EMISSION REDUCTION THROUGH PRODUCTION SCHEDULING BY PRIORITY RULES AND ENERGY ONSITE GENERATION

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ABSTRACT

This article describes primary findings of various simulation runs on job shop scheduling dealing with energy consumption and emission pollution. By two combinations of priority rules, production is linked to the generation output of a renewable energy source installed onsite. The resulting schedules show a reduction of energy-related emissions and makespan compared to several conventional priority rules often used in industrial practice.

INTRODUCTION

Climate change, resource scarcity and the associated costs are causing companies to pay more attention to sustainability. Along with this, also increasing social interest as well as legal and structural framework conditions are reinforcing the need for companies to act more sustainably.

For manufacturing companies, enormous potential for improvement in terms of sustainability is given in production. This potential can be addressed through sustainable production planning and control, for example by planning methods associated with the concept of hierarchical production planning (regarding this, see Herrmann and Manitz (2021)). In addition to classic economic objectives, ecological and social indicators are increasingly being taken into account in production planning (Trost et al. (2019)). A comprehensive listing of a large number of articles in the context of sustainable production planning can be found in the online literature database on sustainable production planning, developed by the authors' research group (see Terbrack et al. (2020), Terbrack et al. (2021c)).

In the field of ecologically oriented production planning, the integration of energy in particular has attracted enormous interest in recent years. Numerous scientific papers in the context of production planning already address energy issues in the form of different objectives and restrictions. Especially the integration of different energy sources and energy storage systems within production planning is increasing. Some of these articles address energy-related emissions as well, although the emphasis is mainly on reducing energy costs and energy consumption so far (Bänsch et al. (2021), Terbrack et al. (2021b)).

However, current developments show that the reduction of emissions is becoming increasingly important as well. Germany is pursuing the goals of reducing greenhouse gas emissions by 65 % by 2030 in relation to the year 1990 and achieving climate neutrality by 2045 (BKSG (2021)). Moreover, the Paris Agreement aims to achieve global greenhouse gas neutrality in the second half of the 21st century (UN (2015)). A need for action can be inferred from these goals, also for the manufacturing industry.

For these reasons, the article at hand aims to make a contribution to the consideration of emissions, in specific energy-related emissions, in the context of production scheduling.

By extending our preliminary work in Terbrack et al. (2021a), the application of commonly used priority rules in a job shop environment combined with renewable energy onsite generation is investigated by means of a simulation study. Two different combinations of priority rules are discussed which allow production to be adjusted to self-generated energy and thus a reduction in energy-related emissions. The resulting production schedules are analyzed in terms of makespan, consumption of electrical energy and emissions.

The remainder of the paper is structured as follows. The next chapter presents the literature review and the problem definition. In chapter 3, the design of the simulation study is outlined, followed by the results and their discussion. The article ends with a conclusion and an outlook on further proposed research.

LITERATURE REVIEW AND PROBLEM DEFINITION

In general, production scheduling aims at an optimal allocation of jobs to the respective machines required for processing. Therefore, it is determined at which time, on which machine and in which order each job is processed. Common objective criteria are for example the minimization of completion time or tardiness (Herrmann (2009)).

Nonetheless, some scientific articles already take into account the minimization of energy-related emissions within production scheduling. For example Wang et al. (2019) consider emissions in a single machine scheduling and vehicle routing problem. Guo et al. (2020) present a flow shop scheduling approach to minimize energy-related emissions, makespan and noise. In Foumani and Smith-Miles (2019), a flow shop scheduling problem is introduced to minimize both, emission quantity and costs, as well as makespan. For a flexible job shop environment, Coca et al. (2019) address the minimization of emissions and energy consumption costs along with several economic and social indicators as total completion time, water consumption, penalties for waste and others.

Several approaches from the literature argue that a significant share of electrical energy is generated by fossil fuels as coal or gas and the efficient utilization of energy offers enormous potential for emission reduction. Following that, the reduction of energy-related emissions in

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short-term production planning is achieved by minimizing total energy consumption (e.g. Ding et al. (2016)). However, the decrease of energy-related emissions does not necessarily correlate with a reduction of total energy consumption. Thus, another approach lies in the utilization of renewable energy – generated onsite and with zero emissions, as for example through photovoltaic systems and wind turbines (Wu et al. (2018)).

By using renewable energy sources like photovoltaic (PV) systems, a certain proportion of total electricity consumption in production can be covered by emission-free electricity. Yet the amount of solar power generated depends strongly on different factors such as the time of day, the hours of sunshine and the season. Therefore, companies with photovoltaic systems have different amounts of solar electricity available every day. Due to this correlation between time and the amount of solar electricity generated, it is important to consider that the generation of emission-free electricity can fluctuate over the course of the day. In this manner, for instance Liu (2016) presents two optimization models for single machine scheduling, both taking such renewable energy uncertainty into account while addressing total weighted flow time and energy-related emissions.

Besides optimization, metaheuristics and simple heuristics like priority rules are used for production scheduling. For the latter, basically, the jobs released for processing are queued in buffers in front of the individual machines. As soon as a machine is free and ready for operation, the job with the highest priority from the corresponding queue is assigned to the machine for processing (Herrmann (2011)).

Due to the fact that especially heuristics such as priority rules are used in industrial practice, the paper at hand further analyses the application of conventional priority rules for job shop scheduling combined with a photovoltaic system and macrogrid procurement. For this, we present two combinations of conventional priority rules that address energy onsite generation. To the best of the authors' knowledge, such an approach has not yet been further discussed in research.

SIMULATION STUDY

We continue the work described in Terbrack et al. (2021a) as presented in the following. The simulation study is performed in Plant Simulation, version 2201. The simulation layout is shown in figure 1. A job shop is considered as the underlying shopfloor layout, consisting of five different production machines ("M1" to "M5"). In front of each machine, a buffer is placed representing the queue. For each of those machines, the machine states "working", "setting up", "operational", "standby" and "off" as well as the corresponding state transitions "off → operational", "operational → off", "operational → standby", "standby → operational" and "standby → off" are modelled. Power demand takes a value between 0 and 7 kW for each machine state and follows this relation:

$P_{\text{working}} > P_{\text{setting up}} > P_{\text{operational}} > P_{\text{standby}} \geq P_{\text{off}}$.

These power values are assumed to be constant for each state. In following the EnergyBlocks methodology as introduced in Weinert et al. (2011), this means that each machine state equals one energy block.

In the job shop, three different products (P1, P2, P3) are processed whereby P1 and P3 undergo seven processing steps and P2 passes eight operations, each in different order. The product- and machine-specific setup and processing times range between 5 and 17 minutes. In total, 9 jobs with production quantities between 1 and 4 units are processed and are released at the beginning of the work day (06.00 am).

In performing production scheduling by the application of priority rules, the jobs in every queue are sorted according to the respective priority indicator every time

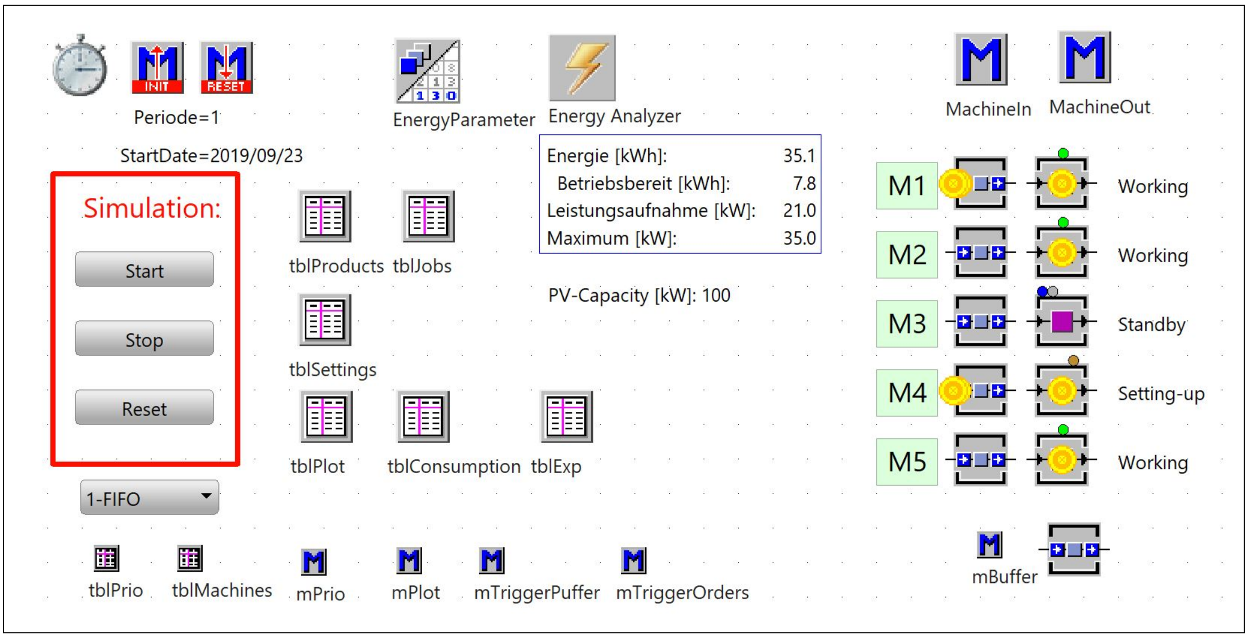

Figure 1: Layout of the simulation model (see Terbrack et al. (2021a)).

a production machine has finished an operation and the job just processed is passed on to the next machine in the shopfloor. Then, the job with the highest priority score is processed next. In every simulation run, job scheduling is carried out through the following six priority rules and by two combinations of these as described in more detail in the next chapter.

- FIFO, LIFO: First in, first out (FIFO) and Last in, first out (LIFO) priority rules. The jobs in a queue are sorted according to the length of the waiting time in descending (FIFO) or ascending (LIFO) order.
- KOZ, LOZ: shortest processing time (KOZ) and longest processing time (LOZ) priority rules. The priority of a job is determined by the length of the processing time on the machine. The highest priority is given to the job with the shortest processing time (KOZ, equiv. SPT) or the longest processing time (LOZ, equiv. LPT).
- KRB, GRB: shortest remaining processing time (KRB) and largest remaining processing time (GRB) priority rules. The priority of a job is determined depending on the remaining processing time of the outstanding operations. According to the GRB rule, the job with the largest remaining processing time receives the highest priority – according to the KRB rule, the job with the shortest remaining processing time.
- Two combinations: LOZ-KOZ-s and GRB-KRB-s – combinations of the LOZ and KOZ rules respectively GRB and KRB priority rules. Both combinations depend on a threshold value s, which relates on the generated power of a renewable energy source.

To determine the energy demand and energy consumption in the shopfloor, the PlantSimulation tool "Energy-Analyzer" is used. Note that in our study, solely production machines demand energy while indirect energy consumption for example caused by transportation between the machines and HVAC (heating, ventilation, air conditioning) is neglected since it is out of the scope of our current research.

Energy is provided by two sources: a renewable energy source and the macrogrid. A photovoltaic system supplies electricity as renewable and thus emission-free energy. Based on surveys conducted by our industry partner, a capacity of 100 kW and 30 degrees south orientation are assumed for this PV system. To analyze the influence of variable solar energy supply, five different generation profiles of the PV system are considered as weather scenarios and each production schedule is assessed with each weather scenario. For this, the data for five typical days in September in Regensburg (Germany) are taken from PV*SOL®. A graphical illustration of the weather scenarios is shown as figure 2.

As long as the PV system can meet the energy demand caused in production, zero energy is supplied from the macrogrid. However, as soon as the shopfloor's energy demand exceeds the generation of the photovoltaic system, energy is procured from the macrogrid. While the surplus power of the PV system is not further addressed in this study (e.g. by means of energy storage systems or feed-in possibilities), the excess in energy demand above the generated solar energy results in energy-related emissions. In that sense, the procurement of energy from the macrogrid is assumed to cause energy-related emissions as further discussed in the following.

For each kWh supplied by the macrogrid, a constant conversion factor equal to 401 gCO_2/kWh is used to calculate the associated emissions. This value is based on a study by Icha and Kuhs (2019) and represents the average emission factor for the German energy mix in 2019. Although we are aware of the fact that in reality, the conversion factor depends on the current energy mix and therefore varies over time and depending on location, a large share of research approaches that include energy-related emissions in production scheduling consider a constant emission factor in their studies, as for example Jiang et al. (2017), Piroozfard et al. (2018) and Zheng and Wang (2018). Therefore, we conclude that the considered constant conversion factor equal to 401 gCO_2/kWh is sufficient for our study.

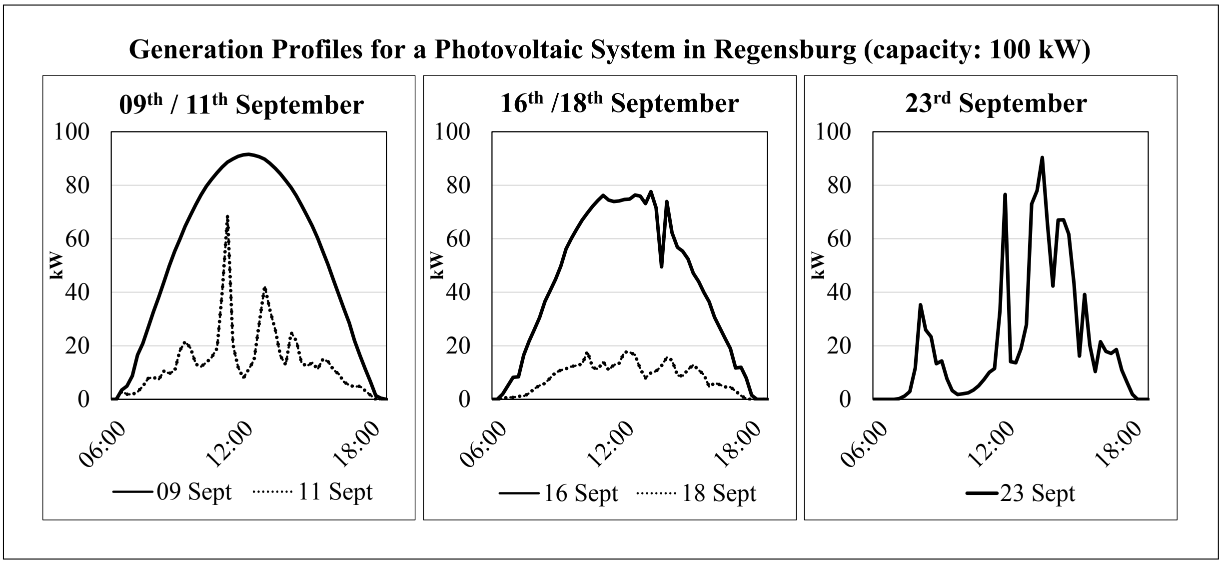

Figure 2: Generation profiles for the photovoltaic system used in the simulation study: data for five September days in Regensburg, Germany.

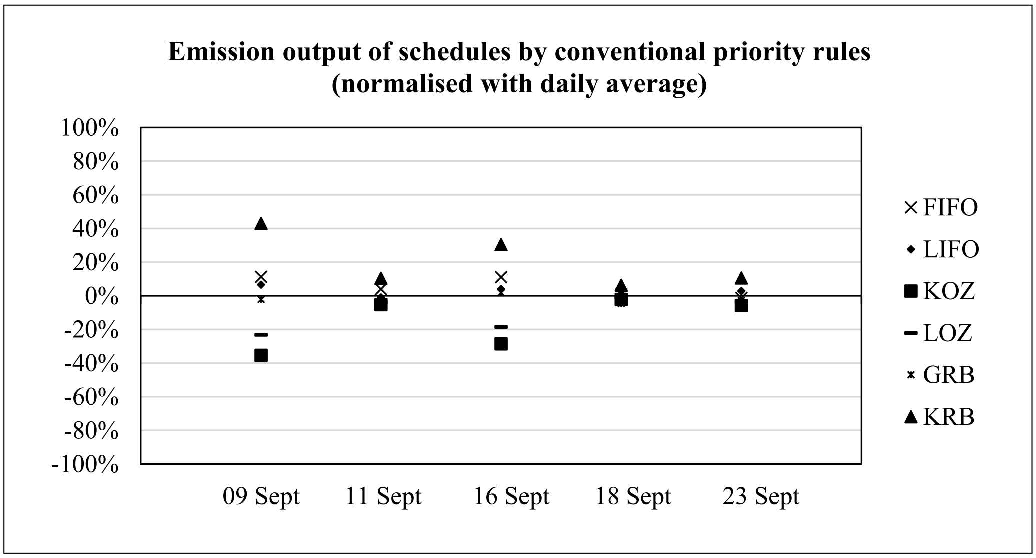

Figure 3: Variation in the amount of energy-related emissions associated with the production schedules based on conventional priority rules.

RESULTS

Previous results

We were able to show in Terbrack et al. (2021a) that the amount of energy-related emissions associated with production can relate on the production schedule. Besides differences in makespan and energy consumption of the production schedules depending on the respective priority rule, the emission output in production differed in respect to the choice of the priority rule as well. This is summarized in figure 3, which shows the emission output of the different production schedules for each weather scenario in relation to the day-specific average of the six schedules. As can be seen, there are weather scenarios in which the emission output differs strongly based on the chosen priority rule. For example on September 9th, the emission output by the KRB priority rule is 43% higher than the day average of 7.44 kgCO2 while the production schedule received through the KOZ priority rule leads to an amount of energy-related emissions 35% less than the average. For some of the weather scenarios illustrated in figure 3, the differences between the production schedules' emission output might not seem large. However, it should be noted that even small savings in production-related emissions are beneficial in respect to ecological sustainability.

It was further recognized that in four of five weather scenarios, even the production based on the schedules with the lowest emissions still does not utilize the entire amount of generated solar energy, representing an improvement potential by increasing the utilisation level of the photovoltaic system.

While the presented conventional priority rules do not take into account the amount of onsite generated energy in production scheduling, a combination of two priority rules – KOZ and LOZ – was introduced in the above cited article that considers the renewable energy source to some extent. This combination relies on the choice of the KOZ priority rule as long as the average generation power of the photovoltaic system within the next hour is less than a specific threshold value s multiplied with the nominal capacity of the PV system (100 kW). Otherwise, in case the average generation of the next hour is equal to or higher than the product of s and the nominal capacity of the PV system, the LOZ priority rule is chosen. Note that the generation output of the PV system for the next hour is assumed to be known.

With this heuristic, production schedules with reduced emissions compared to the conventional priority rules were achieved for each of the five weather scenarios. In fact, also the makespan was reduced by this combination. These findings are reflected in table 1.

Table 1: Results of the first combination of priority rules compared to the conventional priority rules (PR) with lowest makespan and lowest emissions in each weather scenario: makespan (MS), emission quantity (E) and threshold value (s) are listed. Note that in two weather scenarios, an interval for s is given.

Weather Scenario	PR with lowest makespan			PR with lowest emissions			LOZ-KOZ-s		
	Rule	MS [h]	E [kg]	Rule	MS [h]	E [kg]	s	MS [h]	E [kg]
09 Sept	LOZ	12.78	5.71	KOZ	13.02	4.81	[0.64; 0.76]	12.42	2.07
11 Sept	LOZ	12.78	33.95	KOZ	13.02	33.42	0.16	12.20	28.90
16 Sept	LOZ	12.78	8.04	KOZ	13.02	7.04	[0.50; 0.60]	12.42	4.23
18 Sept	LOZ	12.78	50.51	GRB	12.87	48.71	0.13	12.73	47.60
23 Sept	LOZ	12.78	32.28	KOZ	13.02	31.49	0.33	12.73	28.78

Scheduling by a second combination of priority rules: GRB-KRB-s

As described above, we were able to reduce energy-related emissions and makespan in every weather scenario by applying the LOZ-KOZ-s heuristic. However, we concluded further optimization potential due to the fact that electricity was procured from the macrogrid in every weather scenario although the photovoltaic system's output exceeded the production's consumption of solar energy in four of five weather scenarios. Therefore, we extended our research approach as described next.

Based on a similar idea as for the LOZ-KOZ-s heuristic – namely that a longer processing duration results in higher energy consumption since the energy demand of a production machine remains the same for every job – we repeated our simulation runs with a new combination of priority rules. The combination of the GRB priority rule and the KRB priority rule was tested, whereby the choice of priority rule depends on a threshold value s and the generation output of the PV system.

In specific, the jobs within the queue in front of a production machine are sorted in ascending order of remaining processing time as long as the average PV output within the next hour is less than the threshold value s multiplied with the nominal capacity of the photovoltaic system. So, when a machine finished an operation and is available for processing the next job, the one with the lowest remaining processing time is next. In reverse, as soon as the the average generation power of the PV system of the next hour is greater than or equal to the threshold value s multiplied with the photovoltaic generation capacity, the job with the longest remaining processing time is processed next. To summarize our attempt, scheduling by the new combination GRB-KRB-s follows this logic:

if $\overline{PV}_{Power}^{next\ hour} < s \cdot PV_{Capacity}$ *then*

Apply KRB priority rule

else Apply GRB priority rule

We conducted 101 simulation runs for each weather scenario while increasing the threshold value s iteratively by 0.01, starting at s = 0 and ending at s = 1. By this, different s values were derived that lead to a reduction in makespan and emissions compared to the conventional priority rules. Out of these 505 runs, the results of the simulation runs with the most suitable s values per weather scenario are stated in table 2. In relation to the schedules of the conventional priority rules with the lowest makespan and the lowest emissions, this second combination of priority rules achieves improvements in terms of economic and ecological manner as well. In every weather scenario, the makespan of the schedules by the GRB-KRB-s heuristic is lower than the minimal makespan of the conventional priority rules, equal to 12.78 h. Moreover, the emission quantity is reduced in each scenario, between 3.1% (18 Sept) and 60.3% (09 Sept).

However, as can be inferred from table 2, the value of s is essential to obtain these favourable results. For example for the weather scenario September 11th, the stated results are only achieved for a threshold value s equal to 0.14. Similarly, the intervals of the s values in the other scenarios are rather small. To some extent, the same holds true for our first heuristic LOZ-KOZ-s. Based on the data presented in table 3, we discuss both heuristics, LOZ-KOZ-s and GRB-KRB-s, in the following.

DISCUSSION

According to our results, both heuristics provide schedules with lower makespan and energy-related emissions than the considered conventional priority rules. Since the two combinations LOZ-KOZ-s and GRB-KRB-s take into account onsite generated solar energy to some extent, the amount of energy procured from the macrogrid is reduced.

In comparing both heuristics, it can be observed from the results in table 3 that the two heuristics yield to different values for makespan and emission quantity. The first combination, LOZ-KOZ-s, achieves a lower makespan in the first three weather scenarios and a lower emission quantity in the second and fifth weather scenario. Consequently, the GRB-KRB-s heuristic delivers better results for makespan in the fourth and fifth weather scenario as well as lower emission quantity in the first, third and fourth weather scenario.

These reduced values in emission output are based either on differences in total energy consumption or due to differences in consumption of generated solar energy and the amount of procured energy from the macrogrid. The former is the case for the GRB-KRB-s combination on September 16th for example. Although the consumption of solar energy is higher for the LOZ-KOZ-s schedule and therefore, the amount of unused solar energy is lower, the GRB-KRB-s schedule results in less energy-related emissions for that day because it causes a lower

Table 2: Results of the second combination of priority rules compared to the conventional priority rules (PR) with lowest makespan and lowest emissions in each weather scenario: makespan (MS), emission quantity (E) and threshold value (s) are listed. Note that in four weather scenarios, an interval for s is given.

Weather Scenario	PR with lowest makespan			PR with lowest emissions			GRB-KRB-s		
	Rule	MS [h]	E [kg]	Rule	MS [h]	E [kg]	s	MS [h]	E [kg]
09 Sept	LOZ	12.78	5.71	KOZ	13.02	4.81	[0.53; 0.59]	12.45	1.91
11 Sept	LOZ	12.78	33.95	KOZ	13.02	33.42	0.14	12.47	29.55
16 Sept	LOZ	12.78	8.04	KOZ	13.02	7.04	[0.48; 0.50]	12.47	3.12
18 Sept	LOZ	12.78	50.51	GRB	12.87	48.71	[0.09; 0.10]	12.45	47.20
23 Sept	LOZ	12.78	32.28	KOZ	13.02	31.49	[0.08; 0.12]	12.25	29.38

Table 3: Comparison of the two outlined combinations LOZ-KOS-s and GRB-KRB-s: threshold value (s), makespan (MS), total energy consumption (TEC), consumption of generated solar energy (SEC), amount of unused solar energy (USE), energy procurement from the macrogrid (EPG) and emission quantity (E) are stated.

Weather Scenario	Heuristic	s	MS [h]	TEC [kWh]	SEC [kWh]	USE [kWh]	EPG [kWh]	E [kg]
09 Sept	LOZ-KOZ-s	[0.64; 0.76]	12.42	225.50	220.33	472.85	5.17	2.07
	GRB-KRB-s	[0.53; 0.59]	12.45	222.75	217.98	475.21	4.77	1.91
11 Sept	LOZ-KOZ-s	0.16	12.20	222.00	149.92	28.01	72.08	28.90
	GRB-KRB-s	0.14	12.47	220.75	147.05	30.88	73.70	29.55
16 Sept	LOZ-KOZ-s	[0.50; 0.60]	12.42	225.50	214.95	341.62	10.55	4.23
	GRB-KRB-s	[0.48; 0.50]	12.47	220.75	212.98	343.59	7.77	3.12
18 Sept	LOZ-KOZ-s	0.13	12.73	223.75	105.04	0	118.71	47.60
	GRB-KRB-s	[0.09; 0.10]	12.45	222.75	105.04	0	117.71	47.20
23 Sept	LOZ-KOZ-s	0.33	12.73	225.75	153.98	129.88	71.77	28.78
	GRB-KRB-s	[0.08; 0.12]	12.25	226.75	153.47	130.39	73.28	29.38

total energy consumption. Conversely, on September 11th for instance, scheduling by the GRB-KRB-s combination achieves a higher amount of emissions than LOZ-KOZ-s even though the total energy consumption is lower than that of the first combination. Rather, the reason for this lies in the higher utilization of the generated solar energy by the LOZ-KOZ-s heuristic which is reflected by the corresponding values for SEC and USE in table 3.

Based on the present data, it appears that the first heuristic uses the onsite generated energy to a higher proportion in most cases, while the second heuristic achieves lower total energy consumption. Moreover, the comparison of the two combinations of priority rules shows that there is a very high dependence on the weather data and the threshold values when choosing the appropriate heuristic.

Nonetheless, the two heuristics only provide good results under certain conditions. As such, none of the outlined combination of priority rules leads to superior results in all weather scenarios. Consequently, further adjustments are necessary to achieve more sufficient results. For instance, this could be realised in terms of an optimization model combined with the simulation of weather scenarios.

CONCLUSION AND OUTLOOK

Throughout this article, we presented different production scheduling approaches with regard to energy-related emissions. For a job shop environment with a renewable energy source onsite, several simulation runs were performed and two combinations of conventional priority rules were analyzed in terms of makespan, energy consumption and emission output. By addressing the varying energy generation to some extent, both heuristics were able to reduce emissions in production. The outlined research expands previous work and provides additional insights on the relation between total energy consumption, the utilization of renewable energy and the associated emissions in production scheduling.

Regarding the objective of reducing energy-related emissions by production scheduling, further research is planned for the future. For a large share of the production schedules stated, there was still a high proportion of solar energy that remained unused. An increased flexibility in production, e.g. by heterogeneous production machines or speed scaling strategies, could lead to a higher utilisation of such renewable energy sources. By taking into account variations in the energy demand of parallel machines for instance, production scheduling could align jobs to the production machine with higher energy demand especially in periods of high solar energy supply. Vice versa, less jobs would be scheduled for processing by this machine in periods with lower power output of the photovoltaic system. Moreover, the adjustment of the machine speed and thus the energy demand depending on the renewable energy supply could serve as a further improvement option. In this context, modifying the prediction horizon for the PV generation output may bring further benefits. Besides that, a consideration of time-varying emission factors could help to align research closer to reality.

Since these extensions are unlikely to be representable by simple heuristics such as priority rules, these issues should be addressed by means of a multi-criteria optimization model. With this, a sufficient balance between economic and ecological objectives could be derived and the indicated trade-off between reduced total energy consumption and increased consumption of renewable energy could be further investigated. Furthermore, a practical approach might lie in single machine scheduling, as soon as individual larger energy consumers occur in the shopfloor.

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