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IMPACT OF USING PEM FORKLIFTS ON MANUFACTURING LAYOUTS

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ABSTRACT

The popularity of forklifts that use fuel cells based on proton exchange membranes (PEMs) has steadily increased with time in manufacturing industries and distribution centers. Because they potentially reduce our dependence on fossil fuels that emit carbon dioxide while generating energy, they have certain environmental benefits in comparison to forklifts driven by lead-acid batteries that are typically charged using regular sources of energy. In this paper, we study the impact of using PEM forklifts on material-handling costs and lead times, which are commonly used in measuring the cost-effectiveness of a manufacturing system's layout. We report some initial findings in this paper. In general, we find that layouts designed for PEM forklifts tend to have lower material-handling costs, improved closeness ratings, and higher area utilization, while the shop-floor lead times tend to be shorter, leading to lower inventory and higher flexibility in responding to fluctuations in customer demand. Overall, PEM forklifts may hence improve the health of the supply chain of the product by making it more flexible and cost-effective.

INTRODUCTION

Forklifts trucks or forklift trucks are industrial trucks commonly used for moving material within manufacturing industries and distribution centers. They are growing in popularity because they are *flexible* in terms of the path of transportation needed on the shop floor. Conveyors and Automated Guided Vehicles (AGVs), two of the popular equipment for material handling, are less flexible in comparison because they can transport material only on pre-designed, *fixed* routes. This is of less importance in flow shops, but in job shops, product routes are highly variable, and as a result the ability of forklifts to traverse variable routes becomes critical. As a result, it is not uncommon to see the forklift as the most commonly used equipment for material transport in job shops. In any production shop including a flow shop, a few forklifts are always necessary for moving heavy machine tooling and performing non-routine tasks. Consequently, despite the increasing use of group technology and cellular layouts in manufacturing, the forklifts remain popular on manufacturing shop floors. Welgama and Gibson (1996) were amongst the first authors to study the relationship between forklifts, layouts, and material-handling costs. Since, then the impact of a material-handling device on the material-handling costs and layout analysis has been a widely studied topic in the literature that is covered in depth in many textbooks, e.g., Heragu (2008).

Most modern forklifts are driven by lead-acid batteries that require recharging or swapping, which consumes time, resulting in the forklift becoming unavailable for long periods of time. Since forklifts are quite expensive, extra capacity is rarely available; hence, when a forklift vehicle being recharged while it is needed, production gets disrupted, which lengthens production lead times.

Long lead times are increasingly being viewed unfavorably in most manufacturing firms because they increase inventory of finished stock, thereby increasing operational costs and making the system inflexible to changes in demand and markets. In fact, shortening the lead time can make the difference between thriving and surviving in the globalized economy. Consequently, production managers make every possible effort to reduce lead times (Askin and Goldberg, 2002; Hopp et al. 1990). Also, an increasing number of industries are shifting from make-to-stock (MTS) to make-to-order (MTO) in an attempt to minimize the risks of unsold inventory. Reducing lead time is critical for a successful transition from MTS to MTO and to thrive in an MTO environment.

Fossil-based fuels have some well accepted deleterious environmental effects, which have amplified interest in the development of alternative sources of energy. In recent times, forklifts operating on alternative energy, e.g., fuel cells based on proton exchange membranes (PEM), are gaining popularity; they are some of the first vehicles to run on alternative sources of energy. PEM forklifts, which use hydrogen as the source of energy, have a minimal direct environmental impact. What is appealing is that they do not produce carbon dioxide during energy generation (DOE Website, 2010). It is true that hydrogen does not exist in nature naturally, and it requires energy to produce hydrogen. If the energy used to produce hydrogen in turn generates carbon dioxide, then clearly the usefulness of hydrogen energy in terms of environmental pollution becomes questionable. However, it is also true that alternative sources of energy, such as wind and solar, which are variable in their output, can be used to produce hydrogen; this can lead to a win-win situation, since some of these sources are highly variable, requiring a mechanism to store energy, while hydrogen production needs a source of energy that is itself not polluting. It is also likely that other breakthroughs in generating hydrogen will result in the near future making hydrogen generation without carbon dioxide production a reality.

Battery-powered forklifts suffer from voltage drops when power discharges. This usually leads to lowered power and ability to lift. Downtimes for recharging and cooling of the forklift can have durations of fifteen minutes to half an hour. PEM forklifts do not lose power as long as they have fuel. Also, they can refuel in an amount of time shorter than the recharging time for their battery-powered counterparts. In many facilities, batteries are swapped, which also consumes time, in addition to requiring additional workforce. As a result, PEM forklifts have the ability to function *continuously* in a plant that operate on two or even three shifts.

As stated above, PEM forklifts have the potential to reduce the lead time. Also, in systems with PEM forklifts, travel from machines to the battery-recharging areas and back can be eliminated if hydrogen dispensers are located in appropriate locations. This reduction of travel leads to reduced material-handling costs. Material-handling is known to be a non-value-adding activity which if left uncontrolled can account for 70 % of the product's total cost (Heragu, 2008). Consequently, any reduction of material handling reduces the manufacturing cost, thereby expanding profit margins. According to Tompkins and White (1984), material-handling expenditure can account for up to 50% of a company's working budget, which is indicative of the fact that that material-handling is a major source of expenditure and should be carefully controlled.

Material-handling costs, closeness rankings (or ratings), and productive area utilization are three of the most commonly used measures for quantifying the performance of a layout (Raman et al., 2009). Further, the lead time of a product also depends on the layout chosen; we will study the impact of using PEM forklifts on the layouts and the lead time.

To the best of our knowledge, we are the first to study the strategic, tactical and operational issues of using PEM forklifts; further, we attempt to characterize these issues with quantitative metrics. This may be an important gap in the literature, and our findings we hope will provide inspiration to both practitioners, who could potentially replace their lead-acid battery-driven forklifts with PEM forklifts, and to the academic community, which needs to play a significant role in making PEM forklifts economically viable.

The rest of this article is organized as follows. The section entitled SUPPLY CHAIN discusses supply chain issues. In the section entitled LAYOUTS, we discuss the impact of PEM forklifts on layout designing and issues related to the impact on lead times. Conclusions from this research are placed in the final section.

SUPPLY CHAIN

In North America alone there are approximately 5,000 large distribution centers which use forklifts in their daily operations. Some of these include several early adopters of PEM fuel cell-powered forklifts, e.g., Wal-Mart, GM and Fed Ex (www.hydrogen.energy.gov, 2008).

PEM fuel-cell-powered forklifts offer numerous strategic advantages, including the fact that they are more sustainable in comparison to battery-powered forklifts. Not only do PEM fuel cell forklifts use a renewable energy carrier but they also have zero operational emissions; these are extremely attractive in closed facilities. Historically, LPG forklifts have been associated to carbon monoxide poisoning (McCammon, 1996; Gallagher and Mason, 2004). As a result, forklifts with zero emissions are considered to be very safe in an environment in which humans work.

Additionally, PEM fuel cell forklifts have high energy efficiency and reliability; the actual efficiency can be 60% higher than that of an IC engine because the fuel cell process converts chemical energy to electric energy directly (Website 3). Furthermore, PEM fuel cell-powered forklifts have certain lifecycle cost advantages in continuous or double shift operations (Mahadevan *et al*. 2007; pg 139). Lifecycle cost comparisons of PEM fuel cell- and battery powered forklifts show benefits in materials handling applications, particularly in applications of continuous operations and in regions where tax incentives can be combined with federal tax credits. The US government has offered a tax credit of $3000/kW for fuel cells (DOE Website, 2010). PEM fuel cell forklifts require a lifecycle investment of approximately 48% to 50% lower than that of battery-powered pallet trucks in high-throughput applications and have lower total annual operating costs (Mahadevan *et al*., 2007). The latter is due to the fact that they require minimal refilling and maintenance when compared to traditional battery-powered electric forklifts. A 3kW PEM forklift truck consumes 12,000 Btu/kWh, while a 3kW battery-operated forklift would need in excess of 14,000 Btu/kWh (DOE Website, 2010).

The National Academy of Sciences (National Academy Report, 2008) has identified four factors that can influence the cost of delivered hydrogen. They are: (1) the feedstock used to generate hydrogen, (2) scale of the production unit and transportation requirements, (3) level of technology readiness, and (4) use of carbon dioxide by-product sequestration if fossil fuels are used feedstock.

LAYOUTS

The performance of layouts is measured with metrics such as material-handling costs (MHC), closeness ratings or rankings (CR), lead time, and productive area utilization (PAU) (Raman et al., 2009). When PEM forklifts are used, the impact on the layout is likely to be positive, but in order to measure improvements, one must use one or more of these metrics. We performed some experiments to determine how much improvement can be produced. We first present a discussion on the three metrics.

We denote the cost of moving unit material over unit distance from department i to department j by $c(i,j)$. Also, $f(i,j)$ and $d(i,j)$ will denote the frequency of trips between i and j over a given time horizon (e.g., one day) and the distance between i and j respectively. Then, the total material handling cost for a given layout can be given by:

$$MHC = \sum_{i=1}^{n} \sum_{j=i+1}^{n} c(i,j) f(i,j) d(i,j), \quad (1)$$

where n denotes the number of departments. In the real world of manufacturing industries, the cost elements $c(i,j)$ are difficult to obtain. In such a scenario, one seeks to minimize the total distance traveled over a given time horizon:

$$CR = \sum_{i=1}^{n} \sum_{j=i+1}^{n} f(i,j) d(i,j).$$

The above can be heuristically maximized using the closeness rank of each department, which is defined as follows. $CR(i,j)$, which denotes the closeness rank for department pair i and j, is assigned a unique number from a set of numbers that rank the relative interactions between departments. The following set {8, 6, 4, 2, 0} is popular in the literature; here 8 indicates that the two departments have the greatest interaction while 0 indicates the lowest interaction. Other sets such as {4,3,2,1,0} can also be used. Note that:

$$CR(i,j) = CR(j,i).$$

The closeness ranks can be used to heuristically minimize the total distance traveled in a layout (Francis et al., 1992). Most commercial software programs including FACTORY FLOW use this approach to develop the layout.

The lead time is usually computed using the following formula:

$$LT = S + Bp + MHT + W, \quad (2)$$

where LT denotes the lead time of a given batch at a given machine/department, S denotes the set-up time, B denotes batch size, p denotes the production time of one unit on the machine, MHT denotes the material handling time to and from that machine, and W denotes the time spent by the batch in front of the machine waiting for its turn. The total production lead time is usually the sum of the lead times of the batch at all the machines visited by the batch. The waiting time, W, at each machine can be estimated either using closed-form queuing approximations (Askin and Goldberg, 2002) or via simulation.

The PAU (productive area utilization) metric is the following ratio:

$$\frac{A_v}{A},$$

where A_v denotes the area of the layout used for value-adding activities and A denotes the total area used by the layout. Clearly, a higher value for PAU is preferable.

We conducted a simple experiment to study the impact of using PEM forklifts on some layout metrics. We considered a job shop setting where every part has a unique sequence of machines visited. In order to conduct experiments, it is necessary to assume some values for the input parameters to the model used for measuring the metric. Some of the critical input parameters are: the frequency of trips after which the forklift must be recharged, the time it takes to recharge the forklift, the average increase in material-handling time due to filling hydrogen in a PEM forklift, and the dollars-per-foot cost of

PEM and battery-operated forklifts. The values of some of these inputs (especially those related to costs) depend on labor costs and hence vary from country to country. It is necessary to stress that the specific values of the outputs (layout metrics) will change when the values of the inputs are changed. However, we note that (i) we choose values that are reasonable, and, in fact, conservative, and (ii) performing a sensitivity analysis of these values on the outputs is beyond the scope of this paper. We will, however, conduct a more detailed analysis in future studies targeted at journal papers. What is important is that even with the conservative values we choose, we are able to show improvements with PEM forklifts. For instance, we assume that the battery-driven forklift can be recharged in 15 minutes. However, in reality, many forklifts take much longer, and with longer recharging times, the lead time benefits of PEM forklifts should be even higher than what we find with our conservative estimates.

We assume that on the average, one shift witnesses about 20 trips between machines. The actual number per shift may depend on the production rates etc. However, it is typical for the forklift (see DOE Website) to (i) travel once per shift to a recharging station and (ii) take about 15 minutes for recharging. We hence use these values in our computations. With PEM forklifts, trips to the recharging station are eliminated, but the total material handling time is increased due to the fact that hydrogen has to be filled in the forklift. This leads to some increase in the material-handling time, but the refilling time is usually about 5-10 minutes (DOE Website), and hence we approximate this by considering that the material-handling time for the PEM forklift will be about 5% higher than that of the regular forklift. In reality, this time could account for less than 5 % of the material handling time, which would lead to even more significant lead time savings with the PEM forklifts.

The dollars-per-foot cost rate, ρ, is based on the following equation:

$$\rho = \frac{hourly\ rate}{average\ speed}. \qquad (3)$$

Note, since we use the same material-handling device for travel between all machines, the values of $c(i,j)$ are the same for each (i,j) pair in our analysis and equal ρ. The hourly cost rate for using the forklift includes the labor costs, the maintenance costs, and the overhead costs. The sum of maintenance and overheads can be a significant amount, often equaling the labor costs. The labor costs for the forklift operator are assumed to be $18 per hour based on the website www.payscale.com (Website 2); we assume that the sum maintenance and overheads equal the labor cost rate, leading to and hourly rate of $36/hr. It needs to be underscored that these costs vary by organization, region, and country. When forklifts are in operation, their speed should not exceed 5 miles per hour (440 feet per minute), but they are not available all the time. Therefore, their effective speed is much lower. We assume that the average speed of a forklift is about 60 feet per minute, which is the best you can obtain with a conveyor, typically (Website 2), and it is rare for a forklift to be faster than the conveyor on the average. When we use an hourly rate of $36/hr and an average speed of 60 feet per minute, via Equation (3), we obtain 1 cent per foot as the dollars-per-foot rate of a battery-driven forklift.

PEM forklifts have 1.5 times lower maintenance cost and two times lower net present value of total system cost (DOE Website). Hence, it is reasonable to assume that the dollar-per-foot cost rates for the PEM forklifts are lower than those of battery-operated forklifts. Therefore, we use a PEM forklift cost rate of about 0.8 cents per foot to move material, when the same cost for regular battery-operated forklifts is 1 cent per foot. This is actually a conservative estimate, and the actual cost of the PEM forklift on a dollars-per-foot basis may be significantly lower than 0.8 cents per foot. Also, while this difference is not of a very high magnitude, an increase in this difference is likely to show higher cost improvements with the PEM forklifts.

Table 1 shows the machining sequence for each part type, which can be usually obtained from routing sheets from a shop floor. The number of trips per batch for any element in the machining sequence (e.g., M5 to M4 for Part type 1; M2 to M3 for part type 5) can be calculated as follows:

$$\lambda = \frac{Demand}{Batch\ size}.$$

Note that the number of trips between a pair of machines, *i* and *j*, is defined by $f(i,j)$. From the formula above for λ and from the entire sequence of machines visited by each batch for all the parts, one can compute the value of $f(i,j)$ for each (i,j) pair. This computational process is explained in most standard textbooks on material handling (e.g., Heragu, 2008), and hence we skip the details here.

The software FLAP was used to determine the best layout. For each layout, MHC and the lead time were calculated using the formulas given above, i.e., Equations (1) and (2) respectively. We assumed the waiting times to be negligible in this study, but in future studies we intend to use discrete-event simulation in order to develop better estimates of the lead time. Table 2 shows the dimensions of each machine, while Table 3 shows the values of MHC and distance traveled for the layouts.

As is clear from Table 3, the PEM forklifts save money in material handling costs and result in lower distance traveled. For Part 1, we computed the lead time to be 4069.55 minutes with the PEM layout and 4091.48 minutes with the non-PEM layout. Thus the lead time also appears to be lower with the PEM forklifts. We intend to perform additional computations in the future to test the effectiveness of the PEM forklifts on material-handling costs, distances traveled, lead times, and PAU. Preliminary tests conducted above indicate that the PEM forklift appears to have lower costs and makes the system more efficient in terms of lead times as well.

Table 1. Mx(y) denotes the Machine *x* and that a batch of the associated part takes *y* minutes on it.

Part type	*Sequence*	*Demand*	*Trips Per Batch*
1	M5(11),M4(15),M3(4),M6(9)	10,000	100
2	M1(6),M2(7),M4(14),M6(10)	15,000	150
3	M2(7),M4(14),M5(12),M3(4)	20,000	200
4	M1(6),M5(10),M3(4)	10,000	100
5	M1(6),M2(7),M3(4),M5(10)	5,000	50

Table 2. Dimensions of machines in feet

Machine	M1	M2	M3	M4	M5	M6
Length	10	10	20	10	10	10
Width	20	10	20	10	20	20

Table 3. Performance metrics for the layout using PEM forklifts and the non-PEM layout, which uses battery-driven forklifts

Metric	*PEM*	*Non-PEM*
MHC	\$545.32	\$809.11
Distance	68,165 ft	80,911

CONCLUSIONS

Our work considered a novel problem of testing the usefulness of PEM forklifts in a manufacturing setting. While the environmental benefits of PEM forklifts are already well-known, our work attempted to study the advantages of these forklifts in terms of material-handling costs, distances traveled, and lead times. We reported some of our preliminary findings here. Future work will test additional case instances and also use discrete-event simulations to estimate lead times more accurately. We will also test other metrics useful in testing the layout's effectiveness. Finally, we hope that our study highlights the economic advantages of using PEM forklifts and helps to increase their popularity in the industrial setting.

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