Operations scheduling for waste minimization: a review ☆

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Abstract

This article proposes a review on waste minimization at the operational level of production planning. After defining the research scope and the concept of waste minimization through scheduling, the state-of-the-art is presented. A classification based on environmental and scheduling criteria is proposed, which details the various types of scheduling problems encountered and groups them into different categories. Results show that despite having developed in the recent years, literature on waste-minimizing scheduling remains scarce and lacks a unified terminology. While research on energy-efficient scheduling has garnered a lot of attention, improving resource efficiency and reducing waste generation is also an important step towards a greener production. Thus, research perspectives for the inclusion of waste reduction concerns in scheduling are proposed based on the analysis of the literature classification.

Keywords: Literature review, scheduling, waste, multicriteria optimization, manufacturing operations

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15054 words

Acronyms: 1DCSP - 1-Dimensional Cutting Stock Problem, B&B - Branch and Bound, CSP - Cutting Stock Problem, ICSP - Integrated Cutting Stock Problem, ILP - Integer Linear Programming, INLP - Integer Non Linear Programming, LCA - Life Cycle Analysis, LP - Linear Programming, LSP -

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Lot Sizing Problem, MILFP - Mixed Integer Linear Fractional Programming, MILP - Mixed Integer Linear Programming, MINLP - Mixed Integer Non Linear Programming

1. Introduction

Sustainable production is defined as “the creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers, communities, and consumers; and socially and creatively rewarding for all working people” (LCSP, 1998). In recent years, more and more research has been devoted to it as a possible answer to the environmental issues affecting industrial companies, such as stricter regulations, highly volatile energy prices, the shortage of raw materials and natural resources and customer demand for more environmentally-friendly products (Giret et al., 2015). Sustainable production concerns the manufacturing industry as a whole, and covers many aspects such as waste management (Memon, 2010), process planning (Shojaeipour, 2015), logistics (Govindan et al., 2015; LMI Goverment Consulting, 2003) and clean technologies (Jawahir and Jayal, 2011). Those manufacturing operations can concern both discrete manufacturing, which typically produces distinct and individual products, and process manufacturing, which transforms a mix of materials into batches of products. As a key factor in production efficiency, operations scheduling is one of several levers that can be used in order to address the aforementioned environmental issues, and without the need for high investment since no new machines are required (Trentesaux and Prabhu, 2014). Thus, by implementing more environmentally aware scheduling, it becomes easier to enable the 3R policy (Reduce, Reuse and Recycle) advocated by the European parliament (European Parliament and Council, 2008).

In their literature reviews on sustainability in manufacturing operations scheduling, Giret et al. (2015) and Fang et al. (2011) show that research thus far has mostly focused on the reduction of energy consumption; detailed reviews on energy efficient scheduling can be found in Gahm et al. (2016) and

Biel and Glock (2016). Giret et al. (2015) also emphasize the need to address the outputs resulting from scheduling (waste, scrap, pollution) to design sustainable schedules, since there are few works on this topic. Hence, this work aims at **reviewing the existing literature on waste minimization in operations scheduling taking into account both the economic and environmental aspects, and provide insights into facilitating future research in this field**.

Waste is defined by the European Parliament and Council (2008) as "any substance or object which the holder discards or intends or is required to discard", a substance being "any chemical element and its compounds" (European Council, 2010). Gaseous effluents are not considered as waste in the 2008 directive, as they are part of a broader category called "emissions" which also includes heat, vibrations or noise. This article focuses on the reduction of waste as defined by the European parliament, that is to say solid substances and objects as well as wastewater. According to Pinedo (2008), scheduling "deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives". Those objectives typically feature economic indicators such as the makespan and production costs. In the case of sustainable manufacturing, an environmental aspect is also included, such as the environmental impact of production and the quantity of waste generated. Improvements in scheduling affect resource efficiency, and thus reduce the resource consumption and waste generation of the production process. This review focuses on preventing upstream waste generation (i.e. reducing its quantity or impact) through operations scheduling. Therefore, topics such as sustainable manufacturing processes, end-of-pipe management or waste treatment technologies are not covered in this review. Similarly, municipal waste management, which is the most investigated topic as far as waste and scheduling are concerned (interested readers can refer to Ghiani et al. (2014)), is not studied here.

Although not very extensive, the literature dealing with waste generation through operations scheduling is diverse, both in terms of industrial contexts (type of waste and process concerned) and the scheduling problems involved. Research in this field does not yet possess a unified framework, and is not often labeled as pertaining to waste-minimizing scheduling. The interdisciplinarity as well as the lack of a standardized terminology do not allow for easy knowledge-sharing. This makes the realization of a state-of-the-art all the more important, along with the means to compare and analyze the articles reviewed. Thus, we propose a classification including the identification, listing and appropriate description of the different problem characteristics that can impact waste generation at the scheduling level. Through the classification process, we define categories of problems sharing similar characteristics and identify areas where further research is needed.

As previously stated, the motivation for this work stems from the review on sustainable scheduling by Giret et al. (2015). Although our purposes are similar, the scope of our review is much more specific. Since their study includes all kinds of works regarding sustainable operations scheduling, Giret et al. (2015) include only a portion of the existing literature judged "representative of the diversity of studies relevant to sustainable manufacturing operations scheduling". As a result, 92% of their referenced papers deal with the minimization of energy consumption, and only four articles address waste and are present in our review. Since waste represents a lesser portion of the literature, our aim is to be as complete as possible.

Section 2 describes the methodology used for the review process. In section 3, the existing literature on waste minimization in operations scheduling is reviewed, and a classification based on the observed problem characteristics is proposed in section 4. Section 5 provides information on the ways to address these issues, as well as prospective improvements; possible expansions of the research field are also considered. Conclusions are presented in the last section.

2. Methodology

Based on a sample of existing articles regarding scheduling-based waste minimization, a set of keywords was identified and listed in Table 1. The terms “waste” and “scheduling” were combined with a keyword from both the environmental and scheduling aspects, resulting in a total of 12 combinations. The Web Of Science search engine was then used to identify peer-reviewed articles featuring at least one of these combinations in their title, abstract and keywords.

Table 1: Keywords used in the literature search

Scheduling aspect related keywords	Sustainability aspect related keywords
Scheduling	Waste
Manufacturing	Environmental
Production	Sustainable

More than 2000 articles resulting from this literature search were screened to check whether they belong to our scope. Further research was made by looking at the references cited in the selected papers, as well as the articles citing our sampled papers. In case specific types of scheduling problems involving waste reduction were identified (e.g. the batch scheduling problem or cutting stock problem), additional research was made on this particular topic.

As a result, a total of 70 papers were selected. In Figure 1, they are grouped according to their publication year and in different fields of scientific journals, oriented towards operational research, chemistry and sustainable production respectively. The category “Other” regroups conference proceedings and journals with no specific affiliation. Relatively few articles were published prior to year 2000, with the numbers rising sharply after 2007. This trend is present not only in the waste-minimizing scheduling literature, but more generally representative of the sustainable production literature as a whole. More than half (38) of the selected articles were published in operational research journals, followed by chemistry oriented journals (15), and sustainable production (9). A consequence of this fragmentation of disciplines is the difficulty to connect articles to one another. Those are usually addressing a specific problem of their field and do not automatically mention the waste-related scheduling aspect, thus highlighting the need for a state-of-the-art.

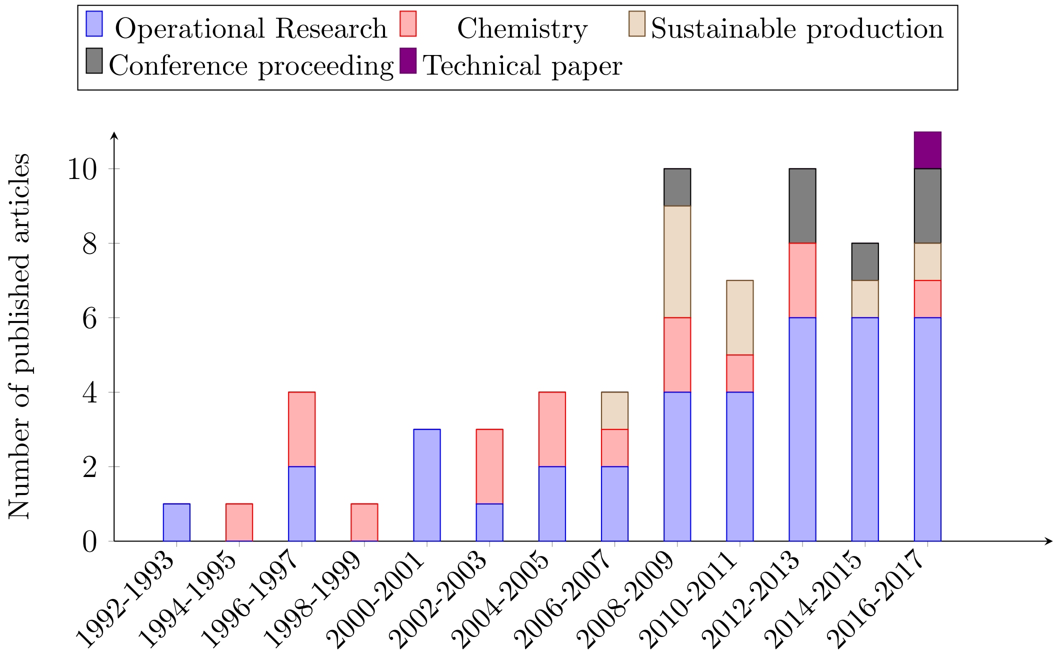

Figure 1: Number of publications on waste-minimizing scheduling with journal affiliation per year of publication

3. Operations scheduling for waste minimization in the literature

In this section, a state-of-the-art of the current literature on waste minimization through operations scheduling is presented. The reviewed articles have been grouped into four main categories related to the scheduling problem they address, and subdivised according to the way the waste-minimization issue is handled. A classification of this review is presented in Section 4.

3.1. The batch and hoist scheduling problems

The process industry is a big waste producer, and one of the biggest contributor regarding hazardous waste (USEPA, 2006). Due to the nature of the processes and materials used, large quantities of wastewater are generated during the production and equipment cleaning steps. The two biggest types of problem encountered are the batch scheduling problem (e.g. for the production of chemicals or food products) and the hoist scheduling problem (e.g. for surface treatment).

Batch scheduling, which is related to process manufacturing, occurs when several jobs can be processed simultaneously on a single machine. Its fundamental characteristic is that the batch processing time is equal to the longest processing time of the jobs included on the batch. Thus, determining the composition of a batch becomes an important factor for the overall makespan and production costs. Batch scheduling optimization is extensively covered in the scientific literature (Méndez et al., 2006) regarding economic criteria (production costs, productivity...). However, new legislations regarding the management of hazardous waste (European Parliament and Council, 2008), as well as an increasing awareness regarding environmental issues have fostered the inclusion of environmental factors into the more recent studies.

The hoist scheduling problem deals with the scheduling of handling devices, also called hoists, mostly in electroplating lines. This includes the determination of the soaking times, the use of several tanks, and the coordination of multiple hoists on possibly conflicting routes with possible improvements regarding the wastewater generation. More information is available in Manier and Bloch (2003). In the specific case of batch and hoist scheduling problems, the design and operation of the water reuse network and plant design problem is addressed in this review only if combined with a scheduling problem. Other works concerning plant or water reuse network design can be found in Stefanis et al. (1997) or Barbosa-Póvoa (2007).

In the following, the literature concerning waste reduction in the batch and hoist scheduling problems is reviewed and organized into five subcategories featuring different angles from which to address waste generation.

3.1.1. Equipment cleaning and setup considerations

Seminal works on sustainable operations scheduling are mostly focused on reducing the waste outputs, mainly wastewater originating from equipment cleaning.

Grau et al. (1994) propose to identify all generated wastes and by-products and classify them according to a pollution index (based on a product's properties such as toxicity). Production apparatuses and material collectors are also listed. A first production plan being established, an environmental impact is calculated by multiplying each output quantity by its corresponding pollution index. The output with the biggest impact is identified, and a new schedule is made that minimizes its impact, e.g. by allocating it to the most efficient equipment available or reducing the quantity used. Once this is done, all the production steps where materials collecting and/or reuse are possible are identified, and the most beneficial are implemented. While waiting times might be introduced to enable such measures, all production constraints still have to be complied with. When all possible changes are done, the output with the second biggest impact is considered, and so on until the end of the list. A formal methodology combining these steps is proposed by the authors and applied to a batch production example. An additional work (Grau et al., 1996) includes energy consumption into the objective function as well. Adonyi et al. (2008) tackle the problem of reducing the outputs generated by equipment cleaning due to setups in a paint production factory. They propose an algorithm based on previous work by Sanmartí et al. (2002) on S-graphs, which takes into account the cleaning costs of the various equipments. Alternative solutions are obtained by allowing for different operating times resulting in different cleaning schedules. The efficiency of their algorithm is compared with the Mixed Integer Linear Programming (MILP) model from Endez and Cerda (2003), showing drastically reduced computation times while providing multiple solutions.

In Capon-Garcia et al. (2011), both MILP and Mixed Integer Non Linear Programming (MINLP) are used in the case of setup-waste minimization for acrylic fibers fabrication. Using Messac et al. (2003)'s normal constraint method, a Pareto front is generated. A Pareto front represents the set of non-dominated solutions in the case of multiobjective optimization, i.e. solutions that cannot be improved without degrading at least one of the other objectives (more details about Pareto fronts are available in Blasco et al. (2008)). The tri-objective problem with the profit, operating time and environmental impact criteria is also considered and a tri-dimensional Pareto frontier generated. Yue and You (2013) tackle the issue of the multi-product multi-purpose batch scheduling problem in surface treatment. They propose a bi-objective optimization of productivity and environmental impact originating from changeovers in production, calculated from a Life Cycle Assessment (LCA) database. A Mixed Integer Linear Fractional Program (MILFP) is used with the ε-constraint method (Mavrotas, 2009) to obtain a Pareto frontier of possible solutions in a satisfactory time.

Zhang et al. (2017) propose to use particle swarm optimization and local search in order to minimize the pollutant emissions in a textile dyeing process with sequence-dependent family setup costs. A bi-objective function considering total tardiness and emission of water pollutants caused by the cleaning operations is defined and alternative Pareto efficient solutions are obtained. Adekola and Majozi (2017) also consider sequence-dependent setup costs along with a profit maximization objective. Based on a MILP formulation by Seid and Majozi (2012), their goal is to minimize an aggregated cost function accounting for profit and either setup or freshwater consumption cost.

In the food industry, Berlin et al. (2006) develop a heuristic which minimizes the number of setups in a dairy production plant. This heuristic is applied to two scenarios in Berlin and Sonesson (2008), which shows a significant decrease in setup-related waste generation. The consequences of implementing such schedules onto the planning of downstream activities are also discussed, and are shown to be particularly relevant in industries with perishable products such as the dairy industry.

3.1.2. Process requirements

Process requirements refer to all the operational constraints regarding the processes themselves. Such constraints are e.g. the concentration of chemicals in a tank, the soaking duration for a bath or the recipe used for a product. Using alternative recipes, concentrations or soaking times, it is possible to adjust the schedule to reduce waste generation.

Song et al. (2002) use MILP with the ε-constraint method in the case of an oil refinery. They obtain a Pareto front of trade-off solutions balancing profit and environmental impact (based on an LCA tool assessment) by adapting the production schedule based on oil flow rates between storage, blending and product tanks. Chaturvedi and Bandyopadhyay (2014) propose a MILP formulation of the bi-objective optimization of freshwater consumption and productivity. Based on the required chemical concentrations for different processes, they use the ε-constraint method to obtain a Pareto front of alternative schedules. Xu and Huang (2004) consider freshwater consumption reduction for a single product hoist scheduling problem. They propose a search algorithm based on a free move matrix which first determines all the possible optimal schedules from a cycle time perspective, which may have different soaking times or soaking bath concentrations. Then, water consumption for all of these schedules is determined, and the most environmentally-friendly one is selected. Kuntay et al. (2006) choose the same approach, using a two-step algorithm which first maximizes the production rate and then minimizes the quantity of chemicals and water used.

Subaï et al. (2006) address the subject of wastewater output regulation in a surface treatment plant. In addition to the criteria of chemical concentrations and bathing time, they consider the energy consumption and smoothing of wastewater discharge over time in order to avoid overloading the water treatment plant. They proceed in two steps, first solving a classical hoist scheduling problem and then selecting the best remaining solutions after adding additional constraints. They show that environmental criteria can be included into objective functions without negatively affecting productivity and with reasonable computation times.

El Amraoui and Mesghouni (2014) propose a bi-objective optimization of cycle time and waste generation using a genetic algorithm. Process requirements in terms of soaking time and chemicals concentration are included into the problem formulation in order to reduce the wastewater generated. Likewise, Liu et al. (2012) propose a triple-objective optimization aiming at reducing simultaneously the water and electricity consumption while maximizing productivity. Using a mixed integer dynamic optimization model, they generate a three-dimensional Pareto frontier from which a schedule can be selected. Arbiza et al. (2008) present an LCA-based optimization process, where financial and environmental modules that assess a schedule's economic and environmental impacts are proposed. By using different recipes and raw materials for a same product, the schedule can be adapted according to both modules. Using a genetic algorithm, they are able to generate Pareto-efficient solutions providing trade-off between environmental impact and economic efficiency. Finally, Vaklieva-Bancheva and Kirilova (2010) address the case of optimal production recipes choice in multipurpose batch scheduling. Using the example of curd production from the dairy industry, a genetic algorithm is developed to choose the most appropriate recipes in order to minimize the environmental impact of production while still complying with production goals.

3.1.3. Use of intermediate storage tanks

An intermediate storage in the batch production context is a vessel used to store either a byproduct, a co-product, or wastewater. This storage can be combined with a regeneration equipment, or used simply to wait for later reuse or discharge.

Majozi (2005), further developed in Majozi and Gouws (2009), tackles the case of wastewater output minimization in the presence of an intermediate storage tank. Using MINLP, they compare scenarios where a storage tank for wastewater is present or not, and adapt the production schedule in order to minimize the wastewater output. Experiments showed that a reduction up to 20% of the wastewater generated is possible. In Gouws and Majozi (2008), the authors consider the same problem with multiple storage vessels and multiple contaminants. They also allow for reuse of stored wastewater for some processes, and use MINLP to obtain the schedule that minimizes the amount of wastewater in a set time horizon. Adekola and Majozi (2011) consider the problem of batch scheduling with intermediate storage and wastewater regeneration unit. By linearizing a MINLP formulation of the problem, they manage to obtain schedules that minimize the wastewater generation by allowing for an efficient use of the regeneration unit. Based on the previous work of Majozi and Gouws (2009), Nonyane and Majozi (2012) propose a state sequence network representation which also aims at minimizing the wastewater output in presence of a storage tank. The novelty of their work is the use of cyclic scheduling to tackle larger planning horizons, dividing it into eight 23-hours long periods.

3.1.4. Plant and process design

This section refers to scheduling problems that involve process or plant design, be it proactive or for a retrofitting.

Stefanis et al. (1997) study the relationship between environmental impact, scheduling and production plant design. They apply previous work from Barbosa-Póvoa and Macchietto (1994) to three food industry cases and obtain trade-off solutions between production cost, plant design cost and wastewater generation in a dairy plant using MILP. Similarly, Al-Mutairi and El-Halwagi (2010) propose to use MINLP to generate trade-off solutions between both design and scheduling issues with economic and waste reduction objectives. They apply their model to the case of a refinery, comparing scenarios with and without retrofitting of equipments.

3.2. The Cutting Stock Problem with scheduling aspects

Cutting Stock Problems (CSPs) are widely studied in operational research. Those problems appear when one or several materials need to be cut into products of smaller dimensions, and are present in many industries such as textile, paper, furniture or metal sheet production. For a more precise typology of cutting and packing problems, readers can refer to the works of Dyckhoff (1990) and Wäscher et al. (2007). The traditional objective of a CSP is the minimization of wasted material, also called trim loss. Trim loss occurs when residual material is left after all possible products have been cut from the primary material. Those typically have dimensions inferior to those of the smallest available product, which makes them unusable for posterior processing. Since minimizing trim loss equates to increasing productivity and reducing materials cost, it has been the usual objective of CSPs. One important aspect about the recent CSP literature is the need to treat the production scheduling as a whole, and not simply from a cutting patterns viewpoint. This has lead to the appearance of new forms of CSP such as the CSP with pattern reduction or CSP with usable leftovers. Those typically take into account both the trim loss minimization through efficient patterns, and the effect of using such patterns on production scheduling. As an example, using only the most efficient patterns typically requires switching patterns more often in order to fulfill demand. This in turn leads to larger setup times and costs, which can offset the gains made by reducing trim loss. Thus, new criteria for production efficiency have been introduced besides trim loss, such as the number of different patterns, sequencing or overproduction. This leads to merging traditional CSP and Lot Sizing Problems (LSPs) that deal with determining efficient production schedules. Moreover, trade-off solutions have become necessary to balance the materials and operating costs and better reflect real-life situations. In this section, the literature regarding the CSP problem with scheduling and waste minimization concerns is reviewed and classified.

3.2.1. CSP with setup considerations

Minimizing trim loss might require the use of a large number of patterns, and thus a large number of setups (adjustment of the knives in paper cutting for example). This is not necessarily a problem as long as the impact of a setup is negligible when compared with material losses. When the setup time or cost is big enough however, it becomes sensible to limit the number of patterns used even if it generates more trim loss.

Harjunkoski et al. (1999) consider the 1-dimensional CSP (1DCSP) using MINLP in the paper converting industry. They define various objective functions that take into account respectively the number of patterns, number of pattern changes, total waste, makespan, energy consumption and overproduction. They compare the results of each objective over these different criteria, and also propose a hybrid objective function minimizing total waste and energy consumption. They emphasize the interest of such hybrid functions, and the fact that knowledge of the processes, while requiring additional research, is key in improving the quality of the results. Likewise, Schilling and Georgiadis (2002) study the 1DCSP with setup costs. The authors define an aggregated objective function that includes the profit, the setup cost and, interestingly, the waste disposal cost. They propose a MILP model, stressing that the addition of changeover and waste disposal costs are responsible for an increased problem difficulty. Similarly, Kolen and Spieksma (2000) study the case of the 1DCSP with trim loss and pattern number minimization. They also consider two types of jobs, one that allows for a certain degree of over or underproduction, and one with exact demand. They develop a Branch and Bound (B&B) algorithm that produces a set of Pareto-optimal solutions.

In Westerlund (1998), a two-dimensional CSP with setup times is modeled using MILP. Two aggregated objective functions are tested, one based on Westerlund et al. (1996) that minimizes losses due to trim waste, overproduction and setups, and one maximizing the profit represented by income from deliveries and overproduction minus all production costs. This method was successfully implemented in a Finnish paper-converting mill. Wuttke and Heese (2018) propose a more detailed version of this problem, with sequence-dependent setup times (based on the previous position of the cutting knives) and tolerances on product widths. A two-stage heuristic first identifies a set of efficient patterns, then determines a sequence to optimize the knife-mounting operations, thus reducing the setup times. This heuristic is able to treat instances of realistic size, and is effectively tested on data reflecting the annual demand of a textile firm, showing improvement in setup times up to 50% with low trim loss.

In Nonas and Thorstenson (2000), a CSP with setup and inventory considerations is studied. The authors use the case of steel plate cutting with an aggregated objective function combining the cost of waste during the cutting operation, the steel plates holding cost and the setup cost incurred for each new pattern or steel dimension. Both problems are solved simultaneously using various methods such as the one proposed by Murty (1968), three local search algorithms and a column generation procedure. The authors improve their column generation algorithm in Nonas and Thorstenson (2008) using their previous work and a heuristic proposed by Haessler (1971), obtaining better solutions in less time. Mobasher and Ekici (2013) look at the same problem and propose two local search algorithms and a column generation algorithm, then study the impact of the respective weights of the waste and setup costs in the objective function. Their column generation algorithm is more effective when dealing with low setup costs, while local search is better when setup costs are high.

de Araujo et al. (2014) consider a bi-objective optimization of the number of patterns used and the trim loss incurred. Using a genetic algorithm, they generate a set of non-dominated solutions. Compared with other existing solving methods for similar problems using both real-life and randomly generated instances, they obtain good quality results with reasonable computing times. Golfeto et al. (2009) also use a genetic algorithm with a multi-objective optimization for the 1DCSP. They produce a Pareto front showing the trade-offs between trim loss and the number of setups, and suggest parallel processing as a perspective to improve their genetic algorithm computation time. Cui and Liu (2011) also address the issue of the number of patterns in the 1DCSP and propose a sequential heuristic procedure based on the successive generation of pattern sets (called C-sets) that fit the remaining products to be cut. Although their proposed method might require large computing time when applied to practical cases, the authors acknowledge the potential of C-sets for future research in this area. Cui et al. (2014) and Cui et al. (2015) later propose a two-step procedure where a set of patterns is first generated using a sequential grouping procedure. MILP is then used to obtain a solution based on this pattern set, showing nearly optimal results in minimizing the pattern number without increasing trim loss.

3.2.2. CSP with inventory considerations

In some cases, inventory capacity and cost are the limiting factors in scheduling. Bolat (2000) looks at a scheduling problem with buffer stock capacity in the corrugated boxes industry. Several parameters are considered, the aim being to maximize the throughput of converting machines under a constraint of maximum acceptable trim loss and limited storage capacity for boards to be processed. Setup and loading times of the boards into the converting machines are also considered. A successive linear programming relaxations algorithm is proposed, which first maximizes throughput and then the trim losses, and analyses the trade-offs between those two objectives. A similar problem is considered in Gramani and França (2006), where inventory and setup costs are considered with the minimization of cut plates. MILP is used first, followed by a staged combined model heuristic to solve a shortest path problem. Experiments on real life data show that gain up to 13% can be made on profits when considering both problems at the same time instead of sequentially. Lucero et al. (2015) address the issue of a 2-scheme strip cutting problem with sequencing constraints in the corrugated cardboard industry. Their goal is to define a schedule minimizing trim loss when only two different products can be processed at a time (the number of products stacks being limited to two). Additionally, a maximum lateral waste per pattern is allowed, and a small over and underproduction is permitted for each order. After developing four different integer programming methods based on a graph approach, they propose a greedy heuristic which greatly improves the computation time without losing in solution quality. Na et al. (2013) propose a heuristic for solving a scheduling problem of float glass production. Their goal is to produce a schedule that meets demand while minimizing two types of scrap: layout scrap, which is linked to the glass snapping patterns used, and cycle time scrap, which originates from the inefficient offloading of cut glass panels into inventory. They use a two phase heuristic in order to maximize a yield ratio based on the total quantity of scrap divided by the overall quantity of glass used, and manage to improve manufacturing yields from 95% up to 99%.

3.2.3. CSP with due dates

While most cases consider a time horizon for the processing of all orders, some articles consider due dates for each job to be processed. Reinertsen and Vossen (2010) address the CSP with due dates in a steel manufacturing process. Using Integer Linear Programming (ILP) and a sequential heuristic procedure, the operational performance is calculated based on the resulting waste and tardiness of the orders. The objective function consists of the aggregated costs of raw materials and tardiness. Arbib and Marinelli (2014) consider the same problem and propose a more efficient formulation using ILP and a dynamic period splitting procedure. An interesting point raised by the authors is that the weights given to each objective (tardiness and raw materials consumption respectively) are largely dependent on the industry and materials used.

3.3. The Integrated Cutting Stock Problem

In this section, articles addressing the Integrated Cutting Stock Problem (ICSP) are reviewed. A recent literature review of ICSP has been proposed by Melega et al. (2018), who describe the ICSP as a problem that "considers simultaneously the decisions related to both problems [LSP and CSP] so as to capture the interdependency between these decisions in order to obtain a better global solution". Along with their review, the authors propose a generalized 3-level integrated lot-sizing and cutting stock model based on formulations by Gilmore and Gomory (1961) (for the CSP) and Trigeiro et al. (1989) (for the LSP). They consider two types of integration which are necessary for a problem to be considered as an ICSP. The first one is the integration across time periods, with inventory providing a link between those. The second one is the integration across production levels, i.e. purchase/fabrication of material (L1, related to LSP), cutting of pieces (L2, related to CSP) and finally assembly into the final product (L3, related to LSP). They consider that a problem must include at least two production levels (L1-L2, L2-L3 or L1-L2-L3) and have a multi-period dimension to be categorized as an ICSP. Their work is extensive, and is mostly focused on the modelization aspect with information regarding the type of pieces being cut, and operational constraints such as setups and capacity. In order to obtain the additional information needed for our classification, especially regarding waste minimization, a review of the papers cited in Melega et al. (2018) was conducted. As a result, 21 out of the 30 papers present in their work are considered in this study, as the others did not include environmental aspects relating waste generation and scheduling.

3.3.1. ICSP with setup considerations

In Hendry et al. (1996), a two-stage procedure is used to solve an ICSP with setup times. The study takes place in a foundry where copper logs are melted, then cut to the appropriate size. The aim is to reduce both the number of furnace charges and the trim loss due to the logs cutting, with the possibility of storing both molten copper and surplus cut logs at a negligible cost. The problem is solved by first determining the number of logs necessary, and then determining a furnace schedule which meets the demand. The authors test several heuristic methods in order to solve the first step, and use integer programming for the second step. This procedure is tested using real data from a manufacturer, showing improved results on both makespan and trim loss compared to the method previously in place.

3.3.2. ICSP with inventory considerations

In Reinders (1992), the case of a wood-processing company is considered. Two cutting stages (one for tree trunks and one for boards) are integrated into a larger tactical level, where machine capacity constraints, inventory costs and lot-sizing are included. The authors use column generation with dynamic programming for the cutting stages and goal programming is used for scheduling at the tactical level, with different scenarios considered. While the results of numerical experimentations are not discussed, the use of an integral optimization over a search of multiple local optima is considered more efficient. In Correia et al. (2004), the case of paper reels and sheets production is addressed. All the operational constraints (such as dimension specification, capacity, paper types...) are included in a linear program, where the objective function consists simply of minimizing material consumption. Additionally, some of the produced paper reels may be cut into paper sheets, thus a need to manage the production and inventory over time in order to fulfill demand of both reels and sheets. Using a three-stage procedure, the authors first generate the cutting patterns, then use LP and a heuristic to obtain a schedule that minimizes raw material consumption. They offer two different LP where overproduction is either allowed or not. Their method was implemented in a paper mill, showing good results with paper pulp saving.

Gramani et al. (2011) use a model based on work by Gramani et al. (2009) for a case of metal plate-cutting, but remove the setup cost from the objective function. They propose an exact solution method based on column generation that minimizes storage and production costs, that is compared with the decomposition method commonly used in the industry. Gains up to 12% are made on global costs, and other scenarios with different production parameters are also investigated. Silva et al. (2014) consider a case of 2-dimensional ICSP with possible storage of leftovers. They minimize an objective function composed of waste, material, operational and storage costs and propose two ILP models based on work by Silva et al. (2010) and Dyckhoff (1981) respectively. Two heuristics are also proposed, and results show that the two ILP models manage to obtain exact solutions even for large instances. Poldi and de Araujo (2016) consider a multi-period 1-dimensional ICSP. The objectives are to minimize the trim loss and inventory costs (of both raw materials and finished products) over a set of production periods. An arc flow formulation based on Valério De Carvalho (1999) complemented by a heuristic procedure is proposed, and instances are solved with different weights assigned to the holding costs. The results show effective computation time even with large instances. The authors also point out that their approach requires less patterns than the classical approach.

The skiving option in ICSP is introduced by Arbib and Marinelli (2005) in a gear belt manufacturing plant: it is the possibility to combine components (including leftovers) to obtain larger parts. The authors introduce a two-stage method, with a cut-and-reuse and inventory focus at the operational level, and transportation and lot sizing focus for the mid-term planning level (one week horizon instead of day-by-day). Using ILP, they integrate those aspects into an aggregated objective function, and also consider the integration of last-minute orders into the schedule. While the quality of the solutions is high (up to 40% cost reduction compared to previous models), computational time for real-life instances remains prohibitive.

3.3.3. ICSP with setup and inventory considerations

dos Santos et al. (2011) use MILP for the 2-dimensional ICSP in the furniture industry. The authors consider a problem with rolling horizon where setup, inventory and production costs are minimized with the trim loss. Additionally, saw cycle times are considered and security stocks are defined with penalties incurred when these are not respected. Their model is tested on data from a furniture manufacturing firm, but no comparison is made with the actual results from the plant since several real-life techniques used are not included in the model. Campello et al. (2017) also address the integrated 1-dimensional ICSP with setup and inventory cost considerations. Using MILP and a heuristic, they construct a Pareto front of the LSP (inventory and setup cost) and CSP (trim loss and inventory cost) using the ε-constraint method. They observe the variations between the two and the possible trade-offs, concluding that increasing inventory is an effective way of reducing material waste. Suliman et al. (2014) address a similar problem in the aluminum industry. They first propose an Integer Non Linear Program (INLP) for the cost and trim loss minimization problem over several planning periods. Given the complexity of the problem, they then propose an algorithm that proceeds from the last planning period to the first, assessing the needs for inventory pieces based on demand for this period and the available production capacity. Patterns are generated and selected according to different criteria using a pattern generation-selection algorithm. The algorithm produces efficient results when compared to the INLP and industry standards.

An integrated model is proposed by Vanzela et al. (2017), which solves the CSP and LSP simultaneously in order to minimize the production and inventory costs for furniture production. The results from the integrated model are compared with the sequential solving of the LSP then CSP, showing good results. An impact analysis of the different cost weights is then done by varying the inventory and material costs. Gramani et al. (2009) use the same approach in the case of a 2-dimensional ICSP involving plate cutting. Their objective function accounts for material, setup and inventory costs, and is minimized using a heuristic based on Lagrangian relaxation. They compare the performance of their heuristic with a decomposed approach which solves the LSP and CSP consecutively, and observe a slight increase in inventory but substantial reduction in setup costs and material use. In Melega et al. (2016), the authors propose three integrated models based on Trigeiro et al. (1989) and Eppen and Martin (1987) for the LSP. The CSP part is based on work by respectively Kantorovich (1960), Valério De Carvalho (1999) and Gilmore and Gomory (1961), and extended to accommodate the multiperiod and multi-object cases. Two heuristics are proposed to minimize an aggregated function of setup and inventory cost, and the results of numerical experimentations emphasize the difficulty of obtaining large numbers of feasible solutions.

Wu et al. (2017) consider the same model as Gramani et al. (2009) but transform the capacity constraint on the surface of processed material into a time capacity constraint. They propose a new approach based on Dantzig-Wolfe decomposition for obtaining lower bounds, which are then used in a progressive selection algorithm. This algorithm is compared with the Lagrangian-relaxation heuristic from Gramani et al. (2009). Leao et al. (2017) address an ICSP with multiple machines having different sizes and capacities. An aggregated objective function regroups the holding cost of items, setup and production costs as well as waste cost from the cutting stage. The authors propose three mathematical formulations, with item, pattern and machine decomposition orientations respectively. Those formulations are used for finding lower bounds, and a rounding heuristic and a neighborhood search heuristic are tested on literature and real-world instances. While the rounding heuristic performs poorly on real-life data, the neighborhood search heuristic produces good schedules in reasonable time. Poltroniere et al. (2008) address the issue of an ICSP with parallel machines and setup time and cost. Using the paper industry as an example, they aim at minimizing an aggregated function of production, setup, waste and inventory costs. They propose two methods using heuristics for the cutting-stock problem and the lot-sizing one. The first one solves the LSP and then the CSP using several iterations. The second one proceeds in the opposite order, solving the CSP first and then the LSP, showing better performances. In Poltroniere et al. (2016), the authors propose an extension to their heuristic and model, and develop a new model with an arc flow formulation based on the work by Valério De Carvalho (1999) which obtains better upper bounds.

A case of robust scheduling for the ICSP is addressed by Alem and Morabito (2012) in the furniture industry with the objective of minimizing production, setup, inventory and backlog costs in addition to trim loss. A first deterministic mathematical formulation based on Gramani et al. (2009) is proposed, and three robust models are then detailed. Those models account for uncertainties in either the objective function coefficients, the demand parameters, or both at the same time. After experimenting on real and simulated instances, the authors conclude that uncertainty in demand parameters has more impact on solution quality than uncertainty in objective function coefficients. In Alem and Morabito (2013), a similar problem with stochastic demand is also considered and uncertainty is added to the setup times, which are now counted as a capacity constraint and not as a cost. A deterministic model and four 2-stage stochastic models with different risk management strategies are tested. The performance of each model is compared using real life data and different scenarios. Risk mitigation comes at the expanse of higher production costs, and the authors consider extending their framework for risk-aversion to different types of industries.

3.3.4. ICSP with setup and due dates considerations

In Aktin and Özdemir (2009) a case of ICSP is handled with a two-stage method. First, a heuristic generates a set of cutting patterns that cover the demand with the objective of minimizing trim loss. Then, an ILP model is responsible for finding a cutting plan minimizing an aggregated cost function that includes material, setup and lateness costs. Their method is implemented in a coronary stent manufacturing company, providing efficient full cutting plans and patterns. Malik et al. (2009) propose a genetic algorithm for solving an ICSP with cycle service level, which represent the probability that the customer's demand will be met on time. In their model, that allows for a certain delay in meeting demand, an aggregated function of inventory, setup and trim loss costs is minimized. The authors compare their approach to a decomposed one where the CSP and LSP are solved sequentially. While their integrated approach delivers more cost-efficient solutions, it also tends to worsen the cycle service level. Thus, the authors propose to use multi-objective optimization to find trade-off solutions.

3.4. Shop floor scheduling

Apart from batch, hoist, CSP and ICSP scheduling problems, research dealing with waste minimization has been conducted for less specific production processes. Those are labeled as shop floor scheduling problems, and regroup various shop floor configurations such as jobshops, flowshops or parallel machines.

3.4.1. Setup considerations

Freeman et al. (2014) study the case of non-identical parallel machines subject to sequence-dependent setup costs and times, where the waste generated and processing time of a product depend on machine assignments. The authors minimize an aggregated function of the cost of waste (which originates from setups and operation processing) and overtime (when the hiring of additional workforce is needed). They solve the problem using greedy and decomposition heuristics, and conclude that considering the trade-off between waste and overtime cost is financially beneficial, especially in high value manufacturing environments. In Pulluru et al. (2017), the authors propose a water-integrated lot-sizing and scheduling approach for hybrid flowshops. Their study takes place in a cheese manufacturing plant that includes two production stages: a milk skimming step refers to process manufacturing while the cheese production step belongs to discrete manufacturing. The authors base their model on a previous MILP developed by Camargo et al. (2012) for parallel-machines in cases involving both continuous and discrete manufacturing. Their MIP aims either at minimizing the freshwater consumption by avoiding cleanings due to sequence-dependent setups and production campaign changes, or alternatively at minimizing the makespan with a restricted amount of available water. Le Hesran et al. (2018) address the case of a painting line in hubcap manufacturing. The authors propose a bi-objective MILP which considers the number of setups (responsible for paint sludge generation) and the inventory cost of finished and semi-finished products. The model also includes re-entrance and drying time. A Pareto front is generated using the ε-constraint method, showing various trade-offs between the waste produced and the holding costs. A similar problem is studied in Zhang (2018) in the automotive industry. Cars have to pass through a painting line, with a sequence-dependent amount of waste generated at each color change, before continuing to an assembly line. A buffer is available in-between that allows for a partial re-sequencing of the painted cars. The authors first propose a MILP, then use a multi-objective particle swarm optimization heuristic to obtain a Pareto front of solutions minimizing the painting line waste and tardiness. They compare the results of their heuristic with two existing genetic algorithms, obtaining near-optimal results and an overall better performance.

3.4.2. Idle time considerations

In Harbaoui et al. (2017), the problem of waste due to machine idle-time in a hybrid flowshop is tackled. The problem occurs in an industrial case of pasta production where the machines need to be cleaned if production is interrupted for more than 30 minutes, resulting in wasted material. The authors propose two MILP formulations, one aiming at minimizing production time and the other aiming at minimizing the material waste due to long production interruptions. Both models are tested on generated instances, showing that material waste can be avoided at the expense of an increase in makespan. They conclude by stating the need for metaheuristic methods in order to solve large instances and the possible inclusion of multi-objective optimization techniques.

3.4.3. Operations sequencing

Hanoun and Nahavandi (2012) address a bi-objective optimization problem in the joinery industry, with a flowshop where tardiness and materials cost are to be minimized. Jobs using similar materials possess a saving factor which represents the achievable waste reduction when processing those jobs sequentially on the first machine. Moreover, different materials have different prices, meaning that reducing waste is more advantageous for some materials than for others. The problem is solved in lexicographic order using a greedy heuristic for waste minimization followed by simulated annealing for lateness minimization. Near optimal results are obtained with low computation times. The authors consider extending their model to handle hybrid flowshops and provide the decision-maker with a set of Pareto-optimal solutions for more flexibility. A similar problem is considered in Hanoun et al. (2012), this time solved using a cuckoo search heuristic. An approximate Pareto front is generated and compared with the true Pareto front obtained using a complete enumeration method. The authors report high accuracy with low computational cost, and aim at comparing their heuristic with other methods in further research.

4. Literature classification

In this section, all seventy previously reviewed articles are shown in classification tables, which are then discussed. Defining such a classification enables a grouping of the issues addressed and provides a standardized terminology. Table 2, 3, 4 and 5 list the papers related to the batch and hoist, CSP, ICSP, and shop floor scheduling problems respectively, and their respective proportions are shown in Figure 2.

In Giret et al. (2015), the reviewed articles are organized using three keys in addition to the modeling approach, which reflect observed typologies:

- type of means addressed in the scheduling method, respectively the input (i.e. reducing resource consumption), output (i.e. reducing emissions) and mixed approaches considering input and output simultaneously.
- multi-objective approach considered (i.e. what objectives are to be minimized in priority or considered as constraints)

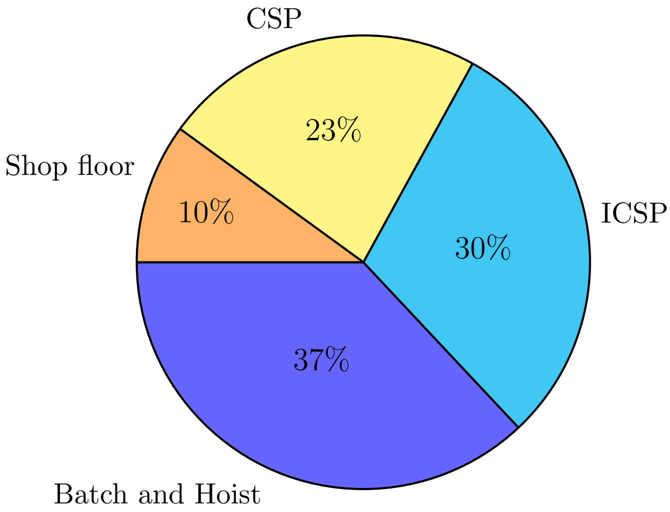

Figure 2: Percentage of articles reviewed per type of scheduling problem

- scheduling approach used, respectively proactive (i.e. uncertainties are taken into account with off-line scheduling), reactive (i.e. the schedule can be adjusted on-line in response to unforeseen events) or hybrid (i.e. both off-line and on-line scheduling)

Similarly, we present this review using key features reflecting the different typologies observed. Our classification features new entries, specifying the economic and environmental objectives, and aims at identifying more accurately the different factors that are influencing waste generation and can be addressed through scheduling.

4.1. Classification criteria

The reviewed articles are grouped by problem type and scheduling concerns, then classified according to six criteria described below:

- **Economic objective:** economic aspect of the objective function (if there is one) to optimize in the scheduling problem. This includes both cost functions (such as production or inventory costs) and traditional scheduling objectives such as the makespan. The possible entries are:
  - Productivity: amount of product(s) produced per unit of time;

- Profit: financial gain after all production (materials and operating) costs have been deduced from the selling price of the products;
- Makespan: date of the end of the last operation to be processed;
- Tardiness: difference between a job's last operation's due date and its execution date;
- Setup time: time loss incurred at each operation changeover;
- Number of patterns (in the case of a CSP);
- Setup, inventory, materials, backlogging, transportation and overtime costs.

- **Environmental objective:** environmental aspect of the objective function (if there is one) to optimize in the scheduling problem. Those objectives can be related to resource efficiency (such as the trim loss, wastewater generation or freshwater consumption), or environmental impact (chemicals concentration, environmental impacts). The entries present are:
  - Waste and wastewater: output of waste and wastewater resulting from the production process;
  - Environmental impact: impact of the waste generation according to one or several criteria commonly used in LCA;
  - Materials and freshwater consumption: materials and freshwater input into the production system;
  - Cleaning and environmental management cost: economic cost resulting from either the equipment cleaning operations or the environmental management measures in place, such as operating a water treatment plant;
  - Discharged effluents: quantity of wastewater discharged per unit of time (i.e. volume that the wastewater treatment plant needs to handle at a given moment);

- Trim loss (cost or quantity): loss of material resulting from inefficient patterns during a cutting operation.

- **Solution method:** type of method used to solve the scheduling problem, in accordance with the common denominations found in the scientific literature. In case multiple methods were used, several entries can be present. Two entries separated with an '/' means that the two approaches were used separately. A '+' between two entries means that the approaches were used jointly to solve the problem.

- **Multiobjective approach:** refers to the way the multiplicity of objectives (if relevant) was handled:

  - Lexicographic : the objectives are arranged in order of importance during the resolution process;
  - Pareto front : a Pareto front is obtained which represents the set of non-dominated solutions for the multiobjective optimization, i.e. solutions that cannot be improved without degrading at least one of the other objectives;
  - Alternative solutions : several solutions with various trade-offs are provided, which might or might not be part of the Pareto-efficient solution set;
  - Aggregated cost function : all objectives are combined into a single-objective function.

- **Scheduling approach:** type of scheduling approach used, according to three different entries (see Chaari et al. (2014) for more details):

  - Deterministic: no uncertainty in the data;
  - Proactive: scheduling takes uncertainty into account when designing off-line schedules;
  - Reactive: the schedule can be updated on-line to react to unpredicted events such as machine breakdowns or new orders.

- **Industry**: Type of industry in which the scheduling problem takes place.

Table 2: Classification of batch and hoist scheduling related literature

Concern	Study	Economic obj	Environmental obj	Solution method	Multiobjective approach	Deterministic	Proactive	Reactive	Industry
Setup considerations	Grau et al. (1994)	Makespan	Environmental Impact	Algorithm	Lexicographic	✓			Chemical plant
	Adonyi et al. (2008)	Makespan	Cleaning cost	S-Graph	Alternative solutions	✓			Paint
	Capon-Garcia et al. (2011)	Profit	Environmental impact & heat consumption	MILP / MINLP	Bi and tridimensional Pareto front	✓			Acrylic fibers
	Malmborg (1996)	Makespan	Waste minimization	Random search heuristic	Alternative solutions	✓			Chemical plant
	Berlin et al. (2006)		Environmental impact	Heuristic		✓			Dairy
	Berlin and Sonesson (2008)		Environmental impact	Heuristic		✓			Dairy
	Zhang et al. (2017)	Tardiness	Waste minimization	Local Search algorithm + Particle Swarm Optimization	Alternative solutions	✓			Textile dyeing
	Adekola and Majozi (2017)	Profit	Freshwater consumption	MILP	Aggregated cost function	✓			
	Grau et al. (1996)	Makespan, Productivity	Energy and waste minimization	Algorithm	Lexicographic	✓			Chemical plant
	Yue and You (2013)	Productivity	Environmental impact	MILFP	Pareto front	✓			Multipurpose batch
Process requirements	Xu and Huang (2004)	Productivity	Freshwater consumption	Movement graph	Lexicographic	✓			Electroplating
	Kuntay et al. (2006)	Productivity	Freshwater and chemicals consumption	Two-step algorithm	Lexicographic	✓			Electroplating
	Song et al. (2002)	Profit	Environmental Impact	MILP	Pareto front	✓			Refinery
	Liu et al. (2012)	Productivity	Freshwater and energy consumption	Mixed Integer Dynamic Optimization	Tridimensional Pareto front	✓			Electroplating
	Arbiza et al. (2008)	Profit	Environmental Impact	Genetic Algorithm	Alternative solutions	✓			Chemical plant
	Subaï et al. (2006)	Productivity	Discharged effluents	2-step Algorithm	Lexicographic	✓			Electroplating
	Vaklieva-Bancheva and Kirilova (2010)	Makespan	Environmental impact	Genetic Algorithm	Alternative solutions	✓			Dairy
	Chaturvedi and Bandyopadhyay (2014)	Productivity	Freshwater consumption	MILP	Pareto front	✓			
	El Amraoui and Mesghouni (2014)	Productivity	Energy and waste minimization	Genetic Algorithm	Pareto front / lexicographic	✓			Electroplating
Intermediate storage	Nonyane and Majozi (2012)	Profit	Wastewater treatment cost	State Sequence Network		✓			Multipurpose batch
	Majozi (2005)		Wastewater minimization	MINLP		✓			Multipurpose batch
	Majozi and Gouws (2009)		Wastewater minimization	MINLP		✓			Multipurpose batch
	Gouws and Majozi (2008)		Wastewater minimization	MINLP		✓			Multipurpose batch
	Adekola and Majozi (2011)		Wastewater minimization	MINLP		✓			Multipurpose batch
Plant and process design	Stefanis et al. (1997)	Profit	Environmental impact	MILP	Pareto front	✓			Dairy
	Al-Mutairi and El-Halwagi (2010)	Profit	Environmental management costs	MINLP	Aggregated cost function	✓			Refinery

Table 3: Classification of CSP related literature

Concern	Study	Economic obj	Environmental obj	Solution method	Multiobjective approach	Deterministic	Proactive	Reactive	Industry
Setup considerations	Nonas and Thorstenson (2000)	Cutting, setup, and holding costs	Trim loss cost	Ranking point / local search / column generation	Aggregated cost function	✓			Metal
	Mobasher and Ekici (2013)	Setup cost	Materials cost	local search algorithms + column generation	Aggregated cost function	✓			Chemical fiber
	de Araujo et al. (2014)	Number of patterns	Trim loss	Genetic algorithm	Alternative solutions	✓			Chemical fiber
	Cui et al. (2015)	Setup cost	Materials cost	Sequential Grouping Procedure + MILP	Aggregated cost function	✓			
	Golfeto et al. (2009)	Setup cost	Trim loss	Genetic algorithm	Pareto front	✓			
	Harjunkoski et al. (1999)	Setup number / Makespan	Waste cost / Energy cost	MINLP	Aggregated cost function	✓			Paper
	Kolen and Spieksma (2000)	Number of patterns	Trim loss	B&B algorithm	Alternative solutions	✓			Abrasives
	Cui and Liu (2011)	Number of patterns	Trim loss	Sequential Heuristic Procedure	Lexicographic	✓			
	Schilling and Georgiadis (2002)	Profit	Trim loss	MILP	Aggregated cost function	✓			Paper
	Wuttke and Heese (2018)	Setup time	Trim loss	Heuristic		✓			Textile
Inventory considerations	Bolat (2000)	Productivity	Trim loss	Successive Linear Programming Relaxation	Lexicographic	✓			Cardboard
	Lucero et al. (2015)		Trim loss	MILP / Heuristic		✓			Cardboard
	Gramani and França (2006)	Inventory and setup costs	Trim loss	Staged Combined Model	Aggregated cost function	✓			
	Na et al. (2013)	Materials cost	Trim loss	Two-phase heuristic	Aggregated cost function	✓			Float glass
Due Dates considerations	Arbib and Marinelli (2014)	Tardiness	Materials cost	ILP	Aggregated cost function	✓			Metal
	Reinertsen and Vossen (2010)	Tardiness	Materials cost	ILP + Sequential Heuristic Procedure	Aggregated cost function	✓			Metal

Table 4: Classification of ICSP related literature

Concern	**Study**	**Economic obj**	**Environmental obj**	**Solution method**	**Multiobjective approach**	**Deterministic**	**Proactive**	**Reactive**	**Industry**
Setup considerations	Hendry et al. (1996)	Makespan	Trim loss	Two stage IP procedure	Lexicographic	✓			Metal
Inventory considerations	Reinders (1992)	Capacity and inventory use, service rate	Trim loss	Column generation + dynamic programming and goal programming	Aggregated cost function	✓			Wood
	Correia et al. (2004)		Material cost	Three stage MILP + Heuristic procedure		✓			Paper
	Gramani et al. (2011)	Production, inventory and setup costs	Trim loss	Column generation	Aggregated cost function	✓			Furniture
	Silva et al. (2014)	Material, cutting and storage costs	Waste cost	IP models + heuristics	Aggregated cost function	✓			Furniture
	Poldi and de Araujo (2016)	Inventory cost	Trim loss	Arc flow + heuristic	Aggregated cost function	✓			
	Arbib and Marinelli (2005)	Inventory and transportation costs	Trim loss	ILP	Aggregated cost function	✓		✓	Gear Belt
Setup and inventory considerations	dos Santos et al. (2011)	Production, inventory and setup costs	Trim loss	MILP	Aggregated cost function	✓			Furniture
	Campello et al. (2017)	Production costs	Trim loss	Heuristic	Pareto front	✓			Paper
	Suliman et al. (2014)	Production, inventory and setup costs	Trim loss	INLP / Algorithm	Aggregated cost function	✓			Metal
	Vanzela et al. (2017)	Production and inventory costs	Trim loss cost	MILP	Aggregated cost function	✓			Furniture
	Gramani et al. (2009)	Production, inventory and setup costs	Trim loss	MILP with Lagrangian relaxation heuristic	Aggregated cost function	✓			Furniture
	Melega et al. (2016)	Setup and inventory costs	Trim loss	Heuristics	Aggregated cost function	✓			
	Wu et al. (2017)	Production, inventory and setup costs	Trim loss	Progressive selection method with Dantzig-Wolfe decomposition	Aggregated cost function	✓			
	Leao et al. (2017)	Production costs	Trim loss	MILP / Rounding Heuristic	Aggregated cost function	✓			Paper
	Poltroniere et al. (2016)	Cutting, setup and holding costs	Trim loss cost	Arc flow / Heuristic	Aggregated cost function	✓			Paper
	Alem and Morabito (2012)	Production, setup, inventory and backlogging costs	Trim loss	Stochastic models	Aggregated cost function		✓		Furniture
	Alem and Morabito (2013)	Production, overtime, inventory and backlogging costs	Trim loss	Two-stage stochastic models with risk-aversion strategies	Aggregated cost function		✓		Furniture
Setup and due date considerations	Aktin and Özdemir (2009)	Production costs	Trim loss	Heuristic + ILP / Neighborhood Search Heuristic	Aggregated cost function	✓			Coronary stent
	Malik et al. (2009)	Setup and inventory costs	Trim loss	Genetic algorithm	Aggregated cost function	✓			Paper
	Poltroniere et al. (2008)	Cutting, setup and holding costs	Trim loss cost	Heuristics	Aggregated cost function	✓			Paper

Table 5: Classification of shop floor scheduling related literature

Concern	Study	Economic obj	Environmental obj	Solution method	Multiobjective approach	Deterministic	Proactive	Reactive	Industry
Setup considerations	Le Hesran et al. (2018)	Inventory cost	Waste minimization	MILP	Pareto front	✓			Plastic painting
	Pulluru et al. (2017)	Makespan	Water consumption	MILP	Lexicographic	✓			Dairy
	Freeman et al. (2014)	Overtime cost	Waste minimization	MILP / Greedy and decomposition heuristics	Aggregated cost function	✓			
	Zhang (2018)	Tardiness	Waste minimization	MILP / Particle Swarm Optimization	Pareto front	✓			Automotive
Idle Time	Harbaoui et al. (2017)	Makespan	Waste minimization	MILP		✓			Food
Operations sequencing	Hanoun et al. (2012)	Tardiness	Materials cost	Cuckoo search	Pareto front	✓			Joinery
	Hanoun and Nahavandi (2012)	Tardiness	Materials cost	Greedy heuristic + Simulated annealing	Lexicographic	✓			Joinery

4.2. Classification results

4.2.1. Batch and hoist scheduling related classification

A total of twenty-six papers are classified as batch or hoist scheduling problems with waste reduction concerns (see Table 2). As can be seen from the concern column, the literature is relatively varied regarding the angles from which waste minimization is addressed. Setup and process requirement-related literature represents more than half of the reviewed articles (9 and 7 respectively), while intermediate storage, LCA and plant design make up the rest. Only six articles do not possess any economic objective (Majozi (2005); Majozi and Gouws (2009); Gouws and Majozi (2008); Adekola and Majozi (2011); Berlin et al. (2006); Berlin and Sonesson (2008)). For those which do, productivity and profit are the two main objectives, the others being time-related indicators such as lateness and cycle time. From the perspective of environmental objectives, it can be seen that environmental impact and water-related objectives (wastewater production and freshwater consumption) are predominant. This is consistent with the scheduling problem studied (batch and hoist), and the industries identified, since their processes require intensive use of water and chemical products. Some articles have interpretations of environmental objectives in terms of cost, such as Adonyi et al. (2008) (equipment-cleaning cost), Nonyane and Majozi (2012) (wastewater treatment cost) or Al-Mutairi and El-Halwagi (2010) (environmental management costs). Exact and heuristic solution methods are evenly used (11 and 15 times out of 26 respectively). Only seven articles do not include a multi-objective approach, five of which deal with intermediate storage concerns where only wastewater minimization is considered. For those which do, bi-objective optimization is the most common (17 out of 26), and only two use an aggregated cost function. Only deterministic scheduling is considered. In accordance with the type of scheduling problem studied, all papers deal with process manufacturing, in industries such as the production of chemical products, multipurpose batch plants, food processing or electroplating.

4.2.2. CSP related classification

Sixteen papers involving CSP with scheduling are classified in Table 3. Most of those address setups (10), the rest being focused on due date and inventory considerations (6). In the cutting stock problem, trim loss minimization is considered both as an economic and environmental objective, since reducing losses equates to reducing materials cost and waste generation. As a result, nine economic objectives are cost oriented (this includes materials, production, inventory and setup costs), with respectively four being time-related and three concerning the number of patterns. Similarly, all sixteen environmental objectives refer to either materials cost or trim loss reduction. Regarding the solution method, heuristic approaches are the most common (9 out of 16). Four use linear programming, two propose a combination of both a heuristic and linear program, and one consider both linear programming and heuristic approaches. In accordance with the frequency of cost functions used as objectives, aggregated cost functions (9 out of 16) are the most common way to deal with multiple objectives. The rest propose lexicographic (2), alternative solutions (2) or Pareto front (2) approaches, and one is single objective with the trim loss serving as both environmental and economic indicator. All the reviewed papers use deterministic scheduling, and are set in specific industries such as paper and cardboard, furniture and metal sheet production where cutting operations are prominent.

ICSP related classification. Twenty-one papers addressing ICSP are present in Table 4. Since CSPs and ICSPs are very similar in nature, the same trends can be observed in both Table 3 and Table 4. As a result from solving both the CSP and LSP into one integrated problem, the number of concerns addressed tends to be larger than for the CSP. Seven articles address only one concern, i.e. inventory only (6) or setups only (1). The rest consider both setup and inventory (11) or setup and due date (3) at the same time. Regarding the economic objective, eighteen papers have cost-oriented objective functions and two possess time-related objectives. Same as for the CSP, all environmental objectives consider materials and trim loss cost or trim loss reduction. Eleven papers use a heuristic-only approach and four use only linear programming, while the rest use both either jointly (4) or separately (2). Regarding the multi-objective approach, all but three three papers use aggregated cost functions. The Pareto front and lexicographic approaches are both used one time, and the remaining study uses the trim loss cost as both an economic and environmental objective. While most of the reviewed papers use deterministic scheduling, Alem and Morabito (2012) and Alem and Morabito (2013) account for uncertainty in demand and production parameters, thus providing robust schedules. Arbib and Marinelli (2005), after proposing a deterministic model, consider a reactive feature by allowing for the introduction of urgent orders into the schedule, which results in prohibitive computing time. Finally, the industrial sectors concerned are the same as for CSPs, ranging from the paper, metal or wood to the furniture industry.

4.2.3. Shop floor scheduling related classification

Seven shop floor scheduling problems are classified in Table 5. Setup minimization and operations sequencing are most commonly encountered (four and two times out of seven), idle time concern being the only exception. Time-related economic objectives are considered six times, while Freeman et al. (2014) use overtime costs, which is the monetary consequence of an excessive makespan. The waste minimization objective is used four times out of seven; materials cost and water consumption appear twice and once, respectively. The solution approaches are evenly distributed between heuristics (4) and linear programming (3), all with a deterministic scheduling. The multiple objectives are mainly handled with Pareto front (3) and lexicographic (2) approaches, while aggregated cost function and single objective appear only once. The joinery, plasturgy, automotive and food industries are considered.

5. Discussion and research perspectives

In this section, the trends emerging from the classification are discussed and analyzed in the perspective of waste minimization through scheduling. As the objectives and research approaches may vary depending on the type of industry, scheduling problem and research focus at stake, a transversal analysis provides a good overview of the problems involved. Proposals are made regarding what directions could hold promise for future research.

5.1. Waste environmental impact and cost assessment

The first observation that can be made from this classification is the lack of environmental impact analysis in the objective functions. Most articles focus on waste minimization through better resource efficiency, and only nine (all in the process industry category) consider the environmental impact as an indicator. Only three articles (Yue and You (2013); Song et al. (2002); Arbiza et al. (2008)) propose an LCA analysis, highlighting the need for a better assessment of the actual impact of waste rather than considering only its cost or raw quantity, as was observed in Smith and Ball (2012). Expanding the scope of the environmental objective function might also be necessary in order to avoid deteriorating the overall environmental outcome by focusing solely on one aspect. In order to facilitate this assessment process, several new tools have emerged during the last decades regarding the management of waste streams in the manufacturing field. Among them is the Environmental Management Accounting, and more specifically the Material Flow Cost Accounting. Its aims are the identification, gathering, analysis and use of information regarding the various materials and energy flows in a production system (International Organization for Standardization, 2011). With a better understanding of the costs and environmental impacts of these flows, it becomes easier to design more relevant objective functions for the scheduling problems and for the decision makers to decide on trade-off solutions. It is also important to point out that many times, waste is treated as an economic objective (via waste cost), which is insufficient for several reasons. Firstly, the actual cost of waste tends to be underestimated by companies as those only account for removal fees by external providers (ADEME, 2016). Other internal costs such as production or handling costs are rarely considered in the overall waste cost accounting, leading to a misconsideration of their actual impact. Secondly, environmental impact and economic cost are not necessarily correlated, which can result in skewed priorities in decision making. Hence a need for a better knowledge of processes and waste impacts, which needs to be coupled with multi-objective scheduling to account for all aspects of the problem. It is especially important in the light of how the duality between economic and environmental objectives is handled. In total, 30 papers propose an aggregated cost function, a number largely due to the predominance of cost-oriented objectives in the CSP and ICSP categories (27 out of 37). While aggregated approaches have the benefit of being easier to solve and providing direct information regarding the economic aspect, several studies insist on the importance of considering trade-offs for decision making. The Pareto front, lexicographic and alternative solutions approaches are evenly represented with respectively 12, 10 and 7 cases. Finally, 11 papers consider a single-objective approach, and notably all five articles related to the intermediate storage concern (see Table 2). Providing trade-off solutions enables the introduction of previously ignored criteria into the decision-making process, and serves in raising awareness regarding environmental issues in production scheduling.

In the previous section, our categorization of the papers reviewed was mostly focused on scheduling issues and how they relate to waste minimization. Linear programming and heuristic approaches rely on numerical inputs such as production data for problem solving, and their objective functions provide numerical values regarding costs or impacts. Similarly, decision-makers in industries rely mostly on quantitative information (measuring aspects in terms of magnitude) regarding production planning. This is understandable, as physical units (e.g. flow rates and materials weight) or economic indicators (e.g. costs, productivity and makespan) are the direct and observable causes and consequences of production. However, environmental sciences frequently consider qualitative criteria (examining distinguishing attributes) when determining the suitability of different alternatives (Linkov et al., 2009). Introducing a qualitative approach for impact assessment, e.g. through the use of methods such as AHP, ELECTRE or TOPSIS (Özcan et al., 2011), would allow for new objectives to be considered. For all these reasons, and given the importance of integrating sustainable aspects into scheduling, the use of multi-objective optimization is bound to become systematic in future research.

5.2. From waste to reused product

One way to reduce waste generation is through better resource efficiency, which can be summed up as producing more while using less materials and energy. In this context, by-product, co-product and waste reuse is an effective way to maximize resource usage. In the process industry, the use of intermediate storage tanks and regeneration units enables the reuse of wastewater, while skiving is an option to reuse the trim loss in certain industries with cutting operations. Other concepts such as the CSP with usable leftovers, as reviewed in Cherri et al. (2014), directly account for trim losses in the production schedule in order to optimize their size for reuse. By achieving better resource efficiency, companies can improve the outcome of their production on both the environmental and economical ends, by reducing their material bills and burden on waste management system at the same time. It is also important to consider the reuse of waste and byproducts in an integrated manner, rather than as a consequence of the production process. While it has been shown that environmental criteria can be added without degrading the economic aspect (Subaï et al. (2006); Xu and Huang (2004)), the example of the ICSP shows that sequential problem solving results in less efficient solutions. A global understanding of the production process is needed in order to identify where such improvements can take place and which output flows are susceptible to regeneration or reuse. Opportunities for reuse might also be highly dependent on the type of product considered: reuse of bath-water in an electroplating line avoids discharging potentially harmful wastewater; conversely, in the paper industry, trim loss can be easily recycled and reused for making paper pulp, making reuse less important. Thus, integrating the reuse of waste and by-product in scheduling, e.g. in the case of intermediate storage tanks, requires solid knowledge about the production process and substances involved. However, the potential gains resulting from the implementation of such schemes cannot be overlooked.

5.3. Scheduling concerns for waste minimization

We identified different angles from which scheduling can address the waste minimization issue. Some of those are industry related, such as the intermediate storage in multipurpose batch plants, or the ICSP in industries with cutting operations. Others are present in all four main problem categories, as they are related to a more generic scheduling problem and not to a specific type of production. However, some concerns, while similar in nature, can have different behaviors depending on the type of industry. In the case of setup minimization, which is considered in all four problem categories 23 times out of 70 articles, setups are associated with different properties. They entail an economic cost, be it money, time or both, with additional considerations such as sequence dependence. In the case of process manufacturing, they also come with an environmental impact since the equipment needs to be cleaned after each change of operation. In the case of CSPs however, setups can be environmentally beneficial since they allow for more cutting patterns to be used, and thus a more efficient use of resources. Hence a need to relate each concern to its industrial context in order to grasp its true nature during the scheduling problem modeling. Setups have already been studied in the literature, Allahverdi (2015) providing a review of scheduling problems with setup time or cost. Their environmental impact however remains largely undocumented, barring work by Gungor and Evans (2016) who comment on the need to better study the underlying causes of setups impact. Better knowledge about setup-induced waste generation might lead to the appearance of new scheduling concerns, thus enriching the current classification and providing clearer information for future research. Therefore, further studying the interactions between scheduling and waste, as exemplified by setup-induced waste, should be a priority. Information about those concerns will help bridge the gap between operational research and environmental science, and foster the implementation of waste-minimizing schedules. Additionally, since no waste-related concerns were identified for some scheduling and lot-sizing problems, such as the economic lot or common cycle scheduling problem, we believe that introducing such concerns would be of interest for the community.

5.4. Need for reactive scheduling

An overwhelming majority of the articles reviewed (67 out of 70) chose a deterministic scheduling approach. Alem and Morabito (2012) and Alem and Morabito (2013) do consider uncertainty on demand and operational parameters, providing a robust schedule based on different risk-scenarios. Arbib and Marinelli (2005) is the only study in which reactive scheduling is present, with the possibility to introduce so-called "hot-orders" into a preexisting schedule. This lack of proactive and reactive scheduling approaches has already been highlighted by Giret et al. (2015) in the case of energy-efficient scheduling problems. Since those problems are already NP-Hard, adding reactivity to their formulation has a big impact on computing time. Nevertheless, working on proactive and reactive scheduling will become increasingly necessary in the coming years, as the shift from Make-To-Stock to Make-To-Order and Just-In-Time policies will result in an increased demand for flexibility and reactivity from the production. Providing schedules that account for uncertainty in production will serve as a way to mitigate the risks, which can be viewed from different angles. As shown by Alem and Morabito (2012), uncertainty in different parameters requires different schedules to ensure robustness. Similarly to ensuring a minimum service level even in case of machine breakdown, producing environmentally-robust schedules (i.e. schedules that ensure an acceptable level of waste even in case of unforeseen events) is necessary. Likewise, while the need for reactive scheduling in energy-efficient scheduling has already been discussed to address sudden changes in energy prices and reduce peak loads, its counterpart in waste minimization is equally important. Being able to generate on-line waste efficient schedules to accommodate shifts in demand or control effluent discharge over time in order to avoid overflows in treatment plants will become more and more relevant as research in sustainable manufacturing progresses.

6. Conclusion

Incorporating sustainability aspects into the operational production scheduling can bring substantial improvements without the need for high investments. While current research has been mostly focusing on energy-efficient scheduling, waste minimization strikes as equally important in a context of primary resources scarcity. Thus, this paper proposes a literature review on waste minimization through scheduling, aiming at both filling a gap in the current literature and unifying a heterogeneous field of research with a disparate terminology. A classification composed of six criteria that embrace the complexity of this topic is made, and various concerns linking scheduling and waste are identified. Finally, a comparative overview of the reviewed papers is done, calling up several promising prospects for future research.

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