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Reconfigurable manufacturing systems from an optimisation perspective: a focused review of literature

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ABSTRACT
The concept of reconfigurable manufacturing systems (RMSs) is a current subject that has attracted intensive research. This latter covers the entire RMS life cycle, from the design to the exploitation phase, and includes several important problems requiring the use of optimisation. The objective of this paper is to survey research publications related to RMS optimisation problems and their solution methods. For this, the types of RMS and their components are described. Subsequently, relevant objective functions and performance indicators of RMS are presented. In addition, an overview of the most used solution approaches and a classification of optimisation problems are proposed. Finally, a detailed analysis, our conclusions, and suggestions for future research are provided.

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1. Introduction

At the beginning of the nineteenth century, the invention of the steam engine, and later the electrical motor, allowed the automation of certain manufacturing tasks that were difficult for humans. This led to the emergence of mass production as an alternative to craft. Thus, operators and machines were used to manufacture a single product in large quantities at a low cost. The market situation at that time could be characterised as having a greater demand than supply. As a result, manufactured products were easy to sell. Such production systems are referred to as dedicated manufacturing lines (DMLs).

With the development of better means of transport and the advent of the Internet between the end of the twentieth century and the beginning of the twenty-first century, countries have come closer together and industrial competition has become global and widespread. During this period, there was a shift in the market equilibrium, that is, supply outpaced demand significantly. DMLs, which were designed to manufacture a single type of product, became obsolete in such dynamic and unpredictable market conditions. The latter was characterised by an increasing frequency of new product introduction along with demand fluctuation, constant modification and revision of government regulations, and a rapid evolution of technology.

In order to cope with this situation, flexible manufacturing systems (FMSs) were introduced as a potential solution. FMSs mainly consist of computer numerical control (CNC) machines, which a priori provide a built-in generalised flexibility that enables the production of a wide variety of products. Compared to DMLs, FMSs offer low productivity and require substantial investment costs. Therefore, FMSs are not suitable for many industrial sectors. By considering the advantages and disadvantages of FMSs and DMLs, the most natural improvement of manufacturing systems seems to be a combination of these two.

Consequently, reconfigurable manufacturing systems (RMSs) were introduced by Koren et al. (1999); they are considered to be one of the most suitable solutions that can cope with the changing market conditions. Unlike FMSs, RMSs are designed with a desired level of flexibility in order to handle a predefined family of products. The overall structure of such systems is composed of reconfigurable machines that can be easily added, removed, or reconfigured (by changing their hardware or reprogramming their software) so as to meet market demands or to deal with external changes (new product introduction, machine breakdown, etc.).

According to Koren et al. (1999) and Koren and Shpitalni (2010), a manufacturing system is called ‘*r*econfigurable’ if it has the following characteristics:

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- Modularity: a modular structure for both hardware components and software.
- Integrability: a common interface that helps in integrating the modules and machines easily.
- Customisation: the necessary flexibility around a product family.
- Convertibility: ability to evolve functionality over time.
- Diagnosability: ability to diagnose a system effectively and rapidly.
- Scalability: ability to adapt the production capacity to cope with changes in market demand.

Each of these characteristics provides an RMS with the required degree of responsiveness to adapt to different circumstances. Therefore, the concept of RMS has received increasing attention within the scientific community, with more than 60% of the scientific papers being published between 2010 and 2017 according to Bortolini, Galizia, and Mora (2018). In this latter, a state of the art literature review was proposed, which provided a general view of the various subjects and applications related to RMS. The authors classified and mapped the scientific articles and identified five main research streams. In addition, they presented a broad vision linking RMS to Industry 4.0, and raised some interesting questions that could yield promising leads for future work. Similarly, in Andersen, Brunoe, and Nielsen (2015), the authors provided an overview of the RMS research trends. The classification they proposed is based on different levels of work in a factory, and it identified the research problems of each level that have been addressed in the literature. They concluded that there has been very little research interest on the higher structuring level of a factory in a reconfigurable environment. Both the aforementioned literature reviews provide a global view of the problems related to RMS. They both describe the overall characteristics and performance indicators but do not focus on the types of RMS as well as their components. Moreover, it can be seen (but not in detail) that most RMS related studies were formulated as optimisation problems. Therefore, in this study, which is an extension of Brahimi et al. (2019), we conduct a focused survey of the main components and types of RMS considered in the literature. Subsequently, we explain the role of optimisation in designing and operating such systems. For this, we first describe the most relevant objective functions used to assess and evaluate the performance of an RMS and then propose a classification of the optimisation problems and their solution approaches.

In our survey, we mainly consider journal papers. This is because journal papers generally are detailed. In addition, we have noticed that most conference articles and book chapters are extended in journal papers. The search was mainly performed in two ways. The first method was to collect articles from recent literature reviews. The second was based on an advanced mining of articles having '*reconfigurable*', 'RMS', or 'reconfigurability' in their title, abstract, or keywords in the *SCOPUS* database. Among the articles found, the *International Journal of Production Research* was the most important source related to RMS, followed by *The International Journal of Advanced Manufacturing Technology* and the *Journal of Manufacturing Systems*.

Before tackling RMS optimisation problems, it is necessary to introduce certain concepts and clearly define the context. For this reason, the structure of this paper is organised as follows. First, the different types of RMSs and their main components are described in Section 2. Based on that, Section 3 shows the objective functions and indicators used to assess RMS performance. Section 4 generally analyses the solution approaches used to solve RMS optimisation problems. These latter are classified and described in Section 5. Finally, the conclusion, discussion, and future research directions are given in Section 6.

2. Reconfigurable machines and RMS types

Reconfigurable machines (RMs) are the main components of RMSs that provide the systems with the ability to adapt and respond quickly to changing market conditions. They are essentially designed with the necessary flexibility to handle a particular family of products. Such machines have a modular structure; that is, they are made up of physical components that could be easily replaced and/or reoriented, thus providing a wide range of functionalities. This facilitates the reconfiguration of an RM to produce different products, thereby enabling it to adapt to a new product or cope with a new demand. According to Koren (2010), there are four types of RMs (shown in Figure 1):

- *Reconfigurable machine tools (RMTs)*, which are used in machining centres. They mainly consist of physical modules (like machining tools, spindle heads, turrets, etc.), each of which is able to perform one or several manufacturing tasks. These modules can be placed in several ways within a machine, thereby providing different configurations. Each configuration is characterised by a set of functionalities.
- *Reconfigurable assembly machines (RAMs)*, which are usually used in transfer and assembly lines. Such machines are modular and can be modified to assemble products having certain common characteristics

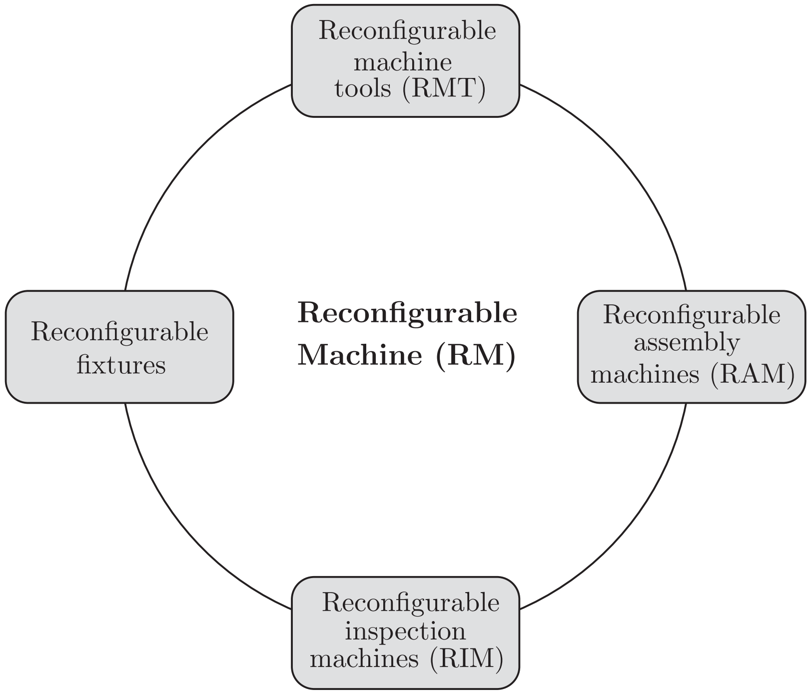

Figure 1. RM types.

(an example of an assembly machine for an automotive heat exchanger was provided by Katz 2006).

- *Reconfigurable inspection machines (RIM)*, which are mainly composed of electro-optical sensors, are used to inspect and measure the in-process machined parts. The number and location of these sensors can be changed depending on the part to be measured.
- *Reconfigurable fixtures*, which are used in the machining of large or complex parts such as cylinder heads of engines. The machining process involves fixing the part on specially designed fixtures to perform different machining tasks such as cutting and welding on its surface.

The use of a particular type of RM depends on the manufacturing application. However, most of the studies conducted on RMS have considered only RMT (see Bortolini, Galizia, and Mora 2018). This is because RMT has attracted the attention of both academics and industrialists (manufacturers and users of machine tools), who have encouraged their research and development (see Gadalla and Xue 2016).

2.1. RMS types

An RMS is mainly composed of a set of RMs, which are arranged in a certain way to manufacture a given family of products while at the same time ensuring a desired production capacity. The layout of these machines defines the type of manufacturing system, whose choice is a major issue in the design phase of RMS. This is a strategic decision, which is costly in terms of investment and has a direct impact on productivity and product quality (Koren 2010). We will now provide an overview of the different types of RMS, based on the survey of research articles.

- Reconfigurable flow lines
  This type of lines consists of a set of workstations. Each workstation is composed of one or more RMs capable of performing a given set of tasks. Figure 2 shows the basic structure of this type of lines. Reconfigurable flow lines are typically found in reconfigurable assembly or machining lines.

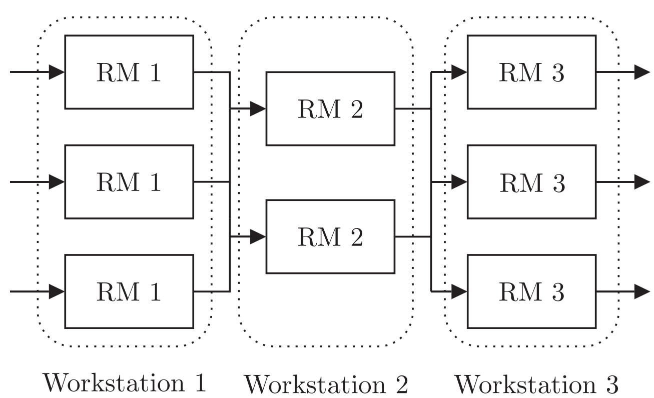

Figure 2. Reconfigurable flow line.

As in Bryan, Hu, and Koren (2013), reconfigurable assembly lines comprise a set of workstations with parallel identical centres. Each centre includes reconfigurable resources that perform tasks. This structure allows the system to be more reactive when a product changes or evolves, by making it possible to reconfigure the centres or to move resources between different workstations. For example, a centre may be composed of conveyors and storage racks, whereas the resources are welding guns and fixtures (Bryan, Hu, and Koren 2013).

Similarly, in reconfigurable machining lines, a workstation (or a stage) has parallel identical RMT and/or CNC machines. This structure has been proven to be efficient (Koren, Wang, and Gu 2016) because it allows scalability to be achieved easily by adding new machines. Moreover, it helps to maintain robustness against machine breakdown or unavailability (Spicer and Carlo 2007; Dou, Dai, and Meng 2008; Carlo, Spicer, and Rivera-Silva 2012; Ashraf and Hasan 2018).

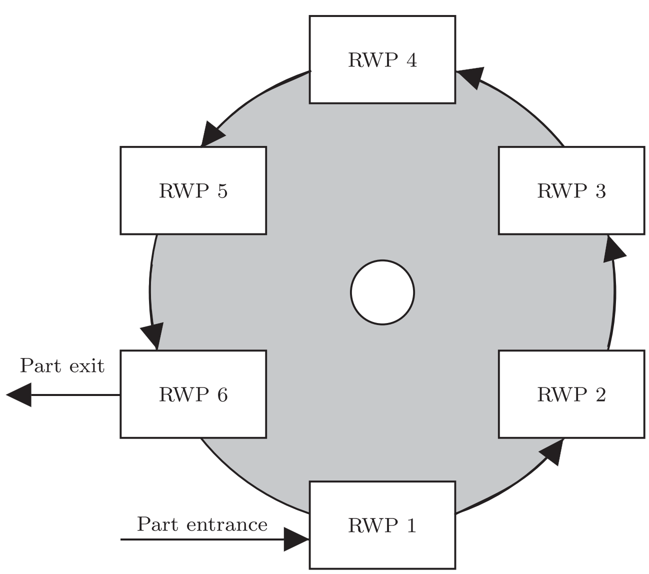

Figure 3. Rotary machining system with six reconfigurable working positions (RWP).

In contrast to the previously mentioned lines, reconfigurable rotary machining systems use a rotary table to transport products through different workstations (or working positions). Each workstation consists of modular machining units (composed of spindle heads or turrets), which can perform different tasks on a set of parts (Battaïa, Dolgui, and Guschinsky 2016; Liu et al. 2018a). Figure 3 illustrates a rotary machining table with six reconfigurable working positions.

- Reconfigurable cellular manufacturing systems (RCMS)

  CMSs are based on the concept of group technology, which aims to increase productivity by grouping common principles, problems, and tasks (Greene and Sadowski 1984). A CMS consists of cells capable of producing a group of parts that share similar production tasks, tools, machines, etc. According to Wemmerlov and Johnson (1997), a CMS helps in reducing the throughput time, work-in-process, response time to consumer orders, and material handling time/distance, as well as in improving the product quality. Similarly, a reconfigurable CMS (RCMS) is defined as a CMS whose cells are composed of RMs (Yu et al. 2012; Aljuneidi and Bulgak 2016) as depicted in Figure 4. In addition, dynamic cellular manufacturing systems (DCMS) can also be considered as a type of RMS. Such systems are composed of movable machines instead of RMs. These machines can be relocated among the existing cells to meet the production requirements over different periods of time (Rheault, Drolet, and Abdulnour 1995).

3. Objective functions

Before addressing the optimisation problems and their solution approaches, it is important to first analyse and discuss in detail the objective functions used for RMS. Since an RMS is mainly composed of reconfigurable machines, many authors have associated their performance indicators with the performance of the entire

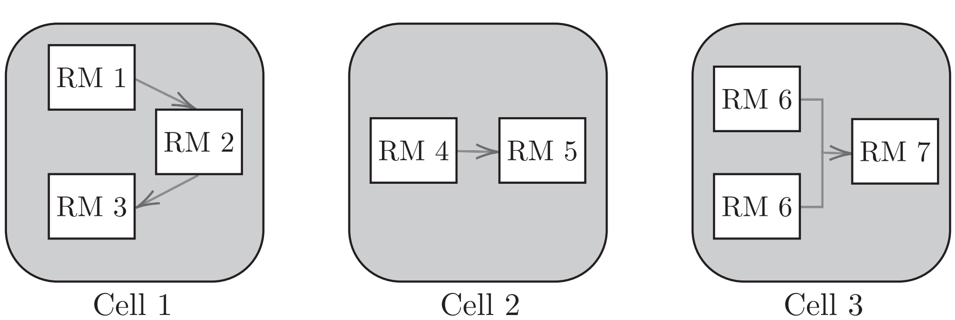

Figure 4. Reconfigurable cellular manufacturing system.

RMS. In this section, we clearly distinguish between the objective functions of the machine and the system.

3.1. Machine level

Several studies have been conducted on RMT. Gadalla and Xue (2016) classified them into three main streams: *architecture design*, *configuration design and optimisation*, and *system integration control*. In this section, we investigate the different objective functions and performance indicators used in the design/selection phase of RMT. We refer the readers to Landers, Min, and Koren (2001), Pasek (2006), and Gadalla and Xue (2016) for more detailed information on RMT-related problems.

3.1.1. Cost-oriented objectives

Cost is the objective that has been considered the most, and it is usually expressed as the sum of the *capital* and *operating costs* (it is also called total cost). The former includes the purchasing cost of modules, axes, spindles, and fixtures (Youssef and ElMaraghy 2006; Maniraj, Pakkirisamy, and Jeyapaul 2015), whereas the latter is the sum of all costs incurred during the production phase (Bensmaine, Benyoucef, and Dahane 2013), which includes the following:

- Usage and maintenance costs of machines, modules, and tools.
- Energy consumption costs related to RMT, modules, and tools.
- RMT reconfiguration cost, which occurs when switching from one configuration to another. It includes the cost of changing and reorienting the tools and the modules of an RMT.

3.1.2. Time-oriented objectives

The *completion time* is one of the most optimised objectives in conventional production systems. It represents the time required to manufacture a single unit of a given product. At the machine level, the completion time is expressed as the sum of the processing time of the performed tasks. When there are several products, the term *makespan* is used to indicate the time required to complete the processing of all the products (Bensmaine, Benyoucef, and Dahane 2014).

In the case of reconfigurable machines, it is also necessary to include the so-called *reconfiguration time*, which is composed of the machine configuration time and tool change time.

3.1.3. Machine reconfigurability

Machine reconfigurability is a performance indicator that shows whether or not a designed RMT has alternative configurations. It is used in order to provide an RMT with the ability to adapt to different production scenarios. In Goyal, Jain, and Jain (2012) and Ashraf and Hasan (2018), this indicator is based on the number of feasible alternative configurations of an RMT and the effort required for the reconfiguration process, which is expressed as the number of removed, moved, or added modules.

3.1.4. Operational capability

This indicator is used by Goyal, Jain, and Jain (2012), Goyal and Jain (2015), and Ashraf and Hasan (2018). It reflects the ability of an RMT to perform a variety of manufacturing tasks with a given configuration.

3.1.5. Other performance indicators

Goyal and Jain (2015) aimed to optimise *machine utilisation*, which was considered as the ratio between demand and the production rate of the machines. Xie, Li, and Xue (2012) considered the maximisation of *machining precision*, which (according to the authors) is related to the configuration of an RMT. Ashraf and Hasan (2018) proposed the maximisation of a reliability measure to ensure proper functioning of the entire line. Similarly, a machine availability index was optimised in Youssef and ElMaraghy (2008b). It considered the probability of machine failure during the production phase.

Table 1 shows the RMT objective functions used in the most relevant journal papers. It can be seen that the RMT cost and time-oriented goals are the most studied objectives. The machine reconfigurability, operational capability, and other performance indicators are just as important as they reflect the ability of an RMT to cope with fluctuations such as product changes, product demand variations, or machine breakdowns.

3.2. System level

The system level is composed of all the elements that constitute an RMS such as reconfigurable machines, workstations, cells, material handling systems, etc. In this section, we provide an overview of the relevant objective functions of RMS.

3.2.1. Cost-oriented objectives

In addition to the aforementioned RMT-related costs, line-specific costs should also be taken into account when considering the overall system. These costs can be classified into three main groups, namely investment/capital costs, RMS operating costs, and RMS reconfiguration costs. It should be noted that the operating and reconfiguration costs represent the production cost (Abbasi and Houshmand 2009).

Table 1. Objective functions of RMT used in some relevant journal papers.

Authors	Cost	Time	Reconfigurability	OC	Others
Ashraf and Hasan (2018)	✓		✓	✓	✓
Battaïa, Dolgui, and Guschinsky (2016)	✓				
Benderbal, Dahane, and Benyoucef (2017a)		✓			
Benderbal, Dahane, and Benyoucef (2017b)	✓	✓			
Bensmaine, Benyoucef, and Dahane (2013, 2014)		✓			
Chaube, Benyoucef, and Tiwari (2010)	✓	✓			
Choi and Xirouchakis (2014)	✓				
Dou, Dai, and Meng (2008)	✓				
Dou, Li, and Su (2016)	✓				
Goyal, Jain, and Jain (2012)	✓		✓	✓	
Goyal and Jain (2015)	✓		✓	✓	✓
Liu et al. (2018a)	✓				
Maniraj, Pakkirisamy, and Parthiban (2014)	✓				
Touzout and Benyoucef (2018)	✓	✓			
Touzout and Benyoucef (2019)		✓			
Xie, Li, and Xue (2012)	✓				✓

Note: OC represents 'operational capability'.

Capital cost is mainly associated with the fixed and one-time expenses related to the purchase of machines, modules, and tools. Authors such as Spicer, Yip-Hoi, and Koren (2005) and Youssef and ElMaraghy (2006, 2008b), considered the capital cost as an objective function that needs to be minimised in the design phase of an RMS. *Operating costs* include all costs incurred during the operational phase. These costs strongly depend on the configuration of an RMS. Operating costs are considered as part of the production cost in Abbasi and Houshmand (2009, 2010), along with an inventory-holding cost, which is also studied in (Choi and Xirouchakis 2014; Eguia et al. 2016). Xie, Li, and Xue (2012) considered operating cost as the sum of production and reconfiguration costs. The former is calculated by considering the line configuration, production volume related, and workstation idleness costs. The setup cost is considered in Aljuneidi and Bulgak (2016). Authors such as Ye and Liang (2006), Musharavati and Hamouda (2012a), Eguia et al. (2016), and Touzout and Benyoucef (2018, 2019) considered the material handling and transportation costs of products between machines, cells, or workstations. Ye and Liang (2006) considered work-in-process cost, which is related to the time a product spends within a line.

Reconfiguration cost is incurred when adding, moving, or removing machines from the RMS. Shabaka and ElMaraghy (2008) and Maniraj, Pakkirisamy, and Parthiban (2014); Maniraj, Pakkirisamy, and Jeyapaul (2015) among others, considered the machine change cost. A machine change is required when other production tasks have to be performed. Deif and ElMaraghy (2006a, 2006b) considered reconfiguration cost as the cost of adding or removing a machine from a line stage. In a cellular manufacturing system, cell-reconfiguration cost is associated with adding, moving, or removing machines from a cell (Ye and Liang 2006)

Figure 5 classifies all the aforementioned cost-related objectives, including machine and system costs.

3.2.2. Time-oriented objectives

In addition to the processing time, machine configuration, and tool change times, the completion time at the system level, which includes the time required for changing a line configuration (*i.e.* changing the layout of line, adding new stages, etc.) and machine change time were considered by (Bensmaine, Benyoucef, and Dahane 2014; Benderbal, Dahane, and Benyoucef 2017a). Chaube, Benyoucef, and Tiwari (2010), Bensmaine, Benyoucef, and Dahane (2014), and Benderbal, Dahane, and Benyoucef (2017b) also considered the transportation time between machines.

The throughput is another RMS performance indicator. It is not considered as much as the completion time in the literature, but it provides information regarding the number of parts produced per time unit (Musharavati and Hamouda 2012a; Choi and Xirouchakis 2014). Liu et al. (2018a) considered *cycle time*, which is defined as the time interval between the release of two finished products. Unlike the completion time, the cycle time only includes the processing times and not the reconfiguration time. Both throughput and cycle time are related indicators of RMS performance.

3.2.3. Energy consumption

Reducing energy consumption and carbon footprint has become a major challenge in the industrial sector during the last decades (Touzout and Benyoucef 2018). Hence, these topics have received considerable attention in RMS research. Choi and Xirouchakis (2014), Liu et al. (2018a), and Touzout and Benyoucef (2018) optimised the energy consumption of an RMS. In Choi and Xirouchakis (2014) and Touzout and Benyoucef (2018), the authors considered the energy consumed by an RMS composed of

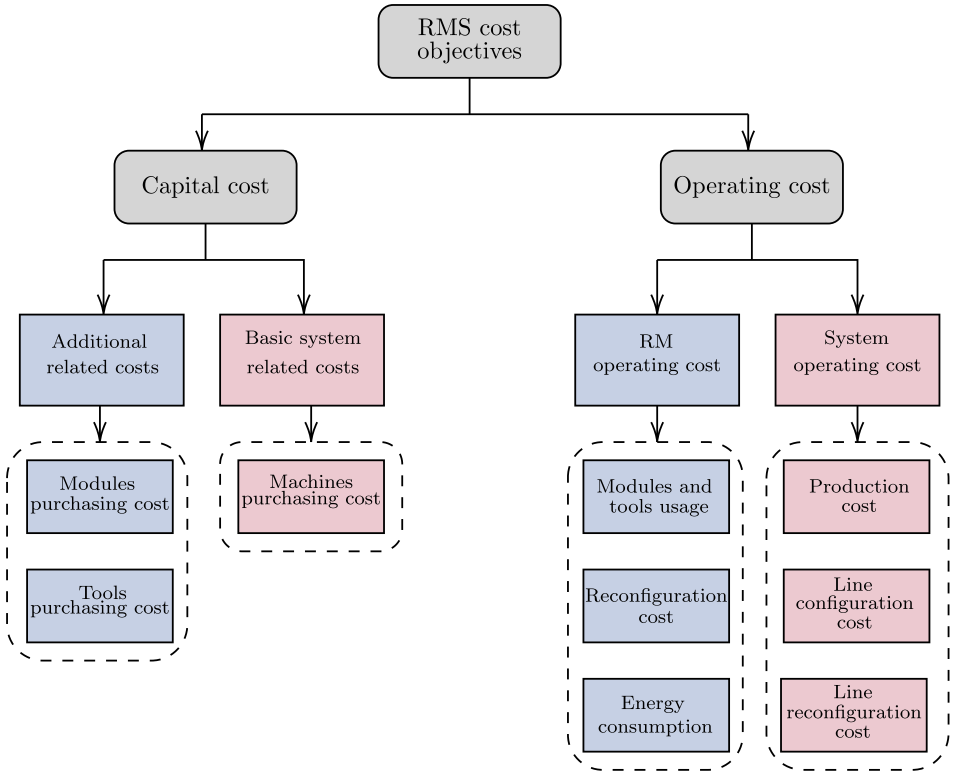

Figure 5. Cost-oriented objectives of RMS.

RMTs. It includes the energy related to machining a part, energy incurred when changing the configuration and tools, energy required for transportation, and material handling energy. Liu et al. (2018a) considered an RMS consisting of a rotary machining table. In this study, the authors calculated the energy consumption as the sum of the machine start-up energy, energy incurred by the table and turrets, and energy required for the tasks.

3.2.4. Other system indicators

In order to quantify the different characteristics of RMS, several authors have proposed various performance indicators. These indicators allow us to measure the level of flexibility and responsiveness of the RMS under different circumstances.

- *System reliability*: Ashraf and Hasan (2018) optimised the reliability indicator of a reconfigurable flow line composed of RMTs. The system reliability was calculated as the product of the reliability of each of the chosen RMTs.
- *System modularity*: As defined in Benderbal, Dahane, and Benyoucef (2017b), this indicator reflects the minimum number of auxiliary modules that should be used to produce different products. Optimising it involves finding as many common modules as possible to be shared among the product families. Hence, this indicator is related to the reconfiguration time and cost.
- *System flexibility*: This performance indicator was used in (Benderbal, Dahane, and Benyoucef 2017a). It reflects the number of alternative configurations provided by an RMS to cope with hazards (such as machine unavailability or breakdown).
- *System availability*: This indicator is related to machine availability and represents the uptime of an RMS within a given period of time (Youssef and ElMaraghy 2008b).
- *System utilisation*: This indicator reflects the scalability aspect and is used to measure the RMS capacity over different scenarios. In Youssef and ElMaraghy (2008b), this indicator is expressed as the ratio of demand requirement (i.e. system output) and expected production capacity.
- *Configuration convertibility*: According to Goyal and Jain (2015), this indicator reflects the capability of the system to be reconfigured (for example, by adding, moving, or removing machines or by changing the layout).

Table 2 summarises the relevant RMS objective functions discussed in the literature.

Table 2. Objective functions of RMS used in some relevant journal papers.

Authors	Cost	Time	Energy	Others
Abbasi and Houshmand (2009)	✓			
Aljuneidi and Bulgak (2016)	✓			
Ashraf and Hasan (2018)				✓
Benderbal, Dahane, and Benyoucef (2017a)		✓		✓
Benderbal, Dahane, and Benyoucef (2017b)				✓
Bensmaine, Benyoucef, and Dahane (2014)		✓		
Carlo, Spicer, and Rivera-Silva (2012)	✓			
Choi and Xirouchakis (2014)	✓	✓	✓	
Deif and ElMaraghy (2006a)	✓			
Dou, Dai, and Meng (2008)	✓			
Eguia et al. (2016)	✓			
Elmaraghy, Nada, and Elmaraghy (2008)	✓			
Liu et al. (2018a)		✓	✓	
Maniraj, Pakkirisamy, and Parthiban (2014)	✓	✓		
Musharavati and Hamouda (2012a)	✓			
Saxena and Jain (2012)	✓			
Shabaka and ElMaraghy (2008)	✓			
Spicer, Yip-Hoi, and Koren (2005)	✓			
Spicer and Carlo (2007)	✓			
Touzout and Benyoucef (2018)	✓	✓	✓	
Wang and Koren (2012)	✓			
Xie, Li, and Xue (2012)	✓			
Ye and Liang (2006)	✓			
Youssef and ElMaraghy (2008b)				✓

Note: The cost-oriented goals have been studied the most, whereas the sustainability aspects of RMS have been considered only by a few papers.

4. Overview of solution approaches

In the previous sections, RMS and its various components (reconfigurable machines and line types) were defined. In addition, the indicators used in the literature to assess the performance of such system were described. This section provides an overview of the solution approaches used to solve RMS optimisation problems. A classification of these problems is given in Section 5.

The solution approaches can be classified into exact and heuristic ones. The former seeks an optimal solution of a given problem, whereas the latter provides good-quality solutions without guaranteeing their optimality.

4.1. Exact methods

The process of solving an optimisation problem requires a mathematical formulation. This allows us to clearly describe the problem by defining its input data, decision variables, and objective function(s). Certain RMS problems can be formulated as linear programming (LP), integer LP (ILP), mixed-integer LP (MILP), or multi-objective integer LP (MOILP) models (Touzout and Benyoucef 2018). Non-linear models can also be used, as in Carlo, Spicer, and Rivera-Silva (2012) and Abbasi and Houshmand (2009), wherein a mixed-integer non-linear programming (MINLP) formulation was proposed.

Commercial solvers are usually used to solve the aforementioned problem formulations. They are based on the branch-and-cut methodology, which is known to be a generic exact method that aims to attain optimal solutions. However, such solvers have limitations when used for large-scale problems. Therefore, some authors developed exact methods by taking advantage of the problem structure to find optimal solutions more quickly. For example, Borisovsky, Delorme, and Dolgui (2013a, 2013b) used dynamic programming (DP) and constraint generation (CG) approaches to solve a reconfigurable machining line balancing problem. CG is an exact algorithm based on a mathematical formulation, in which certain difficult constraints of the original problem are relaxed. Iteratively, new constraints are generated based on the obtained solutions of the relaxed problem. DP is a method that decomposes a problem into smaller sub-problems, which are solved in a recursive manner. However, the efficiency of these approaches strongly depends on the type and structure of the problem.

4.2. Heuristic approaches

Exact methods usually have limitations when handling real-size problem instances. Therefore, heuristic methods are used to obtain good-quality solutions quickly. This is the case for both process planning (see Section 5.1.1) and flow line configuration selection (see Section 5.1.2) problems. Here, genetic algorithms (GAs) and non-dominated sorted GA (NSGA-II), which is a multi-criteria version of GA, are widely used; they have been proven to be efficient (Shabaka and ElMaraghy 2008; Dou, Li, and Su 2016). GA is a population-based evolutionary algorithm, which imitates the process of natural selection. It is based on an initial set of generated candidate solutions. Each solution is considered as a genotype. Subsequently, crossovers and mutations are continuously applied to the genotypes to produce new solutions called offsprings. The algorithm stops when the desired solution quality is obtained or when a stop condition is reached. The reason why many authors use these methods is that they remain one of the best known and the most developed methods in the literature.

Meanwhile, Benderbal, Dahane, and Benyoucef (2017b) proposed multi-objective simulated annealing (MOSA) to solve multi-objective process planning problems. This meta-heuristic is based on simulated annealing (SA), which is inspired by the experimental annealing process in metallurgy, where a metal is heated and then slowly cooled down to reduce defects. Its algorithmic implementation is based on a temperature parameter, which controls the probability of accepting worse solutions when exploring a solution space. The algorithm stops when the ambient temperature is reached. The authors demonstrated the efficiency of this method in finding non-dominated solutions. However, after comparing MOSA and NSGA-II for RMS process planning problems, Touzout and Benyoucef (2018) concluded that NSGA-II is more efficient than MOSA in terms of the quality of the Pareto front approximation. The main reason is that NSGA-II explores the solution space from a generated population, while MOSA iterates around one solution at a time.

Other heuristics were also used in the literature to solve different RMS optimisation problems. Brief descriptions of these methods are given below.

- Ant colony optimisation (ACO) is a population-based algorithm inspired by the behaviour of ants in finding the shortest path from the nest to a food source. In ACO, artificial ants are used to explore a solution space. The solution is constructed based on a pheromone model, which is an organic compound. A greater intensity of pheromone on a path reflects a better solution. This method was used by Maniraj, Pakkirisamy, and Parthiban (2014); Maniraj, Pakkirisamy, and Jeyapaul (2015) to determine a process plan for an RMS.
- Iterated local search (ILS) is a method that aims to explore the neighborhood of a given initial admissible solution. Perturbations are applied randomly to visit other solution neighborhoods, thus avoiding a local optimum. The readers are requested to refer, for example, Touzout and Benyoucef (2019) for an application of ILS to solve a process planning problem.
- Particle swarm optimisation (PSO) is inspired by the social behaviour of birds or fish. It uses agents (or particles) to search for the best solution. Each particle's movement is affected by its best achieved position as well as by the best position of the group. Multi-objective particle swarm optimisation (MOPSO) is a multi-criteria version of PSO. Goyal and Jain (2015) implemented this heuristic to define the best process plans of an RMS.
- Tabu search (TS) is a local search-based algorithm, which checks the immediate neighbors of a given feasible solution. Usually, such methods implement a memory structure to avoid revisiting already visited solutions. Youssef and ElMaraghy (2008a) used a TS heuristic to optimise the capital cost and system availability of RMS configurations.
- Artificial immune system (AIS) is a population-based meta-heuristic. It is inspired by a biological immune system whose aim is to protect the body from antigens. In order to select the optimal RMS configurations (in terms of cost), Saxena and Jain (2012) proposed a multi-phase methodology based on AIS.

5. Classification of RMS optimisation problems

Based on our analysis of the selected articles, RMS optimisation problems can be grouped into four categories: (1) RMS design, (2) production planning and scheduling, (3) layout design, and (4) line balancing and re-balancing.

5.1. RMS design

An RMS is composed of reconfigurable machines, CNC machines, material handling systems, and workers that are linked together in a certain way to produce a family of products. Such resources generally include a cutting-edge technology, which results in high investment and operating costs. Consequently, designing an RMS is a very important issue, which requires making crucial decisions. These decisions include product design, product family formation, process planning/line configuration design, layout design, and line balancing (Battaïa and Dolgui 2013).

A product design provides the necessary information about the manufacturing procedures. Product family formation involves identifying and grouping products into families based on their operational similarities (Abdi and Labib 2004; Galan et al. 2007) or task sequence similarities (Goyal, Jain, and Jain 2013; Gupta, Jain, and Kumar 2013; Bortolini, Galizia, and Mora 2018). Since these two steps are solved using methods other than optimisation (such as clustering techniques and multi-criteria decision-making methods), we do not find it necessary to mention them in detail in this paper (for further information, see Bortolini, Galizia, and Mora 2018). The focus will be mainly on process planning and layout design, where significant optimisation problems arise.

5.1.1. Process planning

As defined in Zhang, Zhang, and Nee (1997), process planning determines the detailed machining requirements for transforming a raw material into a finished part. A part is defined by a set of features, such as a geometric shape, holes, bosses, etc. The aim of process planning is to select tasks and determine their sequence on manufacturing lines. In addition, machining and cutting tools, fixtures, and all the necessary parameters should be selected (Alting and Zhang 1989).

Several authors have addressed the process planning stage when considering the presence of RMTs in a reconfigurable environment (Shabaka and ElMaraghy 2008; Musharavati and Hamouda 2012a, 2012b; Bensmaine, Benyoucef, and Dahane 2014). Table 3 presents the rel-

Table 3. Relevant process planning problems and their solution approaches in the RMS literature.

Authors	Objective(s)	Approaches
Benderbal, Dahane, and Benyoucef (2017a)	↓ Completion time ↑ System flexibility	NSGA-II
Benderbal, Dahane, and Benyoucef (2017b)	↓ Completion time ↑ System modularity	AMOSA
Bensmaine, Benyoucef, and Dahane (2013)	↓ Completion time	NSGA-II
Bensmaine, Benyoucef, and Dahane (2014)	↓ Makespan	Heuristic
Chaube, Benyoucef, and Tiwari (2010)	↓ Total cost ↓ Completion time	NSGA-II
Maniraj, Pakkirisamy, and Parthiban (2014); Maniraj, Pakkirisamy, and Jeyapaul (2015)	↓ Total cost	ACO
Musharavati and Hamouda (2012a)	↓ Total cost ↑ Throughput	SA
Musharavati and Hamouda (2012b)	↓ Total cost	SA
Shabaka and ElMaraghy (2008)	↓ Total cost	GA
Touzout and Benyoucef (2018)	↓ Total cost ↓ Completion time ↓ Energy consumption	MOILP AMOSA NSGA-II
Touzout and Benyoucef (2019)	↓ Total cost ↓ Completion time ↓ Machines exploitation time	ILS NSGA-II
Xie, Li, and Xue (2012)	↓ Total cost ↑ Machine precision ↑ Smoothness	GA

Note: Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise)

evant articles on process planning in RMS, their corresponding objective functions, and solution approaches. The minimisation of total cost is the objective that has been considered the most (Shabaka and ElMaraghy 2008; Chaube, Benyoucef, and Tiwari 2010; Musharavati and Hamouda 2012a; Xie, Li, and Xue 2012; Maniraj, Pakkirisamy, and Parthiban 2014; Touzout and Benyoucef 2019). Many authors have considered multiple objectives. For example, Chaube, Benyoucef, and Tiwari (2010), Bensmaine, Benyoucef, and Dahane (2013), and Benderbal, Dahane, and Benyoucef (2017b) have minimised both total time and completion time. In addition, Benderbal, Dahane, and Benyoucef (2017a) and Benderbal, Dahane, and Benyoucef (2017b) considered the maximisation of system modularity and system flexibility, respectively. Touzout and Benyoucef (2018, 2019) minimised the energy consumption and exploitation time of the machines. Conversely, authors such as Musharavati and Hamouda (2012a) considered the throughput as a second objective besides the total cost. Xie, Li, and Xue (2012) introduced and optimised machine precision as well as smoothness index, which reflects the workload distribution among machines.

It should be noted that most of the above studies do not consider any particular arrangement of RMTs. As with a job shop environment, the only aspect taken into account is the routing of parts and RMT configurations. This means that two parts may have different routes through the same set of available machines. Therefore, such systems may be considered as reconfigurable job shops, which emphasise flexibility rather than productivity. In reconfigurable flow lines/RCMS, a set of workstations/cells are arranged in such a way that all the products follow the same path, *i.e.*, from the first workstation/cell to the last one. Such systems provide a high productivity as well as scalability.

5.1.2. Flow line configuration selection

Selecting a reconfigurable flow line (RFL) configuration is one of the issues that have been studied the most in the literature. Its output consists of the number of stages, number of machines per stage, and task assignment. Each stage disposes one or several parallel RMTs having different configurations, which provide a large number of possible configurations for RFL. Therefore, in Dou, Dai, and Meng (2008, 2009a, 2009c), the authors tried to find the most economical (in terms of capital cost) single product RFL configuration that could meet the demand requirement over a given period. An extension of this study was published in Dou, Dai, and Meng (2009b) by considering an optimisation of multi-product RFL configurations. In Dou, Li, and Su (2016), the authors integrated configuration selection and scheduling. In addition to the total cost, the reconfiguration cost and the total tardiness were minimised. A multi-objective single product RFL design was considered in Goyal, Jain, and Jain (2012), where machine reconfigurability and the operational capability of RMT were maximised and the operating costs were minimised. In addition to the previous objectives, Goyal and Jain (2015) tried to maximise machine utilisation and configuration convertibility.

Research papers such as Youssef and ElMaraghy (2006, 2007, 2008a) have considered the multi-product RFL configuration selection problem. The common objective is the minimisation of the capital cost. In addition, the system availability was maximised in Youssef and ElMaraghy (2007, 2008a). From the same perspective, Ashraf and Hasan (2018) considered a multi-objective approach in which the total cost was minimised and the reconfigurability, operational capability, and reliability of the system were maximised. Similarly, the capital, reconfiguration, operating cost, and maintenance cost were optimised in Saxena and Jain (2012) over different periods of time. In Hasan, Jain, and Kumar (2013), the authors tried to find an optimal order processing sequence based on the configuration of each part and the reconfiguration effort. The objective was to maximise the earned profit. Bryan, Hu, and Koren (2013) proposed an approach to design a reconfigurable assembly system capable of handling a product family, which evolves over time. The aim was to find an optimal reconfiguration plan in order to minimise the life-cycle cost, which is calculated based on the periods of production and reconfiguration of the product family. Similarly, Kumar, Pattanaik, and Agrawal (2018) proposed an optimal configuration sequence of a multi-model reconfigurable assembly system. The authors used a multi-objective self-organising migrating algorithm (MOSOMA) to minimise the reconfiguration cost, while considering the product due date and the system workload balance between different configurations.

The previous research papers have focused on the reconfigurability aspect of the RMS configuration selection problem. However, other authors have considered the scalability aspect. In those studies, the product demand fluctuations over different periods is taken into account while designing a scalable RMS. The objective is to identify when and how to reconfigure the system in order to meet the demand requirements. Reconfiguration generally involves adding, moving, or removing RMTs to different stages. Carlo, Spicer, and Rivera-Silva (2012) proposed an approach for designing an RFL while considering an ordering policy to achieve the required scalability. The objectives consist of minimising the investment and inventory-related costs. Scalable RMS configuration selection was considered in Moghaddam, Houshmand, and Valilai (2017) and Moghaddam et al. (2020). The former considered a single product RMS, whereas the latter considered a multiple product RMS. The objectives that were considered include the minimisation of the capital and reconfiguration costs. Deif and ElMaraghy (2006a) investigated the effects of reconfiguration costs on the RMS scalability planning. Spicer and Carlo (2007) proposed an approach to determine the optimal configuration path for scalable RMS. The objectives included minimisation of the investment and reconfiguration costs over different periods for a known demand. A decision aide tool based on GA was developed by Deif and ElMaraghy (2006b) to help designers decide when and how to reconfigure the system in order to satisfy the demand requirements at a minimum cost. The latter includes the cost associated with the physical capacity unit and the reconfiguration cost. Table 4 summarises the aforementioned papers with their corresponding objective functions and solution approaches.

Table 4. Relevant flow line design problems and their solution approaches in the RMS literature.

Authors	Objective(s)	Approaches
Ashraf and Hasan (2018)	↓ Total cost ↑ Reconfigurability ↑ Operational capability ↑ Reliability	NSGA-II
Bryan, Hu, and Koren (2013)	↓ Life cycle cost	DP & GA
Carlo, Spicer, and Rivera-Silva (2012)	↓ Investment cost ↓ Inventory cost	MINLP GA
Deif and ElMaraghy (2006a, 2006b)	↓ Production cost ↓ Reconfiguration cost	GA DP
Dou, Dai, and Meng (2008, 2009a, 2009b, 2009c)	↓ Capital cost	GA
Dou, Li, and Su (2016)	↓ Capital cost ↓ Reconfiguration cost ↓ Total tardiness	NSGA-II
Goyal, Jain, and Jain (2012)	↑ Machine reconfigurability ↑ Operational capability ↓ Operating cost	NSGA-II
Goyal and Jain (2015)	↓ Capital cost ↑ Operational capability ↑ Machine utilisation ↑ Configuration convertibility	MOPSO
Kumar, Pattanaik, and Agrawal (2018)	↓ Reconfiguration cost ↓ Tardiness ↑ Workload balance	MOSOMA
Moghaddam, Houshmand, and Valilai (2017)	↓ Capital cost	ILP
Moghaddam et al. (2020)	↓ Reconfiguration cost	MILP
Saxena and Jain (2012)	↓ Capital cost ↓ Reconfiguration cost ↓ Operating cost ↓ Maintenance cost	AIS
Spicer and Carlo (2007)	↓ Investment cost ↓ Reconfiguration cost	DP ILP
Youssef and ElMaraghy (2006)	↓ Capital cost	GA
Youssef and ElMaraghy (2007, 2008a)	↓ Capital cost ↑ System availability	GA TS

Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise)

Carlo, Spicer, and Rivera-Silva (2012) used a GA to simultaneously minimise the system investment and operating costs in a multistage multi-product scalable RMS. The GA seeks different machine configurations that are used to compute the optimal batch cycle length.

Dou, Dai, and Meng (2009a, 2009b) developed a GA-based method to generate a set of economical configurations for a multi-product RMS. The proposed genotype links feasible operation clusters with feasible operation sequences.

In Youssef and ElMaraghy (2006, 2007), Youssef and ElMaraghy (2008b), GAs are used to optimise the capital cost as well as the availability of a manufacturing system configuration that satisfies certain demand requirements. The genotype is encoded in three parts corresponding to the sequence of each product, the distribution of operations over the available production stages, and the machine configuration selections of each stage.

5.1.3. RCMS/DCMS design

According to Ghotboddini, Rabbani, and Rahimian (2011), a CMS is designed in four steps: (1) cell formation, which involves grouping similar parts into part families and allocating machines into cells accordingly; (2) intra-cell machine layout selection; (3) scheduling of parts for production; and (4) resource allocation, where tools, workforce, and other resources are assigned.

In an RCMS design problem, RMT and CNC machines are grouped into machining cells based on the similarities of part manufacturing tasks. The aim of such a system is to provide independence to the cells while ensuring a desired flexibility to adapt to the changes in product demand over different periods. Table 5 outlines the relevant RCMS optimisation papers with their corresponding objectives and solution approaches. Renna and Ambrico (2014) proposed three mathematical models. The first model is used to design an RMCS while considering the non-deterministic product demand over different periods and the presence of RMs. The objective here is the minimisation of inter-cell movements and machine investment costs. The second multi-objective model is employed to propose a reconfiguration strategy between periods in a way that maximises the profit and satisfies the customer demands. The third model is used for scheduling the parts in each cell so as to maximise the profit. The three models are solved separately, and the output of one model is the input of the next one. In Pattanaik, Jain, and Mehta (2006) and Eguia et al. (2016), the authors considered the presence of modular RMTs composed of basic and auxiliary modules as well as CNC machines with a limited tool magazine and an automatic tool changer (Eguia et al. 2016). The latter has the ability to be easily reconfigured, which provides the system with a wide range of operational capabilities. The objective of Pattanaik, Jain, and Mehta (2006) was to design machining cells while minimising intercellular movements and overall changes in the auxiliary modules. Eguia et al. (2016) considered a cell design problem taking into account the fact that different products have different process plans. For this, the authors proposed an integer linear programming (ILP) model to minimise inter-cellular movements and maximise the intra-cellular ressource utilisation. Subsequently, a multi-period cell loading problem was formulated as a mixed ILP (MILP). Solving the MILP allows us to determine the optimal routing of different parts as well as the allocation of tools and modules within each cell to minimise the total cost, which includes the inter-cellular transportation cost and the inventory holding cost. Yu et al. (2012) proposed an integer programming formulation to address part grouping and cell loading simultaneously. The objective function aims to balance the workload of the machines. A sustainable manufacturing system design, which combines RCMS and a hybrid manufacturing-remanufacturing system, was proposed in Aljuneidi and Bulgak (2016, 2017). Such a system can either produce new products using a raw material or remanufacture components using disassembled products. The objective, which is achieved using an MILP formulation, is to minimise the machine related costs (maintenance, relocation, operation, etc.) and the costs associated with manufacturing and remanufacturing (production, inventory holding and setup, part disassembly, inventory holding for returned products, etc.).

Table 5. Relevant RCMS design problems and their solution approaches in the RMS literature.

Authors	Objective(s)	Approaches
Aljuneidi and Bulgak (2016, 2017)	↓ Machine related costs ↓ (Re)-Manufacturing costs	MILP
Eguia et al. (2016)	↓ Inter-cellular movements ↓ Intra-cellular void ↓ Total cost	ILP MILP
Pattanaik, Jain, and Mehta (2006)	↓ Inter-cellular movements ↓ Total changes in auxiliary modules	GA
Yu et al. (2012)	↑ Machine workload balancing	IA & ILP

Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise) and IA represents 'Iterative Algorithm'

In comparison to an RCMS, a DCMS is not composed of RMT and CNC machines. However, reconfigurability is achieved through movable machines that can be easily relocated between different cells in order to cope with the product mix and demand variations within different periods. The aim is to allocate appropriate machines to the cells over different periods in order to optimise the desired objective function. For example, in Tavakkoli-Moghaddam et al. (2010), Ghotboddini, Rabbani, and Rahimian (2011) and Rabbani et al. (2014), the authors minimised different costs such as inter/intra-cellular movement, machine relocation, and machine purchasing costs. In addition, Rabbani et al. (2014) maximised the utilisation rate of machines. Ghotboddini, Rabbani, and Rahimian (2011) considered the presence of human workforce with a second objective function that focused on balancing labour assignments for all cells in each period.

5.1.4. Rotary machining system design

Several studies have been conducted on the design of rotary machining systems used for mass production. Battaïa, Dolgui, and Guschinsky (2016) and Liu et al. (2018a) tried to bridge the gap by considering the reconfigurability aspect of such systems to produce several part families. As shown in Table 6, both papers proposed a decision support tool (based on optimisation methods)

Table 6. Relevant rotary machining design problems and their solution approaches in the RMS literature

Authors	Objective(s)	Approaches
Battaïa, Dolgui, and Guschinsky (2016)	↓ Total cost	MILP
Liu et al. (2018a)	↓ Total cost ↓ Cycle time	MILP MOSA

Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise)

to help design such systems while minimising the total cost (costs related to turrets, spindles, and machining modules). Such a problem involves assigning a given set of tasks to machining modules and allocating the appropriate resources (spindle and turrets) to achieve them. In addition, Liu et al. (2018a) offers a sustainable approach by including the energy consumption cost of machines during their operating phase along with the cycle time.

5.2. Production planning and scheduling in RMS

Production planning and scheduling (PPS) aims to maximise the efficiency of a manufacturing system. In a reconfiguration environment, the objective of PPS is to obtain an appropriate production plan, resource and worker allocation, and batch size as well as to ensure proper scheduling of the products to fulfil customer requirements over a given planning horizon. Scheduling problems seek an optimal sequence of products that share one or a group of resources subject to a certain number of constraints (such as due date and resources availability).

In RMS, scheduling is often associated with the configuration design/process planning problem. The reason is that each product requires a particular configuration of machines. The output includes the sequence of products to be released, the selection of machines and their appropriate configurations, product assignments, and sequencing of machines. Table 7 shows the relevant papers dealing with scheduling in RMS. In Bensmaine, Benyoucef, and Dahane (2014), the authors integrated process planning and scheduling to find the best sequence of manufacturing parts while considering the reconfigurable aspects of RMT and their availability. The objective was to minimise the makespan, which includes the task processing time, transportation time, and reconfiguration time. Dou, Li, and Su (2016) considered an integrated configuration generation and scheduling problem in an RFL. The objectives included the minimisation of the total cost and the total tardiness. With regard to RCMS, Ye and Liang (2006) proposed an integrated cell configuration selection and scheduling of modular parts. The objective, which was achieved using a genetic algorithm, was to minimise the total cost (reconfiguration, machine-idle, material-handling, and work-in-process costs). Yu

Table 7. Relevant scheduling problems and their solution approaches in the RMS literature.

Authors	Objective(s)	Approaches
Bensmaine, Benyoucef, and Dahane (2014)	↓ Makespan	Heuristic
Dou, Li, and Su (2016)	↓ Total cost ↓ Total tardiness	NSGA-II
Ye and Liang (2006)	↓ Total cost	GA
Yu et al. (2013)	↓ Makespan ↓ Mean flow time ↓ Mean tardiness	Heuristic

Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise)

et al. (2013) used a priority rule-based approach to propose part scheduling in an RMS while considering the availability of pallets/fixtures. The objectives to be minimised were the makespan, mean flow time, and mean tardiness.

For production planning, Abbasi and Houshmand (2009, 2010) respectively proposed a mathematical formulation and a genetic algorithm approach. In both papers, the objective was to maximise the RMS efficiency while satisfying market demands. For this, the authors considered that the product arrival order is stochastic, and they tried to find an optimal solution in terms of the length of the considered period, the number of production tasks to be achieved, the sequence of products and their appropriate configurations, and the batch size of each production task. The objective function in Abbasi and Houshmand (2009, 2010) was to maximise the earned profit. Choi and Xirouchakis (2014) focused on a production planning problem, aiming to find the optimal production quantity of each product while considering different process plans. The authors studied the energy consumption of the system, environmental impacts, and the throughput, which were optimised. Table 8 summarises the aforementioned papers with their corresponding objectives and solution approaches.

5.3. Layout design in RMS

In general, a layout design problem, which is usually called a facility layout problem (FLP), involves finding an effective arrangement of resources within a production workshop subject to different constraints. The main objectives are to minimise the cost and time related to the

Table 8. Relevant planning problems and their solution approaches in the RMS literature.

Authors	Objective(s)	Approaches
Abbasi and Houshmand (2009, 2010)	↑ Profit	GA & TS MINLP
Choi and Xirouchakis (2014)	↓ Energy consumption ↑ Throughput	LP

Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise) handling of materials, which have a significant impact on productivity. In addition, such a decision is crucial since the material handling cost represents 20–50% of the total cost, and a proper machine layout can reduce the latter by at least 10–30% (Hosseini-Nasab et al. 2017). Owing to the importance of this issue, many studies have been conducted on FLP from different perspectives.

From the literature review of Hosseini-Nasab et al. (2017), it can be seen that most of the papers deal with a static FLP (SFLP). SFLP derives its definition from the fact that the flow of products does not change over time. In other words, it can be considered as a dedicated layout, which obviously does not represent an effective solution for the current market conditions. As a result, during the last two decades, many authors have worked on dynamic FLP (DFLP), where the flow may change during the planning horizons (Hosseini-Nasab et al. 2017). This can be considered as a reconfigurable layout. Here, in addition to the previously mentioned objectives, the authors minimised the cost related to layout rearrangement (McKendall and Shang 2006; McKendall and Hakobyan 2010; Abedzadeh et al. 2012; Derakhshan Asl and Wong 2015). An interesting review on DFLP and their optimisation approaches is provided in Moslemipour, Lee, and Rilling (2011).

In the RMS literature, there are only a few researches on the layout design problem. Similar to that for DFLP, the objective in Guan et al. (2012) was to minimise the material handling and reconfiguration costs by implementing a revised electromagnetism-like mechanism (REM) heuristic. The authors considered automated guided vehicles, which were used to transport any product from one workstation to another. Reconfiguration involves reallocating workstations to meet new demand requirements. From another perspective, Haddou Benderbal and Benyoucef (2019) studied an RMS layout design while considering the evolutionary aspect of the product. In this study, the layout was proposed based on a generated process plan. Subsequently, the authors used an AMOSA to generate the layout design. The objective was to consider the constraints related to given candidate positions within a workshop. Table 9 shows the objectives and solution approaches used in the papers dealing with layout design problems in a reconfigurable environment.

Table 9. Relevant layout design problems and their solution approaches in the RMS literature.

Authors	Objective(s)	Approaches
Guan et al. (2012)	↓ Material handling cost ↓ Reconfiguration cost	REM
Haddou Benderbal and Benyoucef (2019)	↓ Constraint satisfaction penalty	AMOSA

Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise)

5.4. Line balancing and re-balancing

Line balancing issues generally arise in assembly, disassembly, and transfer lines. Such lines are composed of a set of linearly ordered workstations. Each workstation can perform a subset of tasks. The tasks are characterised by their processing time, and a partial order that is usually expressed by a precedence graph. The products pass through the workstations in a synchronised manner defined by the cycle time. Usually, there are two objectives: (i) minimising the cycle time, i.e. maximising the throughput, and (ii) minimising the number of workstations for a given set of constraints regarding cycle time and precedence constraints. The literature on such issues have been widely studied in Battaïa and Dolgui (2013).

A balanced line is designed for a long-term horizon, which makes it more suitable for a DML. However, in order to cope with possible product changes/evolution or hazards (such as machine breakdowns), these lines need to be re-balanced. Re-balancing a balanced line involves reassigning tasks between existing workstations while satisfying the new constraints. These lines are not a part of the RMS, but their ability to be re-balanced in order to respond to external changes gives them a reconfigurability aspect. Hence, we find it necessary to provide an overview of the research on these topics. One of the objectives of the assembly line re-balancing problem (ALRBP) is to minimise the number of reassigned tasks (Grangeon, Leclaire, and Norre 2011; Makssoud et al. 2015; Sancı and Azizoğlu 2017) or the cost associated with the re-balancing (Yang, Gao, and Sun 2013; Makssoud, Battaïa, and Dolgui 2014). Moreover, Grangeon, Leclaire, and Norre (2011) considered additional objectives such as the minimisation of the number of workstations. Makssoud, Battaïa, and Dolgui (2014) proposed a MILP model to minimise the investment cost for new equipment by reusing the existing ones as much as possible. Sancı and Azizoğlu (2017) considered a re-balancing problem in which a workstation breakdown or shutdown occurs. In those cases, the tasks performed by such workstations have to be reassigned among the available ones. The authors aimed to achieve a trade-off between the cycle time and the number of reassigned tasks. Yang, Gao, and Sun (2013) studied a mix-model assembly line with operators while considering seasonal demands. Such a line can be re-balanced (reconfigured) to meet a new demand. The objective function minimises the number of workstations and their workload variations as well as the re-balancing cost.

Table 10. Relevant line balancing problems and their solution approaches in RMS literature.

Authors	Objective(s)	Approaches
Borisovsky, Delorme, and Dolgui (2013a, 2013b)	↓ Number of CNC machines	CG & DP & GA

Here, ↑ (resp. ↓) indicates an objective to maximise (resp. minimise)

Borisovsky, Delorme, and Dolgui (2013a, 2013b) considered a machining line in a reconfigurable environment, where each workstation could be equipped with one or more parallel CNC machines. The CNC machines could be reallocated, allowing the reconfiguration of the line in order to meet new demand requirements. However, the authors only considered the initial line balancing and not the line balancing of the reconfigured line. The objective was to minimise the total number of CNC machines while satisfying certain constraints such as cycle time, precedence relationship between tasks, accessibility, and inclusion and exclusion constraints. The approaches they used are shown in Table 10.

6. Conclusion and perspectives

A literature review on RMS optimisation problems was presented in this paper. First, clear definitions of the various existing concepts of reconfigurable machines were provided. This makes it possible to understand and correctly visualise the composition of an RMS. Different line types and their characteristics were then described based on the literature. The objective was to provide an overview of how an RMS could be implemented in the industry, depending on the type of product family and the desired performances. Subsequently, different performance indicators of an RMS were defined according to two levels: machine level and system level. Finally, different optimisation problems were classified based on relevant journal papers. Here, we showed how the previously mentioned performance indicators were used to achieve different objectives. In addition, the optimisation approaches were described briefly.

Based on our review, we observe that the design of RMS has received more attention compared to other problems. The literature on process planning, reconfigurable flow lines, and RCMS design is richer and more diversified than those on layout design, production planning, scheduling, and line balancing. More than 70% of the papers have considered these problems using approximate approaches. This reflects the fact that RMS optimisation problems are strongly combinatorial and NP-hard in general. However, few authors have solved these problems using exact methods. With regard to the objective function, the main concerns of the authors are the cost and time. Meanwhile, reconfigurability and scalability aspects are the RMS characteristics that have been considered the most. The majority of the problems that have been addressed are related to the machining of parts, whereas the other industrial sectors have received less attention.

As a conclusion and in view of the aforementioned observations, we suggest some future research directions as follows:

- With regard to RMS design, there is a need to develop theoretical and less context-dependent mathematical formulations. The latter can provide a more homogeneous description of an RMS and can be used as a starting point.
- The layout design problems in a reconfigurable environment should be investigated in more detail by considering the layout or material handling system reconfigurations. For this, we suggest bridging the gap between dynamic facility layout and RMS layout design problems since both are meant to adapt to new market conditions.
- Similarly, a combination of reconfigurable cellular manufacturing system (RCMS) and dynamic cellular manufacturing system (DCMS) can be explored.
- Line re-balancing could be considered in an RMS context if it can be planned upstream, (i.e. anticipating rather than reacting to hazards).
- Greater attention should be given to sustainability and environmental issues in the design phase of an RMS.
- Only few authors have investigated the modularity aspect of RMS. Therefore, an interesting research direction regarding this characteristic could be to optimise the number of modules necessary to produce a family of products.
- At present, emerging technologies such as digital twin (DT) are seen as a promising solution in the design and operation of a manufacturing line (Liu et al. 2018b; Ding et al. 2019). DT acts as a real-time decision support tool, which continuously collects data from a manufacturing line. These data are then analysed, processed, and optimised to provide appropriate decisions that maximise the performance of the system. One promising research direction is to investigate how DT can be used for RMS configuration design and reconfiguration planning. This means developing online optimisation approaches.

Disclosure statement

No potential conflict of interest was reported by the authors.

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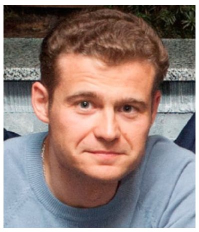

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