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A *MILP* Formulation for an Automated Guided Vehicle Scheduling Problem with Battery Constraints

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Abstract. Nowadays, AGVs are frequently used in industries for the internal transportation of goods or pallets. The aim of an AGV-based internal transportation system is to transfer the right amount of the right material to the right place at the right time. Therefore, the determination of a good scheduling of the AGV tasks is essential to overcome delays in production and material handling processes. In this work, we study a scheduling problem arising from an internal transportation system of a company operating in the manufacturing field where AGVs subject to battery constraints are used for horizontal movement of materials. The aim of this work is to highlight the impact of the AGV battery recharge times on the completion time of the material handling process. To this aim, we propose an original mixed integer linear programming (MILP) formulation to optimally solve the addressed problem. The proposed model is validated on test instances built from real data comparing its results with those obtained disregarding the battery constraints. The results show the effectiveness of the proposed solution method and the impact of the AGV charging time on the handling process completion time.

Keywords: parallel scheduling · AGV recharge · MILP modeling.

1 Introduction

The introduction of automated guided vehicles (AGVs), due to their dexterity, efficiency and flexibility, had a great impact on logistics leading to the creation of new business models [13, 16]. Currently, different kinds of AGVs are used for several logistics operations in the entire supply chain: extraction of raw materials, intermediate transport, last mile delivery to cite only a few [3, 4, 17, 20]. In particular, AGVs are frequently used in industries for the internal transportation of goods or pallets between various departments or locations within the

same factory or for receiving, storage and sorting goods in shipment areas [19]. The aim of an AGV-based internal transportation system is to transfer the right amount of the right material to the right place at the right time. Therefore, the determination of a good scheduling of the AGV tasks is essential to overcome delays in production and material handling processes [10]. The research activity on AGV-based internal transportation system and, in particular, on related scheduling problems has been significant in the last twenty years. The interested reader is addressed to the survey works on the topic published by Kaoud et al [8], Qiu et al. [18] and Xie et al. [21]. In this context, different scheduling problems were defined on the basis of the considered AGV side constraints (e.g., capacity, schedules of additional equipment and limited parking space) [7]. However, as noted in [5, 12], most of the contributions on the topic paid scarce attention to the issues related to the battery usage, being it frequently omitted [6].

Nowadays, consistently with the industry 4.0 paradigm [9], several companies are adapting their processes to operate with a more intensive focus on sustainability through an increasing economic and ecological efficiency (e.g., [2, 11]). In this context, an effective battery management on AGVs can have a significant impact on the overall performance of the manufacturing system, as noted in [20]. On this basis, in this work, we study a scheduling problem arising from an internal transportation system of a company operating in the manufacturing field where AGVs subject to battery constraints are used for horizontal movement of materials. In a nutshell, the AGV transportation system performs as follows: a set of AGVs must move some materials from a central warehouse to different workstations; on each trip, an AGV can be loaded with the materials of a single workstation; the AGV battery consumption depends on the travel time and the weight carried; the battery has to be recharged before it is completely depleted. The problem consists in determining the AGV scheduling that minimizes the time to supply the required materials to all the workstations. This problem will be denoted in the following as the AGV scheduling problem with battery constraints (*ASP-BC*). The aim of this work is to highlight the not negligible impact of the AGV battery recharge times on the completion time of the material handling process. To this aim, we proposed an original mixed-integer linear programming (*MILP*) formulation for the *ASP-BC*. The proposed model is then validated on test instances built from real data comparing its results with those obtained disregarding the battery constraints.

Similar problems have been addressed in literature through heuristic approaches [1, 6]. However, to the best of our knowledge, this is the first work addressing this kind of problem through an exact solution approach. The rest of this paper is structured as follows: in Section 2, we provide a detailed description of the *ASP-BC*; the proposed *MILP* formulation is presented in 3; the computational results are reported in Section 4; conclusions and research perspectives are given in Section 5.

2 Problem Description

In a manufacturing facility, at the beginning of each working day, a set of workstations must be supplied with the materials required for the production tasks. The requested materials are organized within a set of packages as follows:

- all the materials requested by a workstation are included in only one package
- a package contains the materials of only one workstation

This kind of organization creates a one-to-one workstation-package relation. The packages are arranged in a central warehouse and must be carried to the corresponding workstations by a set of AGVs. The AGVs are initially located at the central warehouse and can carry one package at a time. Moreover, the number of available AGVs is much lower than the number of packages. Therefore, an AGV should perform multiple trips since it generally has to serve more than one workstation. On this basis, in the following, We will refer the combination of an AGV loaded trip from warehouse to workstations and the empty trip back as a job. A job can be characterized by a duration given by the sum of the travel time from the warehouse to the workstation and back, and the time needed for the package load and unload operations. Moreover, each job requires a certain amount of energy to be performed by an AGV. Specifically, the required energy depends on the job duration and the package weight. Therefore, since AGVs are battery powered, the number of consecutive jobs that an AGV can perform without battery recharge is limited. The AGV battery is fully charged at the beginning of the working day and it has to be fully recharged before it is completely depleted. The charging time is fixed and does not depend on the residual energy. The manufacturer company aim is to minimize the time required to supply the materials/packages to all the workstations so avoiding delays in the production operations.

The solution of the arising optimization problem involves three kinds of decisions:

- assignment of jobs to the AGVs;
- sequencing of the jobs on each AGV;
- scheduling of AGV battery recharge.

The objective is to minimize the makespan that is given by the maximum completion time of the last job over all the AGVs.

3 Problem Formulation

To formulate the *ASP-BC*, we introduced a notation based on the the previous problem description. For the sake of readability, the notation is reported in Table 1.

Consistently with this notation, the *ASP-BC* can be formulated as follows:

$$\min C_{\max} \tag{1}$$

Table 1. Notation used for the *ASP-BC* formulation.

Problem notation	
Sets:	
J	Set of jobs
K	Set of AGVs
$\{o\}$	Starting dummy job for each AGV
$\{d\}$	Ending dummy job for each AGV
J^+	$J \cup \{o\}$
J^-	$J \cup \{d\}$
Parameters:	
t_j^k	processing time of the job j on the AGV k
w_j^k	energy required for the job j on the AGV k
r	AGV battery charging time
E	AGV battery capacity
M	sufficiently large constant
Variables:	
$C_{\max} \geq 0$	completion time of the handling process
$C_{\max}^k \geq 0$	completion time of the last job performed by the k -th AGV
$s_j^k \geq 0$	starting time of job j on the AGV k
$c_j^k \geq 0$	ending time of job j on the AGV k
$e_j^k \geq 0$	energy spent by the AGV k from its last charge to the completion of job j
$x_j^k \in \{0, 1\}$	equal to 1 if the job j is assigned to the AGV k , 0 otherwise
$y_{ij}^k \in \{0, 1\}$	equal to 1 if job j is performed immediately after job i on the k -th AGV, 0 otherwise
$\delta_j^k \in \{0, 1\}$	equal to 1 if the AGV k is recharged before performing job j , 0 otherwise

s.t.

$$C_{\max} \geq C_{\max}^k \quad \forall k \in K \quad (2)$$

$$C_{\max}^k \geq c_j^k \quad \forall j \in J, k \in K \quad (3)$$

$$C_{\max}^k \geq C_{\max}^{k+1} \quad \forall k \in \{1, \dots, |K| - 1\} \quad (4)$$

$$c_j^k \geq s_j^k + t_j^k + r\delta_j^k - M(1 - x_j^k) \quad \forall j \in J, k \in K \quad (5)$$

$$c_o^k = 0 \quad \forall k \in K \quad (6)$$

$$\sum_{k \in K} x_j^k = 1 \quad \forall j \in J \quad (7)$$

$$s_j^k + c_j^k \leq Mx_j^k \quad \forall j \in J, k \in K \quad (8)$$

$$s_i^k \geq +c_j^k - M(1 - y_{ji}^k) \quad \forall i \in J, j \in J^+, k \in K \quad (9)$$

$$c_j^k \geq +s_i^k - M(1 - y_{ji}^k) \quad \forall i \in J, j \in J^+, k \in K \quad (10)$$

$$\sum_{j \in J} y_{oj}^k = 1 \quad \forall k \in K \quad (11)$$

$$\sum_{j \in J} y_{jd}^k = 1 \quad \forall k \in K \quad (12)$$

$$\sum_{j \in J^+} y_{ji}^k = \sum_{j \in J^-} y_{ij}^k \quad \forall i \in J, K \in K \quad (13)$$

$$\sum_{i \in J^+} y_{ij}^k = x_j^k \quad \forall j \in J, k \in K \quad (14)$$

$$e_j^k \geq e_i^k + w_j^k - M(1 - y_{ji}^k) - M\delta_j^k \quad \forall i, j \in J, k \in K \quad (15)$$

$$e_j^k \geq w_j^k - M(1 - x_j^k) \quad \forall j \in J, k \in K \quad (16)$$

$$e_j^k + w_i^k \leq E + M(1 - y_{ji}^k) + M\delta_j^k \quad \forall i \in J, j \in J^+, k \in K \quad (17)$$

$$\delta_j^k \leq x_j^k \quad \forall j \in J, k \in K \quad (18)$$

$$\delta_j^k \leq (1 - y_{0j}^k) \quad \forall j \in J, k \in K \quad (19)$$

The objective function (1) minimizes the makespan of the handling process. Constraints (2) set the makespan equal to the maximum completion time among the ones of the used AGVs. Constraints (3) set the makespan of an AGV equal to the completion time of its last processed job. Constraints (4) are symmetry breaking constraints. Constraints (5) ensure that if a job j is assigned to the AGV k then its completion time is equal to its starting time plus the processing time and the charging time (if a recharge is scheduled). Constraints (6) set the completion time of the initial dummy job equal to 0. Constraints (7) guarantee that each job is performed. The consistency between starting and completion time variables and job-AGV assignment variables is granted by constraints (8). The congruence between the completion time and the starting time of jobs that are performed consecutively on the same AGV is guaranteed by constraints (9,10). Constraints (11-13) ensure that each AGV can perform one job at a time. Constraints (14) are consistency constraints among y and x variables.

Constraints (15, 16) set the value of the energy consumption of each AGV after each performed job. Constraints (17) guarantee that an AGV is recharged if, performing a job, the energy consumption would exceed its battery capacity. The consistency between the recharge variables and assignment variables is granted by constraints (18). Finally, constraints (19) ensure that an AGV is not recharged without having performed at least one job.

We highlight that relaxing the battery constraints (15-19) and excluding the recharge variables, the *ASP-BC* turns out to be the well known parallel machine scheduling problem (*PSP*) [14, 15]. Therefore, the optimal solution of the *PSP* is a lower bound for the *ASP-BC*.

4 Computational Results

In this section we present and discuss the computational results of the experimentation performed to validate the proposed *MILP* formulation for the *APS-BC* and to evaluate the impact of the AGV charging time on the handling process completion time. To this aim, we implemented the procedure currently used by the manufacturing company to solve the *ASP-BC*. The procedure first solves the *PSP* and then adds the recharge activities when needed (i.e., immediately before an AGV performs a job that otherwise would completely deplete its battery). The procedure, denoted in the following as *PSP+R*, has been implemented in Python 3.6 and the *ASP-BC* and *PSP* formulations have been solved with a commercial MIP solver (FICO Xpress-MP 8.2) on an Intel(R) Core (TM) i5-8250U, 1.80GHz, 8.00GB of RAM.

The experimentation has been conducted on twenty instances built from real data coming from a manufacturing company. In particular, we generated four sets of five instances each, with 6, 7, 8 and 9 jobs. The number of AGVs is equal to 2 and we considered the same charging time (r) and battery capacity (E) for all the instances. For each instance, we computed:

- the completion time of the related *PSP* solution (C_{PSP});
- the completion time of the optimal *ASP-BC* solution obtained by the proposed *MILP* formulation (C_{MILP});
- the completion time of the *ASP-BC* solution obtained using the procedure *PSP+R* (C_{PROC}).

The *PSP* and *ASP-BC* formulations were optimally solved on all the instances within a time limit of 10800 seconds.

The results of the experimentation are shown in Table 2. In particular, for each solution method we reported the percentage difference (%Diff) with the completion time of the *PSP* optimal solution and the number of recharge activities scheduled (Rech). The percentage differences related to the *PSP+R* and *MILP* solution methods are computed as $(C_{PROC} - C_{PSP})/C_{PSP} \cdot 100$ and $(C_{MILP} - C_{PSP})/C_{PSP} \cdot 100$.

Moreover, we also compute the saving in terms of completion time obtained solving the proposed *MILP* rather than applying *PSP+R* ($\%Sav = (C_{PROC} - C_{MILP})/C_{MILP} \cdot 100$).

Table 2. Comparison of the *PSP+R* and *MILP* solutions

Id	J	PSP+R		MILP		
		%Diff	Rech	%Diff	Rech	%Sav
I.1	6	30.77	2	30.77	2	0.00
I.2		35.09	2	35.09	2	0.00
I.3		62.50	1	1.56	0	60.00
I.4		62.50	1	6.25	0	52.94
I.5		70.18	3	35.09	2	25.97
I.6	7	50.00	3	25.00	2	20.00
I.7		57.14	3	42.86	3	10.00
I.8		48.78	3	40.24	2	6.09
I.9		56.34	3	42.25	3	9.90
I.10		56.34	3	49.30	3	4.72
I.11	8	71.43	5	47.62	4	16.13
I.12		53.33	3	26.67	2	21.05
I.13		58.82	5	39.22	4	14.08
I.14		71.08	5	49.40	4	14.52
I.15		48.19	4	42.17	2	4.24
I.16	9	63.83	5	42.55	4	14.93
I.17		59.41	5	39.60	4	14.18
I.18		72.16	5	41.24	4	21.90
I.19		64.17	5	52.94	5	7.34
I.20		49.76	5	48.78	5	0.66
Average		57.09	3.55	36.93	2.85	15.93

We can observe that, on average, the completion time determined taking into account battery constraints is about 35% greater than the one obtained solving a *PSP*. This result proves the not negligible relevance of charging activities within a internal transportation system operated by AGVs. Indeed, the reported %Diff values show that charging activities represent a significant component of the handling process completion time. For example, on the instance L_20, the %Diff of the *MILP* solution is equal to 52.94%, i.e., the charging activities are around the 30% of the completion time. Moreover, we point out that if the battery issue is not effectively addressed then the charging activities can have even a greater impact on the completion time as we can observe from the average %Diff of *PSP+R* that is around the 60%. Furthermore, the average saving, equal to 15.93%, provides an idea of the completion time reduction that a company can achieve by optimally solving the *ASP-BC*.

Finally, we highlight that on average the optimal solution of the *APS-BC* determines fewer battery recharges compared to the *PSP+R* solution, even if the number of recharges is not directly considered in the objective function. This result is very important not only in terms of completion time, as previously shown, but also in terms of costs. Indeed, a company has to replace the AGV batteries when they reach their cycle life (i.e., the number of charge and discharge cycles that a battery can complete). Therefore, an effective management of the recharges can extend the battery lifespan reducing the costs for battery replacing borne by a company.

5 Conclusions

In this work, we presented a particular scheduling problem arising in the manufacturing field. It consists in the determination of the optimal scheduling of AGVs subject to battery constraints to minimize the completion time of the material handling process. An original *MILP* formulation has been proposed to tackle the problem. The performed experimentation on instances with up to 9 jobs and 2 AGVs, derived from real data, confirm the applicability and the effectiveness of the proposed approach. Preliminary results showed that the running time of the proposed approach on instances with tens of jobs and the same number of AGVs exceeds the considered time limit. Therefore, future works will be aimed at developing heuristic solution methods able to effectively address large scale instances. Moreover, it could be interesting to investigate the possibility of taking into account other operational aspects related to the battery as the performance reduction and the possibility to do partial recharges.

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