ISIJ International, Advance Publication by J-STAGE, DOI: 10.2355/isijinternational.ISIJINT-2019-574

Review

Scheduling in Continuous Steelmaking Casting: A Systematic Review

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(*Received on September 17, 2019; accepted on November 25, 2019; J-STAGE Advance published date: ****** ***, 201**)

The converter furnace and the continuous casting are the most important stages in steel production. Modern integrated processes directly connect the converter furnaces and the continuous casting machines with a flow of molten metal, and the steel is manufactured synchronously between the various machines. Starting from the traditional handmade programs for the management of these processes, during the last two decades there has been a notable increase in studies and publications in this field, trying to formulate scheduling in a rational and automatic way. The process has been approached for years through the development of both physical and operational research models, many of them theoretically. The main purpose of this study is to present a critical and in-depth evaluation of the previous studies, so that the state of the art of scheduling in steelworks can be evaluated. An approach based on a Systematic Literature Review (SLR) has been used, trying to search, evaluate, synthesize and analyze all the relevant studies for this specific field. As a result, the conclusions of the various analyses are presented and a study route is proposed for the design of the optimal planning methodology in the steelworks.

KEY WORDS: scheduling; casting scheduling problem; steelmaking and continuous casting; production planning.

1. Introduction

Modern integrated steel plants comprise a steelmaking process ranging from the conversion of pig iron into molten steel in converters or Basic Oxygen Furnace (BOF), to its final casting in the continuous casting machine (CC), through refining in secondary metallurgy (SM). Since the development of automation and control techniques, the proper integration of planning into the steel plant has been of great importance in reducing costs and improving production.

Steelworks planning is considered to be one of the most complicated problems of industrial organization, as it is a process comprising several stages, each of them with its own restrictions. In recent years, most of the publications try to find optimized models and approaches for the scheduling of the Continuous Casting (CC) process in steelplant,[1,2] including studies in which limited machine availability is considered[3] or cancellations of work in progress. The scheduling problems have already been classified according to different criteria,[4] including, mainly, two types of decisions:[5]

• Batch decisions, in which the primary requirements of orders are transformed into production batches. There are two types of batches in steel mill production. One is called heat and the other is cast. Heat is the basic unit of production in BOF, received in the metallurgical ladle. Cast refers to the sequence of consecutive heats loaded into the CC machine, it could be also known as tundish, as the vessel through which molten metal flows before solidifying in the continuous casting mold.

• Scheduling decisions, *i.e.* allocation, sequencing and timing of heats and casts in the relevant facilities, from steel fabrication to continuous casting production, including intermediate treatments.

The first decisions have to do with product-client scheduling, focusing on the priorities of the different steels and the amount of production of them, and knowing that steels of different quality or format cannot share the same cast usually.

Scheduling decisions, on the other hand, can be seen as a Hybrid Flow Shop (HFS) problem, with batch restrictions in the last phase (CC).[6] The main consequence of this is that in most of the cases studied, when it comes to production planning in a steel plant, the problems that arise are NP-hard,[1,7] where NP (nondeterministic polynomial time) is a set of problems that no algorithm can solve optimally in a reasonable time, being hard those decision problems at least as difficult as a NP problem.[8–10] The development of static, simplified models, which consider a large part of the variables as immutable over time, has been studied from multiple approaches. However, during scheduling in a real environment, many more parameters are subject to variabil-

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DOI: https://doi.org/10.2355/isijinternational.ISIJINT-2019-574

ity, including multiple constraints and changing objectives over time.[11–13)]

This article tries to analyze the current state of the art in steelworks planning, carrying out a systematic literature review (SLR), based on the analysis of these models and approaches, looking for their common characteristics and differences, as well as the advantages and disadvantages they have when applied to a real environment. The objective is to find the gaps in the research regarding the real application of the studies, in order to develop future analyses on the multi-objective planning of steelworks that, considering the uncertainties, provides an optimized programming of heats, machines and equipment.

2. Methodology

The evaluation of research on programming in steelworks and CC has been undertaken as a SLR.[14)] The purpose of an SLR is to provide a listing, as complete as possible, of all published studies relating to a given area. While traditional literature[15)] tried to summarize the results of a certain number of papers, systematic review uses explicit and rigorous criteria to identify, critically evaluate, and synthesize all existing literature in a particular area. In order to carry out the SLR, seven phases have been followed according to **Fig. 1**, starting with a planning of the research process to be carried out, to continue with the definition of the limits of the study, specifying the frame of reference in which the article is placed and formulating a series of questions that will be answered in the discussion phase. Subsequently, work is carried out to search for publications in the field of research, limiting the results based on different inclusion and exclusion criteria, and then synthesizing and analyzing qualitatively and quantitatively the results obtained. Finally, the results of the SLR are described in the results and conclusion section, which will be the basis for the conclusions of the study.

2.1. Planning

In this first phase the literature review should be planned and managed like any other research project.[16)] This phase includes; defining the project's time frame, identifying the databases that will be used, and selecting the software tools needed to manage the different references.

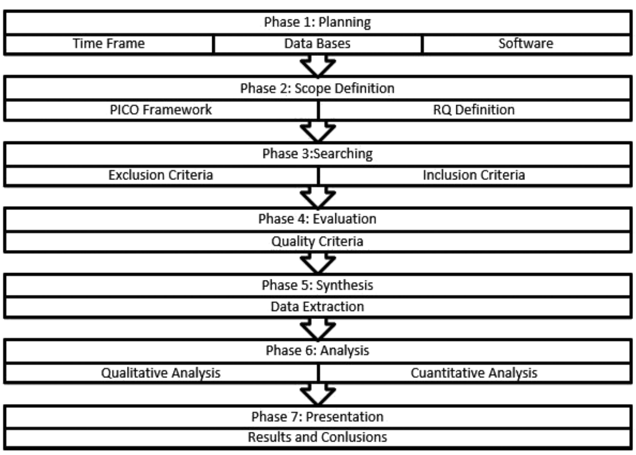

Fig. 1. Systematic literature review phases.

The definition of the time frame of the project leads to limit the analysis of the literature to review in the form of quality and quantity, according to the criteria that are set out below.

Three databases were used, selected on the basis of related studies,[17,18)] due to its relevance in the world of research and the volume of work that is collected in them:

1. ScienceDirect: is the main source of medical, technical and scientific research. It hosts more than 12 million pieces of content from 3 500 academic journals and 34 000 electronic books.[19)]
2. Web of Science (WOS): is a database that collects references to major scientific publications since 1945. It has a platform based on Web technology, and its references cover all areas of knowledge, both scientific and technological, sociological or humanistic.[20)]
3. Scopus: is one of the largest databases in the world. It belongs to the company Elsevier, a prestigious publishing house in the field of research, and specializes in bibliographic references and peer review literature.[21)]

At the time of handling the references, Microsoft Excel was used as a support software tool, due to its versatility, accessibility and availability, from where the diverse articles and authors were compared and valued with different criteria, being contrasted in an iterative way throughout the process.

2.2. Scope Definition

In the second phase, the appropriate questions were asked to the research, called Research Question (RQ).[17)] These questions were chosen after an iterative process in stages, comprising the collection of information from similar studies and a PICO strategy, whose acronyms come from the words Population, Intervention, Control and Outcome. Within this strategy, in this particular case the population is formed by the various steel plants equipped with CC machines and integral operation from the first stage of BOF. The intervention is the use of scheduling procedures. The control is a comparison between the different scheduling methods. Finally, outcomes are the results of the application of the different methods and are reflected in a series of indicators related to production called Key Performance Indicators or KPIs.

Thus, the RQ questions were defined as follows:

- Q1: What is the current state of the art in steel plants scheduling?
- Q2: Are the current theoretical methods powerful enough to deal with the many constraints and uncertainties of the process?
- Q3: What methodology should be developed to be able to optimize the management of the integral production of a steel plant?

2.3. Searching

This phase was divided into three parts; the search for reference articles in the field in which this research is located, the application of exclusion criteria to the results obtained, and finally, the application of inclusion criteria to obtain only results relevant to our study.

In the first place, a filtering of the database publications was carried out, using the string; *Scheduling AND continuous AND casting*, selected taking into account the definition of the final objective of the research and the RQ. The Boolean operator AND was used to refine the search.

After filtering, the databases yielded a total of 7 148 hits, as can be seen in **Fig. 2**. Despite this high number, duplicated or tripled results are included; this is due to the fact that 3 different databases were used, which may have shared or even distant results from the context of this review, such as improvements in software and hardware for transport monitoring in industrial environments[22] or studies related to the chemical compositions of the heats and their impact on the time spent in the machine.[23]

Specific inclusion or exclusion criteria were then applied on the basis of the relevance that these articles may have to RQs.

Four exclusion criteria were defined, denominated with the acronym EC followed by the number of criteria, based on similar studies:[14,15]

- EC1: Publications made before the year 2000
- EC2: Publications in languages other than English
- EC3: Publications unrelated to the field of engineering, mathematical modeling or operational research.
- EC4: Repeated Publications

Once these criteria had been applied, the search was narrowed down to the optimal parameters for research. Thus, applying the first criterion, in which only publications produced from 2000 onwards were taken into account, the coincidences were reduced to 4 724. Resizing the publications and taking into consideration only those made in English, the result was 4 648. Subsequently the field of publication was selected in those relating to engineering, operational research or modeling, obtaining 769 articles. Due to the fact that this number is the sum of the results of the 3 databases, it was possible to eliminate the duplicates by means of comparison, finally obtaining a total of 471 reference articles.

In the last part of the search process, an inclusion criterion denoted by the acronym IC was defined, this criterion chooses only those studies that show the use of planning in steel plants or similar facilities, with the application of developed models.

The selection of this inclusion criterion has been made taking into account the objectives of the study and relying on similar studies carried out.[24,25] From the application of these new criteria, a total of 121 documents were obtained, as can be seen in **Fig. 3**.

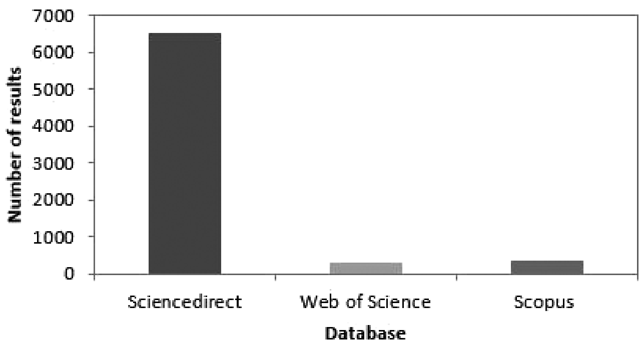

Fig. 2. Results of the research after applying the string.

2.4. Evaluation

In this phase, the evaluation criteria of the documents, or quality criteria (QC), were identified in order to improve the extraction of quantitative and qualitative data for a later phase of synthesis and analysis. The choice was made on the basis of similar studies[14,15,17] as follows:

- QC1: the document is clear
- QC2: the methodology is well explained and detailed
- QC3: the methodology is well explained and detailed
- QC4: the results are applicable to other steel plants
- QC5: Analytical results are detailed

Each of the 121 resulting documents was scored from 0 to 5 according to **Table 1**. These values were the result of summing the scores of the five QCs for each issue, taking the value 1 if the criterion is met, 0.5 if partially met, and 0 if not met. As a result, nearly 35% of the articles met all the criteria, all 121 showing their validity and usefulness in carrying out this review.

2.5. Synthesis

In this phase the resulting articles were synthesized, summarizing the set of fundamental ideas defended in each article.

As a result of the similarities between the different studies[75,135,136,138] and taking into account the needs that may arise as a consequence of the adjustment of the work in the steelworks stages, a series of parameters were selected, as seen in **Table 2**, which provide information regarding the possible use of the various planning methods in steelworks.

2.6. Analysis

The characteristics obtained during the previous phase were analyzed, putting in context the implication of each one of them in the real planning of a steel mill. A percentage comparison of the different values obtained during the synthesis phase was also carried out, analyzing the results obtained and justifying their validity or not at the time of developing an optimal planning.

2.6.1. Steel Grades

The use of various types of steel grades leads to the differentiation of times in the manufacturing process, based on the quality of this steel. In addition, this time differentiation affects all metallurgical stages: BOF, SM and CC.

It is remarkable that while 93.4% of the articles reviewed

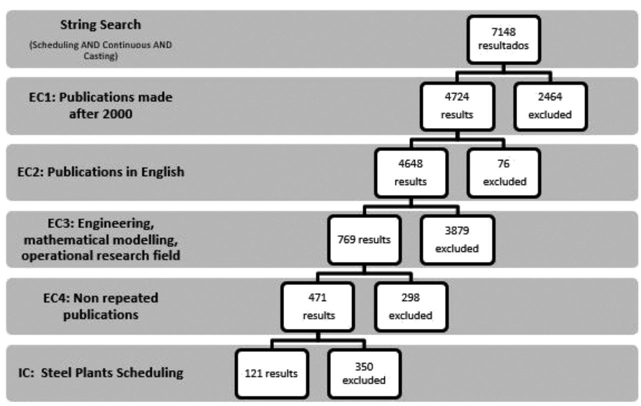

Fig. 3. Steps followed in the SLR search phase.

Table 1. Scoring of quality criteria (QC) in each of the reference documents.

N°	Ref.	QC1	QC2	QC3	QC4	QC5	N°	Ref.	QC1	QC2	QC3	QC4	QC5
1	S. Jiang[26]	1	1	1	1	1	62	Y. Xue[27]	1	0.5	0.5	0.5	0.5
2	Yadollahpour, M. R.[25]	1	0.5	1	0.5	0.5	63	Y. Xue[28]	1	0.5	1	0.5	0.5
3	S. Song[29]	1	1	1	1	1	64	H. Dong[30]	1	0.5	1	0.5	0.5
4	A. Sbihi[31]	1	1	1	1	1	65	L. Tang[32]	1	1	1	1	1
5	M. G. Wichman[33]	1	1	1	1	1	66	K. Lu[34]	0.5	0	0.5	0	0
6	Y. Tan[35]	1	1	1	1	1	67	E. Salazar[36]	1	0.5	1	0.5	0.5
7	J. Li[37]	1	1	1	1	1	68	D. Zhu[38]	0.5	0.5	1	0.5	0.5
8	M. Zarandi[39]	1	1	1	0	1	69	X. Pang[40]	1	0.5	1	0.5	1
9	A. Touil[41]	1	1	1	1	1	70	X. He[42]	1	0.5	1	0.5	0.5
10	J. Long[43]	1	1	1	1	1	71	B. Zhu[44]	1	0.5	1	0.5	0.5
11	L. X. Tang[6]	1	1	1	1	1	72	Y. Ye[45]	0.5	0.5	1	0.5	0.5
12	H. Hu[46]	1	1	1	1	1	73	S. Zanoni[47]	1	1	1	0.5	1
13	A. Bellabdaoui[48]	1	1	1	1	0.5	74	Z. Xujung[49]	1	1	1	0.5	0.5
14	L. Sun[50]	0.5	0.5	1	1	0.5	75	H. Ke-wei[51]	1	0.5	1	0	0.5
15	M. A. Gutiérrez-Limón[52]	1	1	1	0	0.5	76	W. Xu[53]	1	1	1	1	1
16	S. Jiang[54]	1	1	1	1	0.5	77	D. Armellini[55]	1	1	1	1	1
17	L. Tang[56]	1	1	1	1	0.5	78	Y. Tan[57]	1	1	1	1	1
18	T. Otaga[58]	1	1	1	1	0.5	79	M. C. de Souza[59]	1	1	1	0.5	1
19	A. Atighehchian[60]	1	1	1	1	0.5	80	S. Kammammettu[61]	1	1	1	1	1
20	K. Mao[62]	1	1	1	1	0.5	81	L. Sun[63]	1	0.5	1	1	0.5
21	X. Pang[64]	1	0.5	1	1	1	82	W. Höhn[65]	1	1	0.5	0.5	0.5
22	S. Yu[66]	1	0.5	1	0.5	1	83	R. Garzinová[67]	1	1	1	0.5	0
23	S. Jiang[68]	1	1	1	1	1	84	K. Worapradya[69]	1	1	1	1	0.5
24	S. L. Jiang[70]	1	0.5	1	0.5	0.5	85	Z. Gu[71]	1	0.5	1	0.5	0.5
25	S. Yu[72]	1	0.5	0.5	0.5	0.5	86	Y. Xue[73]	1	0.5	1	0.5	0.5
26	L. X. Tang[15]	1	0	0.5	0.5	0	87	W. Jian[74]	1	0.5	1	0.5	0.5
27	Q. Li[75]	1	1	1	1	0.5	88	X. Yun-can[76]	0.5	0.5	1	0.5	0.5
28	H. Missbauer[77]	1	1	1	1	0.5	89	Y. Xue[78]	1	0.5	0.5	0.5	0.5
29	M. P. Fonti[79]	1	1	1	1	1	90	J. Mori[80]	1	1	1	0.5	1
30	J. Hao[81]	1	1	1	1	0.5	91	J. Long[82]	1	1	1	1	1
31	S. Jiang[83]	1	1	1	1	0.5	92	K. Worapradya[84]	1	1	1	1	1
32	D. Hu[85]	1	1	1	1	0.5	93	J. Long[86]	1	0.5	1	0.5	0.5
33	J. Long[87]	1	1	1	1	0.5	94	M. F. Panti[88]	1	0.5	1	1	0.5
34	L. Sun[24]	1	1	1	1	1	95	D. Pacciarelli[89]	1	1	1	1	0.5
35	L. Sun[90]	0.5	0.5	1	1	0.5	96	J. Li[91]	1	1	1	1	1
36	Q. Pan[92]	1	1	1	1	1	97	Z. Zheng[93]	1	1	1	0.5	0.5
37	Q. K. Pan[94]	1	1	1	1	1	98	I. Ferreti[95]	1	1	1	0.5	0.5
38	S. Yu[96]	1	1	1	1	1	99	K. Chen[97]	1	1	1	0.5	0.5
39	K. Mao[98]	1	1	1	1	1	100	L. Sun[99]	1	1	1	1	0.5
40	K. Mao[100]	1	1	1	1	1	101	Y. Ye[101]	1	1	1	1	0
41	J. Li[102]	1	1	1	1	1	102	H. Dong-fen[103]	1	0.5	1	0.5	1
42	K. Peng[104]	1	1	1	1	1	103	H. Y. Dong[105]	1	0.5	1	0.5	0.5
43	K. Peng[106]	1	1	1	1	1	104	J. Long[107]	1	1	1	1	1
44	G. Wang[108]	1	0.5	1	1	1	105	L. Sun[109]	1	1	1	1	0.5
45	L. Tang[110]	1	1	1	1	1	106	T. Zhang[111]	1	1	1	1	1
46	H. Cui[112]	1	1	1	1	0.5	107	K. Neumann[113]	1	0.5	1	0.5	1
47	L. Tang[114]	1	0.5	1	0.5	0.5	108	Z. Yang[115]	1	1	1	1	0.5
48	L. Li[116]	1	0.5	1	1	1	109	A. Flores-Tlacuahuac[117]	1	0.5	1	0.5	0.5
49	C. Xu[118]	1	1	1	1	1	110	A. Janiak[119]	1	0.5	1	0.5	0.5
50	L. Sun[120]	1	1	1	1	1	111	M. G. Wichmann[121]	1	0.5	1	0.5	1
51	V. Kumar[122]	1	0.5	0.5	1	1	112	A. Sbihi[123]	1	1	1	1	1

52	X. Pang[124]	1	1	1	1	1	113	H. B. Wang[125]	1	0.5	1	0.5	0.5
53	T. Li[126]	1	1	1	1	0.5	114	H. B. Wang[127]	0.5	0.5	1	0.5	0.5
54	S. Gay[128]	1	1	1	1	1	115	W. Liu[129]	0.5	0.5	1	0.5	0.5
55	L. Tang[5]	1	0.5	1	1	1	116	J. Liu[130]	1	1	1	1	1
56	N. N. Choksi[131]	1	0.5	1	0.5	0.5	117	W. Liu[132]	1	1	1	1	0.5
57	S. Yu[133]	1	1	1	1	1	118	W. Liu[134]	1	1	1	1	0.5
58	J. Long[135]	1	1	1	1	1	119	P. Chandra[136]	1	0.5	1	0.5	0.5
59	D. F. He[137]	1	0.5	1	1	0.5	120	Y. Tan[138]	1	0.5	1	1	1
60	Y. L. Zhou[139]	1	0.5	1	0.5	0.5	121	H. Huang[140]	1	1	1	1	1
61	S. Lin[141]	0.5	0.5	0.5	1	0.5							

Table 2. Characteristics selected for the scheduling methods in the steel plant.

Steel Grades	Types of CC Machine	Transport at steel plant	Contingencies	Use of coordinator	Workforce requirements	Maintenance
Unique	Unique	Yes	Yes	Yes	Yes	Yes
Multiple	Universal	No	No	No	No	No
		Constant	Breakout			Machine Rearming

explicitly mention "quality of steel" as a differentiating characteristic, 6.6% do not mention it (**Fig. 4**), even when it is taken into account. This means that articles that do not cite this characteristic, practically unanimously, apply a Ti,j formulation that shows the treatment time of the heat i in the machine j, so that there is an effective differentiation[29,75] for the different steel grades.

Due to the great variety of existing steels and the inherent complexity of the iron-carbon (Fe–C) system, any change in the desired final properties implies a substantial change in the method of treatment and obtaining the steel, notably changing the planning of a sequence.

It is also possible that within the same sequence there are several grades of steel, as long as they are chemically sequencible, that is to say, that they can concur in the same cast in a consecutive way without producing degradation in the properties of one or another steel. This can result in different casting durations in the same cast. Because of this, it is common for the planning to be able to work with different qualities of steel, although there are also more limited studies in this sense.[51,74]

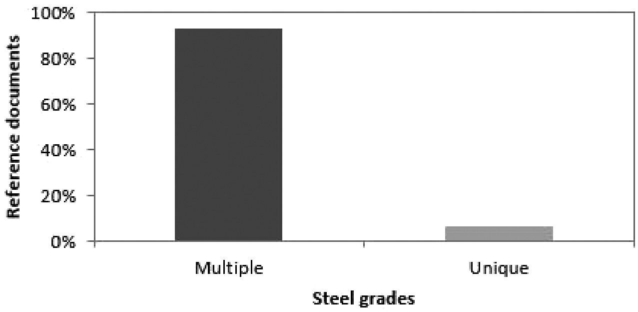

Fig. 4. Steel grades considered in the scheduling.

2.6.2. Types of CC Machines

The existence of several types of CC machine, in a similar way to the different grades of steel, leads to the differentiation of times at this stage (Tij). As in the previous case, all the studies contemplate an own time of treatment for each heat in each machine, comparable to the use of several types of machine, but this does not contemplate a last restriction, fixed by the characteristics of the works in steel mill, in which certain types of steel can only finish in certain types of machines (unique machines). This new restriction, far from facilitating the problem, generates a greater amount of data to handle, increasing the difficult of the planning problem.

According to **Fig. 5**, in (a) a detail of the planning of the process of obtaining steel can be observed, under normal conditions, without sequence breakdown: the steel is treated in Secondary Metallurgy, lines SM1 and SM2, and is transferred to continuous casting, lines CC1 and CC2. In case of sequence breakdown at a given Ti instant, heats may appear already in treatment in the steel plant and with the impossibility of continuing the sequence, as reflected in Figs. 5(b), 5(c) and 5(d).

It is typical for the factory to have unique (slab, billet or bloom) and non-compatible CC machines. In the event of a breakdown in the sequence that would leave products already being processed in the steel plant, there could be greater problems. These products should be returned to the BOF for rework, find a way to modify them by fine tuning in the metallurgical furnaces (re-application of heat), or hold them in the furnace until the rearming of the casting machine (thereby blocking the metallurgical station for the following products). For example, in Fig. 5(b), the arrival of heat 3 in SM1 at the CC1 machine would be delayed by remaining longer in SM1, so that in addition to the reset time in CC1 (shaded area), we would also be delaying the treatment of heat 5 in SM2, and thus delaying the CC2 machine.

Assuming universal casting machines and steels of different class and not sequenced, the workshop maneuvers can be speeded up by casting the remaining heats by the other machine, as can be seen in Fig. 5(c), where heat 3 in SM1 is taken to the CC2 machine, losing only the resetting time of CC1, which is also mitigated in production by effectively casting the product that had been out of sequence (heat 3).

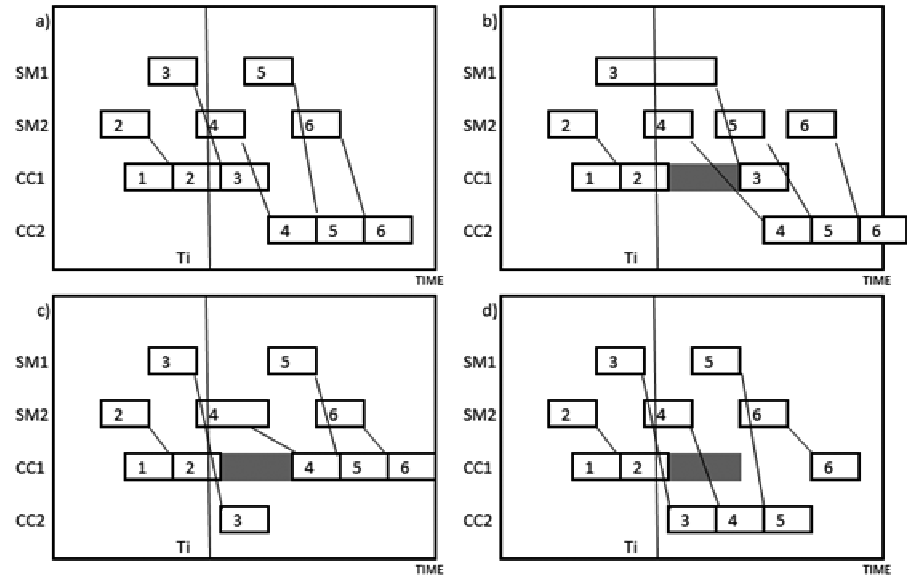

Fig. 5. Scheduling responses to sequence cutting: a) Schedule without sequence breakout, b) Schedule with sequence breakout in Ti and unique machines, c) Schedule with sequence breakout in Ti, universal machines and non-sequential steels, and d) Schedule with sequence breakout in Ti, universal machines and sequential steels.

In the case of equal or sequencible steels, the simple starting by the other machine would already make it possible for the losses to be minimized, as shown in Fig. 5(d), where in addition to taking the SM1 heat 3 to the CC2 machine, the sequence continues with heats 4 and 5, so the CC1 machine does not need to be available until the new cast is finished.

Figure 6 shows that 77.7% of the studies analyzed do not take into consideration the various options, but consider only one type of machine, compared to 22.3% that makes an effective differentiation in the type of machines to be used. However, the latter, in the event of a breakout in the sequence, limit themselves to recalculate the times in order to favor a reset with the heats in the same proposed situation. Any change or modification of the sequence must be carried out externally, either by changing the order form and the grade steel of the heats to adapt to the new machine, or by changing the heats belonging to the cast. Some of the studies have some special restrictions, such as that the assignment of the machine for a certain heat is unique.[70)]

2.6.3. Transports at Steel Plant

The impact of the physical distribution of the steelworks stages is a factor to be taken into account during production scheduling. It is not usual for the transport time between BOF, SM and CC to be the same whatever the number, but the times vary depending on the route they have to make. In addition, it is common to use several cranes and trolleys that may be carrying out several maneuvers simultaneously, making coordination in the steelworks difficult. In this case, in **Fig. 7**, 45% of the studies do not take transport time into consideration, while 30% of them consider it with a constant duration. Both approaches seem insufficient in the work of a real steel plant. The 24% of articles that do contemplate transport include it under a Tjk notation, where j and k are the two consecutive stations through which the heat has to pass. This is a valid approach as long as we have full availability of cranes and trolleys, which is not usual, and additional maneuvers in the steelworks would in all these cases be outside the study and, therefore, the formulations.

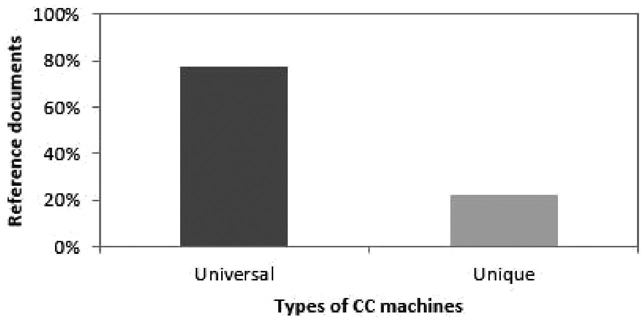

Fig. 6. Types of CC machines considered in scheduling.

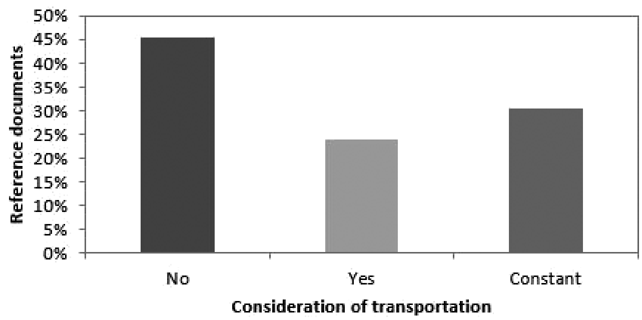

Fig. 7. Consideration of transportation in scheduling.

In **Fig. 8** we can see the influence of the transport capacity on the planning; in Fig. 8(a), the transport of a heat from BOF to SM is carried out as soon as the ladle furnace is released because the previous heat goes to CC (Ti). Thus, it is observed how the transport from BOF to SM is done with a crane (c1) and the transport from SM to CC with a second crane (c2), so that sometimes we will be doing several transports at the same time, using different cranes. In a real steelworks, on the other hand, it may be the case that the same crane carries out both transports, as shown in Fig. 8(b), which means that it is not only necessary for the

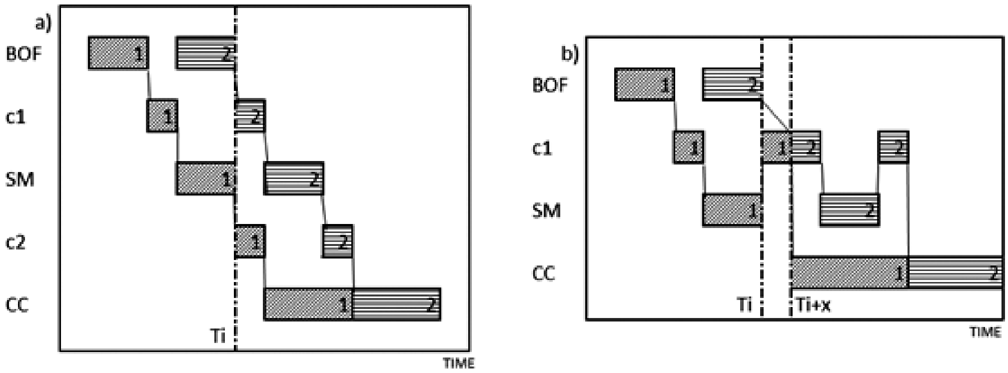

Fig. 8. Schedules with different means of transport in steelworks: a) installation with multiple cranes, and b) installation with limitation of cranes.

furnace (SM) to be free, but also for the crane (c1) to be free (Ti+x), so that heat 2 will suffer a delay during transport to SM , due to the fact that c1 will be carrying out the transport of heat 1 from SM to CC. In order to guarantee the sequence, under these conditions, we may be generating speed losses in the CC machine and delays in the rest of the steel plant processes.

In order to perform the calculations, all intermediate means of transport should be added to the logical sequence of BOF-SM-CC, *i.e.* BOF steel trolleys, SM travel cranes, SM travel trolleys, and CC travel cranes. The use of cranes and trolleys for other parallel activities, such as transporting a new ladle to BOF, or removing the ladle from the casting machine and then deslagging it, should also be taken into account.

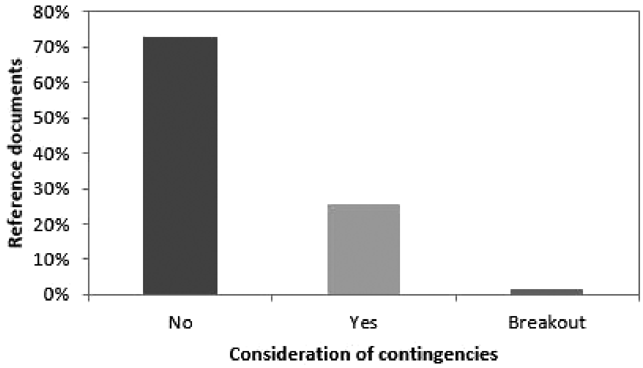

Fig. 9. Consideration of contingencies/unforeseen events in planning.

2.6.4. Contingencies

The steel plant is a living working environment, where the amount of unforeseen events that can affect production is huge. Actual operating time deviates from estimated operating time due to random factors such as operator efficiency, environmental parameters, *etc.*[66] To simplify, any contingency or unforeseen event could be considered as a trigger for a machine stop (in any steel plant area), but reality indicates that sometimes it can simply affect the casting speed[84] or the closure of part of the machine's lines. Some studies already consider the casting time in the machine not only as a decision variable that allows to optimize the process.[26] In case of having an algorithm that provides the ideal schedule, it is not only necessary that it adapts to the different levels of severity of unforeseen events, but also that it knows how to discern the ideal solutions at the time of the event.[66]

Any change in the temperature route during the whole process can be taken into account as a contingence, as long as it can be needed more time to accomplished some stage. In the CC stage, specially, temperature will lead us to deviation in estimated times, in order to fit the casting speed to the casting temperature, and follow the dynamic solidification model established.

In this study, it can be seen that most of the formulations do not accept unforeseen events, as shown in **Fig. 9**, up to 72.7% of the publications studied simply assume the delays, generating new schedules based on the original parameters. This is due to the fact that most of the studies are done from a static and not dynamic point of view of the situation of the steelworks.[135] 25.6% of the sources studied are capable of dealing with various contingencies, and 1.65% only contemplates sequence breakouts, which in practice means redoing planning without dealing with these contingencies. Continuing with the previous example, a crane that has a power variator damaged could invest twice as much time in carrying out a transport, without the different models being able to deal with these situations. Models that are capable of updating themselves do so by assuming that their particular schedules are too fragile to be maintained constantly and by appealing to human help, represented as a coordinator/planner. The disturbances of these mathematical models, caused by unforeseen events, are divided into time variation, machine fault and quality fluctuation, and the response would vary between time adjustment and machine reassignment.[137,142]

Sequence breakouts can be approached by all the formulations presented, although with certain limitations. For example, if we are talking about different types of machines or grades of steel, it will be necessary to specify to the program that the heats in treatment during the sequence break cannot go to another machine that is not the one to be rearm. In the same way, although the machine reset time is stipulated from the end of the previous sequence, there is another series of previous jobs needed that are usually carried out in parallel to the casting operation of the previous sequence, as happens with the heating of the tundish. If these jobs have not yet started, the rearming time will be significantly increased, which makes the restrictions of a sequence break different depending on the cast position of the heat that produces that break. This makes that in a general way, a coordination figure is necessary, although sometimes the program itself identifies the sequence breakout as a restatement point of the scheduling.[37,41)]

2.6.5. Use of Coordinator

The use of algorithms that help to consolidate the programming of a steel plant invites to think about an automation of the process. However, most steel plants operate in a hybrid way, in which a master coordinator is in charge of managing the program[81,140)] and helping it to make decisions, particularly when defining manufacturing priorities, forecasting the arrival of raw materials and optimizing waiting times. This means that some of the variables present in various algorithms have to be determined by the coordinator.[43,54)] In addition, this is the person who has access to communications with the rest of the personnel on the plant to indicate the maneuvers to be carried out on the different trolleys and cranes, so that the shortest possible time is lost.

Although some studies consider the figure of the coordinator/planner to be reliable, the majority of them opt for an approximation of the model that is as optimal as possible, so that decisions are taken a posteriori. **Figure 10** shows that 76% of the publications avoid the management of manufacturing programs by a planner, while 24% do consider the figure to be necessary for the development of planning. In any case, a figure capable of feeding the program with the previously defined manufacturing sequences is needed.[126)]

Some other studies, directly accepts the very first schedule developed as a basis for a human-computer cooperation, in order to get an optimum rescheduling of the plan and had the minimum total waiting time on the steel plant.[143)]

2.6.6. Workforce Requirements

The optimization of the production of a steel plant is inevitably linked to personnel needs. Given a schedule, obtained through the use of algorithms, a modification in it could generate changes in the workforce requirements. This is important in order to check the different production options that can be generated. However, scheduling algorithms hardly ever take personnel disposition into account.

Figure 11 shows how more than 99% of the selected sources avoid the load of manpower when presenting their results, given that their objectives are usually linked to minimizing energy costs or maximizing production.[74,118,144)] Some studies, in particular, take into consideration some restrictions due to personnel, such as the alternative loading of converters.[48)]

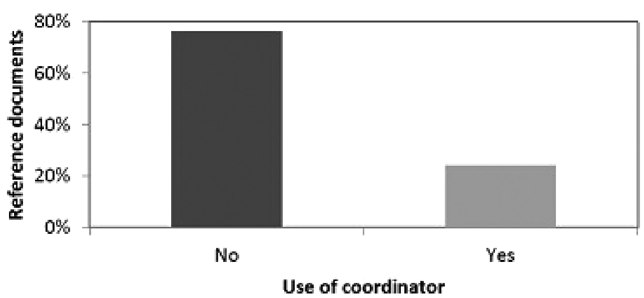

Fig. 10. Use of coordinator in parallel to automatic scheduling.

2.6.7. Maintenance

In addition to the rearming of the CC machines, usually included in the programming algorithms, there are different maintenance times in the different areas of the steel plant that must be taken into account. For example, in SM there is electrode blasting, and gunning of the Ruhrstahl-Heraeus (RH) degassing station, and in the conversion zone, cleaning and reconstructions of the tapping and slagging holes. These operations have to be carried out every certain number of heats, which, unlike in CC, can be variable; however, most of the articles identify these maintenance times as short and ignorable.[92)]

Figure 12 shows that while only 12% of the articles do not include any maintenance work, 82.5% of them only include machine rearming when developing the schedule. A 3.31% of the publications study the scheduling of these operations in order to have the greatest possible availability of the machines. Therefore, for example, there are methodologies for planning the repair of ladles,[145)] or even the contemplation of time windows for maintenance on the different machines.[49)] Other studies directly involve the coordinator in the work of checking the planning in order to comply with the maintenance requirements.[85)]

None of the steel plant scheduling formulations contemplate these assumptions, but focus on optimizing production.[115,133)] Only models with the figure of coordinator are able to correct the planning in an intuitive and effective way.

3. Presentation of Results and Discussion

The results of this study focus on responding to the RQs formulated in the Scope Definition Phase, Q1, Q2 and Q3, described at the beginning of the study. The state of the art in steel plant scheduling is based on trying to optimize the results of energy production or consumption in plants of

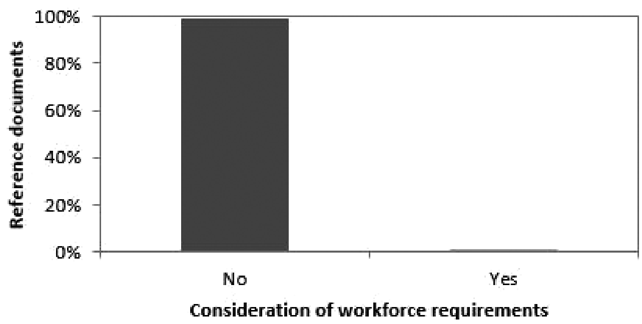

Fig. 11. Consideration of workforce requirements in scheduling.

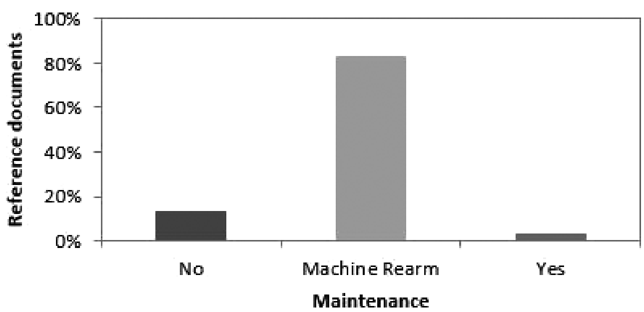

Fig. 12. Maintenance considerations in scheduling.

this type,[57] or even the start-up costs of the operations.[105] The methods used are always algorithms derived from the Job Schedule Problem (JSP) and the greatest differences are found in the mathematical ways of approaching the problem, seeking not only the optimization in the result, but also in the response time.[59,92,114,126]

As has been demonstrated, most articles start from premises in which transport times are either insignificant or determined beforehand.[92] However, in real plants, the position of machines and the availability of trolleys and cranes can affect transport time. These simplifications are also made for maintenance tasks, or unforeseen events, which makes the calculated schedules in some way unrealistic and cannot be perfectly executed in the plant. In addition, the processes themselves are often considered to be of fixed and determined duration, although there are also variations in the algorithms, which can consider standard times and minimum times in the same formulation.[96]

It is remarkable that most articles, despite conceiving CC as a process subject to variation in machine speed, take times as constants,[121] avoiding the possibility of achieving buffers for previous processes, or of increasing the production rhythm continuously throughout production.

The main reason for adopting these simplifications is the NP characteristic of the problem to be solved, which prevents an adequate solution from being obtained in a reasonable time. Most of the proposals studied, in addition to maintaining the final objective of increasing production, seek to improve the response times of the program or algorithm used.

4. Conclusions

As can be seen from the analyzed articles, the great variety of solutions provided by the different researchers corresponds to the numerous and disparate simplifications that are carried out in the development of formulations, and the different ways in which they face the various unforeseen events that may happen during the development of planning.

When looking for optimal planning for improved steel plant production, the type of methodologies that should be considered, as they are the most advantageous, are those mixed methodologies, in which algorithms and programming systems are used under human supervision.[143] It seems inevitable that the development of logarithms and programs, as well as computer equipment and communication networks, improves the speed of resolution of complex problems, being able to adopt a greater variability of input data and therefore, getting closer to what would be a real planning, however, it does not seem that in the short term can avoid some of the simplifications that are taken by default.

Regarding the validity and objectivity of this article, a standard and reproducible methodology has been followed. This study makes a contribution to planning in steelworks and can be used as an approximation to their concepts, both at an industrial and academic level.

The development of a multi-objective schedule in steel plants is proposed as a line of work, covering the various gaps found in the different current methodologies, bringing the existing formulations closer to the work methodologies in a real steelworks.

Funding

This work has been subsidized through the State Program of Research, Development and Innovation of the Spanish Government, focused at the Challenges of Society 2017 under project RTC-2017-6280-5.

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