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Energy-efficient supplying strategies in assembly lines

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Abstract

This paper focusses on the problem of supplying the workstations of assembly lines with components during the production process. The components are assumed to be packed in pallets (or boxes). The pallets are shipped from a co-called supermarket and delivered to the workstations using tow trains with wagons. For each time period, depending on the production plan, a workstation has its specific component demand expressed as a fraction of pallets. The problem is to define the sequence of workstations that have to be visited by the tow train at each time period, as well as the number of pallets delivered at each stop. For that specific problem, this paper presents a Mixed Integer Linear Program that aims at minimizing the energy consumption of the supplying strategy. We particularly discuss which are the most significant energy parameters for that problem and how they can be explicitly modelled into the MILP. We also provide computational experiments and discuss the limitation of the approach.
Key words: Supplying strategy, assembly lines, energy consumption, mixed integer linear programming.

1 Introduction

Nowadays, in most factories row materials supplying is governed by the Just In Time (JIT) paradigm. It concentrates on improving the efficiency, service and quality of the production processes without any regard for their energy performances. There is a need of reviewing JIT under an energy-awareness perspective, aiming at balancing economic and environmental performances. Focusing on the internal logistic of factories, the Eco-Innovera project [1] "Energy-Aware feeding Systems" (EASY) aims at favoring energy-aware practices, taking explicitly energy consumptions factors into account at the very heart of the optimization procedures. Motivated by the challenge associated with the preceding problem, the project target is the design of new optimization and simulation models for the feeding systems of assembly processes, intending to determine which the major energy-consumption factors are and how they can be optimized to reduce energy consumption, still keeping a satisfactory economical efficiency.

In general, feeding systems of assembly lines (see Figure) are composed by a central warehouse (or a supermarket), several workstations organized in sequence in the production line and a fleet of vehicles (tow trains) that are in charged of delivering the component to the workstations. The components are packed in pallet or boxes. The supermarket is a decentralized area of material supplies, which is located next to the assembly line, where the component boxes are stored.

The time is discretized in a set of tours or delivering periods. For each period, a workstation has a component consumption (possibly periodic) expressed i, terms of boxes. At each tour, the tow trains load the boxes which have to be shipped to the assembly line, follow a route, and stop at the appropriate workstations for delivering its boxes. The routes are usually fixed and start and finish at the supermarket. The number of boxes that a tow train can transport in the same tour is limited. The number of boxes available at each workstation should never exceed the storage capacity of the workstation (which is usually low). A supplying strategy defines the number of boxes that the vehicle has to deliver to each workstation at each period.

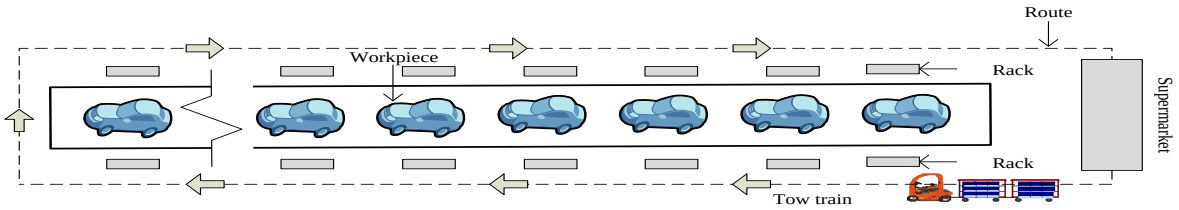


Figure 1: General structure of an assembly line.

In a world where natural resources are limited, issues related to energy are becoming more and more important. Vehicles in factories travel a significant quantity of kilometers for supplying the workstations, causing effects in economic and energetic expenses. Whether they use electric energy or fossil fuel, their energetic consumption is not negligible and more and more attention has to be paid for exhibiting energy-efficient supplying strategies. Several factors that are inherent to the problem have impact on the energy consumption. We take interest in determining the most significant ones.

Many researches on energy consumption in feeding systems' optimization focussed on eco-driving solutions [2] or considered the inventory routing problem [3]. The eco-driving model identifies optimal driving strategies for the purpose of reducing the consumed energy in different traffic congestion, based on vehicle speed and gear ratio decisions. This kind of model, suitable for urban transportation, seems to be inappropriate for our problem where the driving profile cannot be controlled in this way. Our problem turns out to be closer to an inventory routing problem but without the routing part, the routes being fixed. Based on this observation, Fathi et al. [4] proposes a mathematical model in order to minimize the energy consumption in an assembly line taking into account the distance travelled by vehicles.

In this paper, we intend to show that minimizing the travelled distance does not necessarily implies the minimization of the energy. We prove that other parameters can significantly influence the energy spending and should be explicitly taken into account inside the optimization procedures. These parameters are taken from the energy mathematical relationships, which are established in the article written by Garcia et al. [5]. The remainder of this paper is organized as follows. An energy consumption analysis is proposed in Section 2.1 and the most influential energy consumption factors are described in Section 2.2. A mixed linear program for energetic optimization is described in Section 2.3. In Section 3, experiments are provided and a comparison of our model with the distance minimization model of Fathi et al. is made. Conclusions are finally given in Section 4.

2 Energy modeling

Many factors influence the energy consumption of vehicles, the most significant being the traction force and the rolling resistance. The effect of stopping a vehicle in a workstation, then restarting it, has also an important effect in terms of energy expenses [6].

2.1 *Energy consumption analysis*

The mathematical relationships between the physical quantities of energy (E), work (W) and power (P) are :

$$E = \int P * dt \tag{1}$$

$$P = F * v \tag{2}$$

$$E = W = \sum F * dist \tag{3}$$

E refers to the energy consumed expressed in Joule, P the power consumed in Watt, F makes reference to the force that causes a power consumption and dt, v and $dist$ represent the time diferencial, the speed or velocity and the distance, respectively.

The forces that have more influence on the power consumed by the vehicle are: the traction force (F_t) and the rolling resistance (F_r), in Newtons (N). The traction force is used to generate motion between an object and a tangential surface, and it depends on the mass (m_T) and the acceleration of the vehicle ($a(t)$). The rolling resistance is the force resisting the motion when a body rolls on a surface and varies in function of the load (m_T), the rolling coefficient (C_r) and the gravity (g). The parameter (m_T) represents the mass of the vehicle (determined by the kind of vehicle) in addition to the transported load, which varies according to the demand.

$$F_t = m_T a(t) \tag{4}$$

$$F_r = m_T g C_r \tag{5}$$

Therefore, the expresion that expresses the energy consumption is:

$$E = \int m_T(a + gC_r)v(t)dt \tag{6}$$

Looking at the energy formula (6), all the parameters, except the gravity, depend on the vehicle characteristics. For sake of simplicity, the acceleration (constant) and the maximum speed are assumed known. The acceleration and deceleration are considered equal and have opposite directions. Thanks to the literature, the rolling coefficient between a wheel and the floor is also known. Eventually, the only parameters that vary are the mass transported and the working time of the vehicle.

Energy is the integral of the consumed power over the time, thus it can be easily calculated. Figure 2.1 represents the consumed energy between two workstations. Three phases can be differentiated according to the vehicle state. The first phase corresponds to the acceleration phase where a peak of energy is produced, due to the acceleration. The second phase begins when the speed of the vehicle is constant and there is no acceleration anymore. Finally, in the deceleration phase, the energy consumption is null.

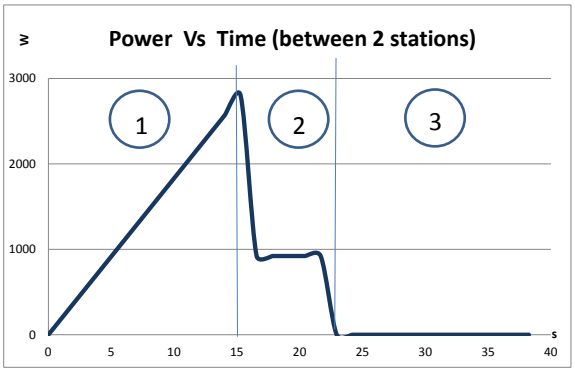


Figure 2: Energy profile between 2 workstations.

The transported load, the travelled distance (length of a tour and number of tours) and the number of stops ([6]) change the energy consumption. We need to analyze the influence of each parameter so as to find optimal strategies.

2.2 *Significant energy-spending parameters*

The transported load is directly proportional to the consumed energy (6), so if the load increases, the consumed energy too. Depending on the way of delivering the load, the energy consumption is different. The load can be supplied in a constant, decreasing or increasing way, whether the box weights are identical, the heaviest boxes are delivered first or, at the reverse, last . The most suitable strategy for the purpose of energy savings is the decreasing one, due to the fact that most part of the distance is travelled with less load.

The effect of stopping at a workstation and restarting cause an important boost in the energy demand. During the acceleration phase, a "peak" in the power needed is produced, so a rise in the energy consumption. Decreasing the number of vehicle stops in every workstation reduces the number of acceleration phases, hence the peaks of energy.

The travelled distance is also directly linked to the energy. Nevertheless, doing some experimentations, we exhibit some situations where it is better to travel over a long distance (make more tours) and transport less load, rather than reduce the travelled distance and carrying a high load.

2.3 *Energy-aware mathematical modelling*

In this section, a mixed integer linear programming (MILP) model is presented. This model includes the previous influential factors. The delivered load and the travelled distance are taken into account in the energy formula. Depending on the vehicle stop policy, four scenarios can be distinguished for computing the energy spent between two contiguous workstations. The energy consumption depends whether the vehicle is stopped in the workstation i or not and whether it is going to stop in workstation $i+1$ or not. Figures 3, 4, 5, 6 shows the four possible scenarios, with their corresponding energy formula.

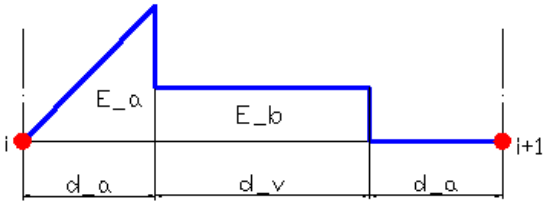


Figure 3: $(M_{i+1} + M_v)(E_a d_a + E_b d_v)$

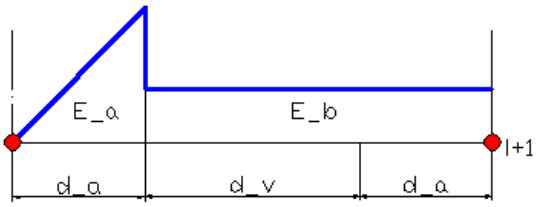


Figure 4: $(M_{i+1} + M_v)(E_a d_a + E_b(d_v + d_a))$

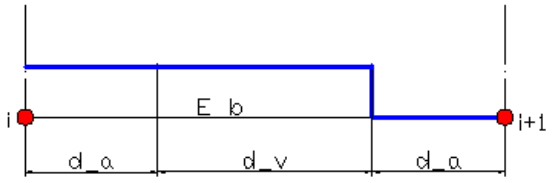


Figure 5: $(M_{i+1} + M_v)(E_b(d_v + d_a))$

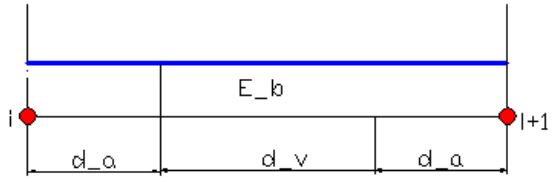


Figure 6: $(M_{i+1} + M_v)(E_b(d_v + 2d_a))$

Where M_{i+1} is the load that is delivered to workstation $i+1$ and M_v, the weight of the vehicle. E_b and E_a are the energy consumed when the tow train has a constant speed (E_b) and when it is in the acceleration phase (E_a), respectively. The distance travelled during the starting phase is denoted d_a and the one of the constant speed phase is referred as d_v.

This four possibilities can be expressed as a single expression using decision variables. To indicate that the vehicle stops or not in a workstation, a binary variable X_i is introduced. It equals 1 only if the vehicle stops in workstation i. The energy consumption between two workstations can be expressed by equation (7).

$$(M_{i+1} + M_v)(E_b d_v + X_i E_a d_a + (1 - X_i)E_b d_a + (1 - X_{i+1})E_b d_a) \quad (7)$$

Extending the energy consumption between two workstations to the whole route and considering all the time periods, the total energy consumed can be computed. It corresponds to the objective function of the following MILP. Each tour has a maximum of n workstations and the total number of possible tours is denoted by NT. Y_t indicates whether the tour t is done or not, P_{it}, is an integer variable that represents the number of delivered components in workstation i during tour t and Z_{ijt} is a linearization variable which is enforced, thanks to linear constraints, to be equal to the product $X_{it}X_{jt}$.

The mixed integer linear programming model is:

$$\text{Min Z} = \sum_{t=1}^{NT}\sum_{i=1}^{n}[Y_t M_v E_b(d_v + 2d_a) + M_v d_a(X_{it}(E_a - E_b) - E_b X_{i+1t}) \sum_{j=i+1}^{n} M_j(P_{jt}E_b(d_v + 2d_a) + Z_{ijt}d_a(E_a - E_b) - Z_{i+1jt}E_b d_a) \quad (8)$$

St:

$$P_{it} + IL_{it-1} - d_{it} = IL_{it} \quad \forall\ (i,t) \quad (9)$$

$$\sum_{i=1}^{n} P_{it} \leq A \quad \forall\ (i,t) \quad (10)$$

$$P_{it} + IL_{it-1} \leq C_i \quad \forall\ (i,t) \quad (11)$$

$$X_{it} \leq Y_t \quad \forall\ (i,t) \quad (12)$$

$$IL_{it} \geq 0 \quad \forall\ (i,t) \quad (13)$$

$$P_{it} \geq 0 \quad \forall\ (i,t) \quad (14)$$

$$X_{it} \in [0,1] \quad \forall\ (i,t) \quad (15)$$

$$Y_t \in [0,1] \quad \forall\ (i,t) \quad (16)$$

The objective function (8) aims at minimizing the total energy consumption, which is proportional to the number of delivered components P_{it}, the fact of stopping in workstation i during tour t (X_{it}) and the realization of a tour Y_t. The first set of constraints (9) ensures the demand satisfaction during each period and for each workstation. The second set of equations (10) ensures the capacity limit of the vehicle and the third set of constraints (11) the capacity of the workstations. Next set of equations (12) ensures the production of a tour, thus if the vehicle stops in a workstation during the tour, Y_t is equal to 1. Equations (13) - (16) defines the domain of each variable.

3 Experimentation

We use the problem instances proposed by Fathi et al. [4] where only a single vehicle is considered. For filling our energy model with the vehicle characteristics, we use the parameters from a real tow train [7]. The instances vary according to the total number of workstations and tours considered, as well as the component demand profiles and the storage and transport capacities. Since Fathi et al. only pays attention to the travelled distance minimization, the weight of each box and the distance between workstations were not specified. We propose to analyze the impact of those parameters with respect to the energy consumption.

The MILP model has been solved using the mathematical solver Gurobi, which is freely available for academics.The solution gives an energy-optimal supplying plan that specifies the number of components delivered to each workstation at each tour.

We highlight that our model allow to minimize either the total travelled distance or the energy consumption, by simply replacing one objective function

by the other. That is the reason why we decided to minimize first the travelled distance then, providing to Gurobi this first initial feasible solution, to optimize the energy consumption. Our purpose is to analyse whether it is worth, with respect to energy spending, to take all the factors into account (delivered load, number of stops and travelled distance) or whether , on the contrary, minimizing the travelled distance (i.e., the number of tours) is enough.

Concerning the computational effort needed for solving the MILP, it has to be noticed that, while minimizing the total number of tours is rather easy, tackling the energy objective function is much more time expensive. Gurobi was not indeed able to solve to optimality most of the problem instances in a reasonable amount of time. So, we decided to limit the optimization effort to one hour, then to compare the best solution obtained after one hour with the initial one, aiming at measuring the energy savings. Consequently, the energy gaps that we observe are lower bounds of the best possible savings.

The energy consumption in function of the number of workstations involved in a tour is represented in Figures 7-12. in these Figures, the consumed energy for every different situation is compared.

We consider various scenarios of weights for the component boxes. In the scenario mA the weight of each component box is the same, in scenarios mB and mC the weights were established randomly, allowing higher variations in scenario mC than in mB. Even if box weights are random, we impose that the total demanded weight for each tour is identical in each scenario, which allow to compare the scenarios in energy terms. Concerning the distance between the workstation, we also consider three scenarios $dist1$, $dist2$ and $dist3$. In scenario $dist1$ the inter-distance. It varies randomly in the other scenarios, allowing higher variation in $dist3$. In any scenario, the length of a tour is enforced to be constant.

All the experiments show that the consumed energy is always lower when all the parameters are taken into account. Increasing the number of workstations make even the energy savings greater, especially when the distances between workstation vary a lot. The mass of the boxes seem also to have an impact, though for the experiments made so far, the effect of mass variations is less obvious.

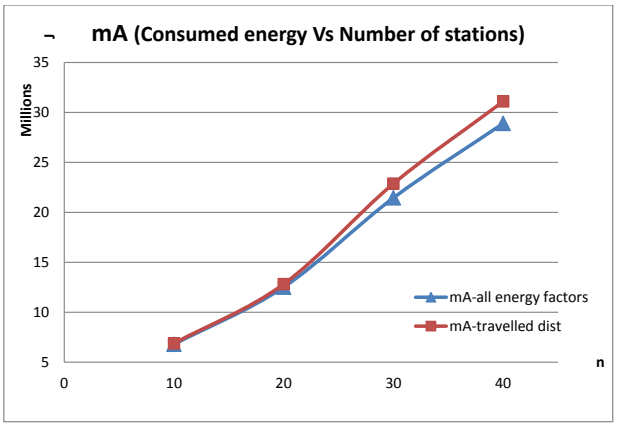


Figure 7: Consumed energy by the two models considering a mA load.

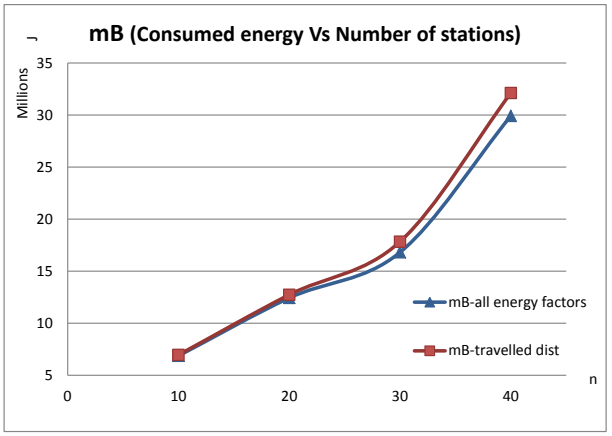


Figure 8: Consumed energy by the two models considering a mB load.

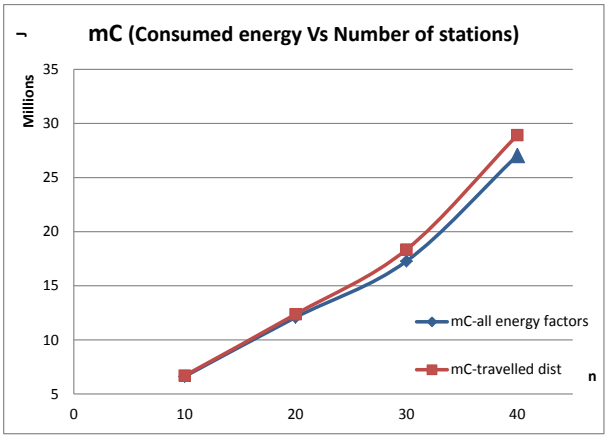


Figure 9: Consumed energy by the two models considering a mC load.

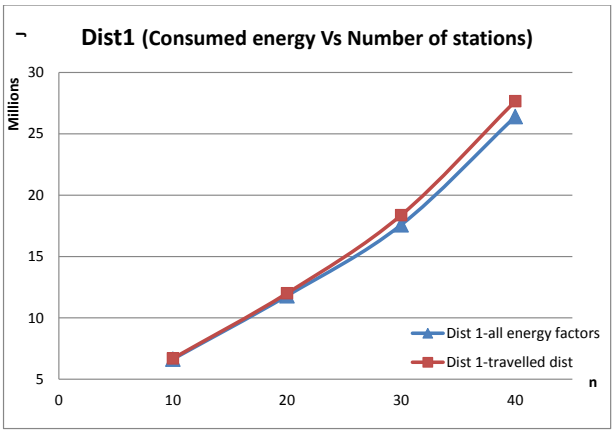


Figure 10: Consumed energy by the two models considering a *dist*1 distance.

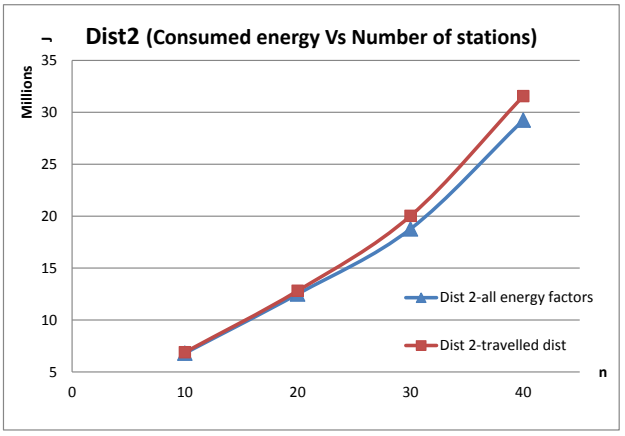


Figure 11: Consumed energy by the two models considering a *dist*2 distance.

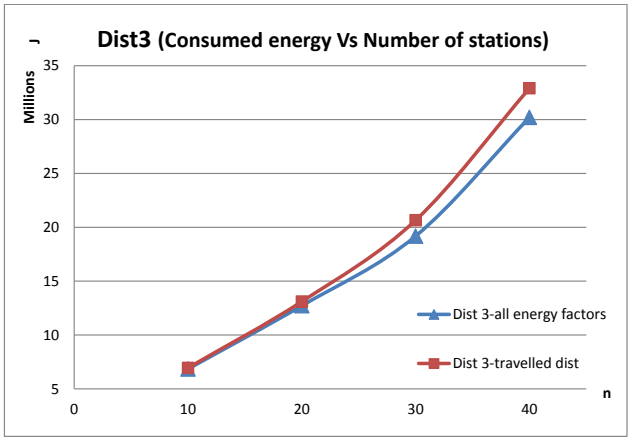


Figure 12: Consumed energy by the two models considering a *dist*3 distance.

4 Conclusion

We can conclude that taking the transported load, the number of stops and the total travelled distance simultaneously into account is worthy. We propose a MILP formulation that takes all theses parameters into account inside the optimization procedure. Nevertheless, the computational effort required for solving efficiently the corresponding model becomes really huge. Additional researches are needed in order to boost the optimization procedure using either more compact MILP formulation or more advanced optimization mechanisms such as valid inequalities generation, variable fixing techniques, or decomposition approaches (column generation).

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