the adaptability of a CMS can be increased by using the workforce reconfiguration strategies. While many studies on multi-period dynamic CMS with workforce considered the possibility of workers' firing (Satoglu & Suresh, 2009; Mahdavi et al., 2010), some of the workforce reconfiguration strategies can provide an alternative, in which the number of workers do not change. Thus, utility, moving or cross-trained workers can travel between cells, providing necessary skills and manpower when and where needed without demoralizing layoffs related to a sudden drop in demand, for example. On the other hand, training costs incurred by these strategies can be relatively high. An adequate trade-off between using these strategies and changing the number of workers should be made.

4.1.3. Flexible Manufacturing System

In general, the literature on workforce in FMS is poor, since a long time they were considered as fully automated systems, mainly composed of CNC machines and robots. It is extremely hard to find even the keyword "workforce" or "workers" in the FMS-related literature, which is itself quite scarce. Sometimes researchers describe another system, using the term FMS. For example, Cronin et al. (2019) call an assembly line an FMS. Bortolini et al. (2019) use the term FMS to denote a CMS.

Lee at al. (2020) used the term FMS in its conventional meaning. The authors considered workers, who load parts of different type on a pallet, which is then released into the system, composed of numerical control machines and the central buffer. The workers also unload the pallets. The studied problem consists in minimizing the total tardiness, taking into account, among other constraints, workers' availability times.

Due to its complexity, an FMS requires the presence of a highly skilled personnel to control the production process (Mehrabi et al., 2002). It comes at a cost and urges a company to reduce the number of such operators as much as possible, taking into account the high cost of an FMS itself. Therefore, it can be concluded that the scope of workforce reconfiguration strategies' application to an FMS was extremely small. Nevertheless, the new tendencies consist in adding workers into FMS to decrease the cost and increase the reliability, thus the workforce planning problems also concern FMS.

4.1.4. Reconfigurable Manufacturing System

Workforce planning in RMS have been generally ignored by the researchers. Only a few papers shed light on this aspect. Askin & Huang (1997) developed two integer programming models to assign workers and determine their individual training programs. Peruzzini & Pellicciari (2017) claimed that in order to create an effective smart factory context (e.g., a FMS or a RMS), human performance should be taken into account and managed in the most efficient way. In the paper (Gyulai et al., 2017), the authors proposed a method to minimize the number of workers in a reconfigurable assembly system with constraint programming and genetic algorithms. Harari et al. (2018) took into account the human resource as a component of the design process of flexible and reconfigurable assembly systems. Andersen et al. (2018) demonstrated that convertibility, i.e.

ability to change the functionality of a system to meet new production requirements, is easier to implement in a high-level manual production than in a less manual manufacturing system. Noticeably, convertibility is one of the main characteristics of RMS (Koren et al., 1999). A flexible workforce increases the convertibility of the manufacturing system.

The following differences between FMS and RMS lead to consider that workforce planning problems in RMS represent a promising research avenue. Firstly, RMS is less automated than FMS. Secondly, in contrast to the numerical control flexibility of FMS, the main principle of RMS is a physical reconfiguration of resources. Finally, RMSs are mixed systems with CNC machines, reconfigurable achines tools (RMT), traditional machines, collaborative robots (cobots) and reconfigurables workstations where workers play an important role. Workforce is one of the main resources in an RMS, and the principles of RMS foster its reconfiguration. Surprisingly, there are only few studies on workforce reconfiguration in RMS. In contrast to machines, human workers are naturally flexible and able to perform a task, which is not necessarily related to the scope of their predestination. A human worker can handle a non-standard situation, in which a machine would definitely fail, because, in case of such situation, it has no predetermined procedure to follow. Even though a recent progress in artificial intelligence may mitigate this flow, the aspect of cost of such smart and adaptive machines cannot be ignored. Usually the worker's training required to improve or acquire certain skills and, therefore, increase his or her flexibility, is cheaper than building a new functionality of a machine. Considering these factors, an application of workforce reconfiguration strategies in RMS represent an interesting research direction for future studies.

In contrast to the large number of studies on workforce planning in single/mixed/multi model assembly lines and CMS, the corresponding literature related to FMS and RMS is poor. Figure 4 positions different manufacturing systems according to two factors: the amount of literature associated with workforce reconfiguration and the importance of system's reconfigurability.

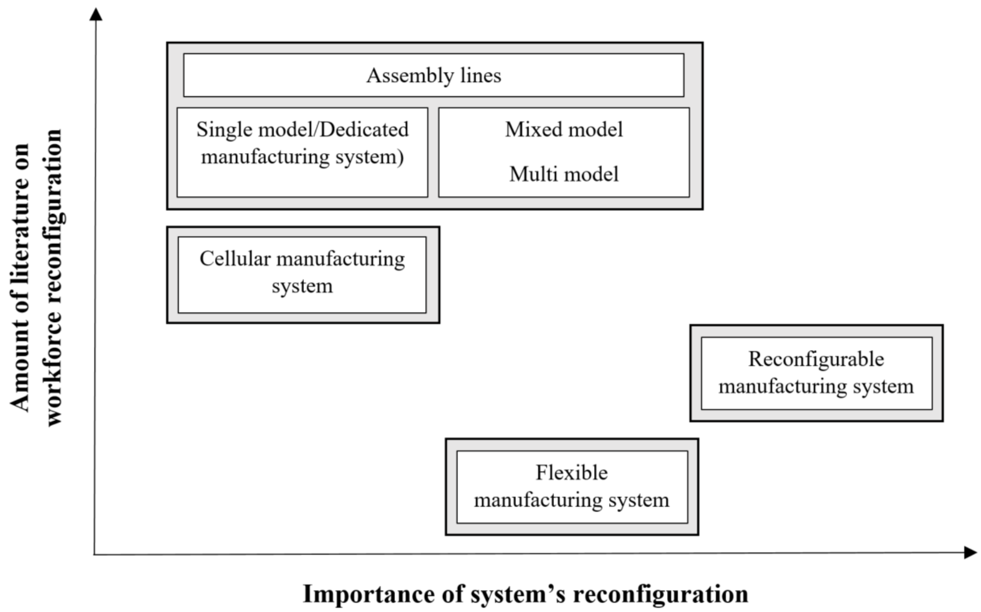

Figure 4. Compliance of the workforce reconfiguration related studies to the importance of system's reconfiguration for different manufacturing systems

Figure 4 shows the mismatch between the high importance of reconfigurability for an RMS and the scarcity of corresponding studies related to workforce reconfiguration, thus emphasizing an interest in such research. In order to enhance the contrast and logical connection between different workforce reconfiguration strategies and the different types of manufacturing system, Table 7 presents them with regard to the existing literature (×) and the open issues for future studies (?). The papers existing the literature have been presented before, and several future research directions are proposed to be taken into account in future researches. In the current state, FMSs and RMSs use only equipment flexibility and re-configurability. For FMSs, this can be explained by the fact that they were considered in the past as fully automated systems. Nevertheless, the last tendencies in industry consist in adding human workers into the FMS. For RMS, this is even more important and crucial, because RMSs are mixed systems with CNC machines, RMT, traditional machines-tools, cobots and reconfigurable workstations, etc. The study of reconfigurability of RMS, based on both machine and workforce reconfigurations is a challenging research issue. The advantages of workforce flexibility and how workforce flexibility can improve the overall adaptability of production systems in the case of FMS and RMS are not studied in literature and can be new promising research directions.

Table 7. Current state of applying workforce reconfiguration strategies to different manufacturing systems

	Dedicated manufacturing system and mixed/multi-model assembly line	Cellular manufacturing system	Flexible and reconfigurable manufacturing system
Utility workers	×	?	?
Temporary workers	×	?	?
Walking workers	×	×	?
Bucket brigades	×	×	?
Cross-trained workers	×	×	?

4.2. Analysis of workforce reconfiguration strategies and promising research directions

Numerous studies show that workforce reconfiguration strategies have a positive impact on the manufacturing system’s efficiency. For instance, the use of utility workers reduces production stoppages, and it decreases the stocks of unfinished goods. Temporary workers help coping with sudden demand increases. Walking workers allow to adjust capacity to different combinations of unfinished goods located in a manufacturing system at a certain moment of time. Bucket brigades provide an easy-to-implement worker assignment rule able to adapt to fluctuating operational conditions. Cross-trained workers apply their broad skills in order to react to unplanned situations.

However, the use of such strategies comes at a cost and may lead to certain side effects like the increased workers' stress and over-load. Using temporary or cross-trained workers may bring several advantages for a company, such as an increased productivity and responsiveness (Stratman et al., 2004; Sayin & Karabati, 2007). However, the implementation of these strategies incurs the increased cost of hiring and training, which may not necessarily be reasonable. The use of walking workers increases the input of a manufacturing system, but an excessive overload of such workers may lead to a fatigue and stress, which, in turn, negatively affects the system's performance. In fact, manufacturers need to properly trade-off advantages against the disadvantages caused by these strategies. For example, (Slopm et al., 2005) try to find the best possible trade-off between the operating costs of a manufacturing cell, related to the workload of the most charged worker, and the cross-training costs.

Most studies on manufacturing systems with workforce consider the criteria of efficiency, throughput and costs. Ergonomic side effects such as fatigue, injuries, absenteeism and stress, caused by overload, frequent task change, movement or inadequate workspace organization, are not yet sufficiently studied. However, this issue becomes more and more relevant in the recent publications on workforce planning. These studies take into account workers' fatigue through repetitive movements (Asensio-Cuesta et al., 2012), metabolic energy expense (Al-Zuheri et al., 2016), risks and psychological costs of the heavy tasks (Gebennini et al., 2018). Otto & Battaïa (2017) surveyed the literature on optimization methods for assembly line balancing and job rotation scheduling, which takes into account physical ergonomic risks. In those studies, ergonomic risks are either included in the objective function or represented as constraints. This survey might be useful for the future studies in this direction. Besides, future studies on ergonomic risks in workforce planning and assignment could benefit from consideration of the workers' cognitive load and its measuring methods.

Specific industrial situations favor a certain workforce reconfiguration strategy. For example, using temporary workers can be useful for a company that produces seasonal products (Corominas et al., 2008), while bucket brigades, thanks to their self-balancing nature and relatively easy implementation, are especially useful in case of short lifecycle products manufacturing (Bartholdi & Einstein, 1996). At the same time, these strategies are closely connected to each other in practice. For instance, bucket brigades and cross-trained workers can be seen as a kind of walking workers. Workers' movement in bucket brigades follows the constant simple rules, while cross-trained workers move from one station to another in case of necessity (Ebeling & Lee, 1994). In fact, a proper combination of strategies may provide better results than implementing only one. For example, Cevikcan & Durmusoglu (2011) and Francas et al. (2011) found the benefits of using moving workers in combination with temporary and utility workers.

The five workforce reconfiguration strategies and two possible research directions, ergonomics aspects and strategies' combination, can be also applied to a so-called hybrid human-robot collaborative system. In fact, each type of manufacturing systems, although with a much lesser degree for an FMS, can employ robots and create a human-robot collaboration environment.

Researchers studying operations management problems have paid a little attention to such hybrid systems. However, using collaborative robots, so-called cobots, helps manufacturing systems to improve their efficiency combining the advantages of workforce (e.g. flexibility, creativity, trainability, intelligence) and the advantages of robots, such as force, accuracy, tirelessness and speed (Hashemi-Petroodi et al., 2020). There are several ways of interaction between robots and humans in a hybrid system that affect the control, balancing and planning of a manufacturing system: independent, simultaneous, sequential, and supportive (El Zaatari et al., 2019). A heavy task, which is dangerous for a worker, can be performed by a robot, while workers can perform certain delicate tasks requiring less force but more flexibility. In order to avoid the monotony of habitual operations, certain safe tasks can be from time to time performed or assisted by workers. In modern quickly changing market conditions, hybrid human-robot manufacturing systems must be adaptive, which requires a high degree of reconfigurability. Such a reconfiguration does not only concern the robots but also the workforce, and the use of utility, temporary, cross-trained, moving workers or bucket brigades would allow a timely and efficient adjustment of resources. The specificity of workforce reconfiguration strategies in such system consists in the consideration of inevitable human-robot interaction, and it opens some promising research directions.

Another future research opportunity consists in investigating the impact of new technologies, which help to improve the interaction between workers, machines and robots. For example, such technologies and communication modes as smart devices, cameras, sensors, teleoperation, message exchange and augmented reality facilitate the interaction between human operators and robots and makes the manufacturing environment safer.

5. Conclusion

The rise of mass customization and shortening product lifecycles drive industrial companies to employ manufacturing systems with a high level of reconfigurability needed to adapt to quickly changing market conditions. The core interest of workforce planning lies in the workforce's ability to enhance the manufacturing system's reconfigurability. The current paper provides a literature review of the research related to workforce reconfiguration. The literature is classified according to five workforce reconfiguration strategies: the use of *utility*, *temporary*, *moving*, *cross-trained* workers and *bucket brigades*. These strategies are presented in the context of different manufacturing system types: *dedicated*, *flexible*, *cellular*, *reconfigurable* manufacturing systems and *assembly lines*.

The review ascertains that most of the studies are dedicated to manual assembly lines, since they are often used in practice. The number of papers with the keyword "assembly line" significantly exceeds the one with the keywords "flexible", "cellular" or, to the less extent, "reconfigurable" manufacturing systems. However, they are not mutually exclusive. For example, an assembly line that has a customized flexibility, changeable workstation structures, product variety and reconfigurable workforce, can be considered as a reconfigurable manufacturing system.

The literature analysis reveals a lack of study on workforce reconfiguration in reconfigurable manufacturing systems. In spite of a significant amount of literature on reconfigurable machines and tools, a combined approach integrating machines' and workers' reconfiguration has not been studied yet. Unlike a flexible manufacturing system, a reconfigurable manufacturing system is not fully automated. Therefore, a joint analysis of machine and workforce reconfigurations in a reconfigurable manufacturing system can enhance its adaptability and robustness.

Several major avenues for future research are identified. The first consists in the consideration of ergonomic aspect. The second suggests applying a proper combination of several workforce strategies. The third calls to consider workforce strategies in an emerging human-robot collaborative environment. The fourth consists in studying the influence of the new technologies, such as smart devices, cameras, sensors, teleoperation, message exchange and augmented reality, on a manufacturing system employing both automated resources and human workers.

Acknowledgment

The authors of this paper would like to thank the Region Pays de la Loire, France (www.paysdelaloire.fr) for financial support of this study.

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