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Technical Paper

A multi-objective approach for determining optimal air compressor location in a manufacturing facility

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ABSTRACT

Determining the optimal location of an air compressor in a manufacturing facility is a challenging problem that can offer significant energy savings. A novel simulation-optimization model is proposed to increase energy efficiency in a facility by determining optimal air compressor location. The optimization strategy is based on an objective function that minimizes the total energy consumption of the air compressor – hence, the energy cost for the facility – while considering the user's preference for the air compressor location. The proposed mathematical model first integrates the facility's characteristics based on user inputs, divides the facility into zones, and generates a rectilinear zone-to-zone distance matrix within the facility. The user location preference is incorporated into the proposed model via a five level user-preference index, assigned using preferential locations as suggested by twenty-two experienced facility managers. A sensitivity analysis is conducted to determine the relationship between the selected user preference level and the resulting energy consumption at each location in the facility. A simulation-driven analysis is performed using a real-life facility layout and typical compressed air equipment with corresponding nameplate data. In order to investigate and demonstrate the effectiveness of the proposed approach, the derived optimal zones are compared with five zones, including the most energy efficient zone, least energy efficient zone, and three other zones selected at random. The results of our study reveal that the proposed method achieves significant energy reductions while maintaining the user's desired air compressor location.

1. Introduction

Compressed air is often regarded as the fourth utility, and is one of the most critical applications in production and process environments [1,2]. Seventy percent of all manufacturing facilities in the United States (U.S.) rely on compressed air systems, and in many cases, failure of these systems leads to the shutdown of their entire manufacturing process [3–5].

Compressed air accounts for approximately 10% of total industrial-energy use in the U.S., resulting in a staggering consumption of 90 billion kilowatt hour (kWh) per year [4,6,7]. Furthermore, the total installed power capacity of compressed air systems in the U.S. is estimated at more than 17 million horsepower [8], accounting for about 16% of the industrial motor system energy use [9]. However, a well-designed compressed air system is only about 11% efficient [2] with some estimates stating that poorly designed systems account for up to $3.2 billion in wasted utility payments in the U.S. each year [10]. This inefficiency, combined with the fact that compressed air is the most expensive form of energy to deliver (Fig. 1 [11]), makes it critical for manufacturing facilities to seek to optimize compressed air energy efficiency and reduce cost.

In 2010 the U.S. Energy information Administration (EIA) conducted a Manufacturing Energy Consumption Survey (MECS) of 15,500 manufacturing facilities in the U.S. [12]. The data gathered from this survey was analyzed and a Manufacturing Energy and Carbon Footprint document illustrated the findings. This data shows that 14,064 TBtu is used in onsite energy at manufacturing facilities in the U.S. Of this 78% is fuel (natural gas, byproducts, coal, etc.), 17% is electricity, and 5% is steam. Of the total energy use, 2012 TBtu is used by machine drive (compressed air, pumps, fans, etc.) and of this 17% or 341 TBtu accounts for compressed air. Furthermore 23% of total electrical consumption to machine drives in manufacturing facilities is consumed by air compressors [13]. According to the Energy and Carbon Footprint document, of the 341 TBtu consumed by the air compressor systems, 87.7% or 299 TBtu is written off as losses, making compressed air the least efficient machine-drive system in the survey.

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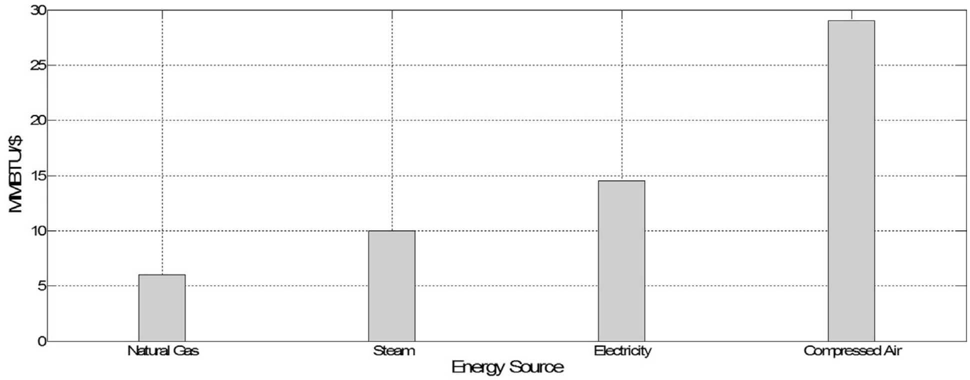

Fig. 1. Cost of energy delivery modes [11].

This further illustrates the importance of optimizing air compressor systems in manufacturing facilities. Unfortunately, compressed air systems are one of the least understood processes in most manufacturing facilities [14,15], mainly due to the widespread misconception that compressed air is inexpensive.

The energy associated with operating a compressed air system accounts for the largest cost to the user, often exceeding the initial cost of the compressor by up to five times over its lifespan [8,16–20]. Sometimes this cost accounts for up to 70% of the total electric bill in manufacturing facilities [14,21,22]. These figures point out that by implementing energy conservation measures, facilities can experience substantial energy and cost savings.

The U.S. Department of Energy (DOE) states that over 50% of industrial facility's compressed air systems harbor large energy opportunity savings with relatively short payback periods [4,23]. Energy savings from compressed air system improvements can range from 20 to 60% of electrical consumption, resulting in thousands, or even hundreds of thousands of dollars in potential annual savings [4,24]. Some of these compressed air efficiency measures include reducing leaks, matching supply with demand, reducing pressure settings, reducing average inlet temperature by using outside air, improving air distribution systems, and optimizing air compressor location. Fig. 2 illustrates some energy savings opportunities present in air compressor systems. As it can be seen, air leaks and air compressor system optimization account for the two largest losses in compressed air systems [25].

Furthermore, studies suggest waste heat can also account for between 50 and 90% of compressed air energy losses. With newer and more efficient motors on the market, the motor efficiency of the air compressor can be improved 2–8% over most existing air compressors [27–29]. The energy wasted in a poorly designed and maintained compressed air system can account for up to 50% of the energy used by the air compressor and it is believed that half of all these losses can be saved through proper system design and energy conservation measures [22]. In this paper the authors propose an optimization model that minimizes the distance compressed air must travel to high demand and high pressure locations in a facility, to reduce pressure drop and air leaks in the system, and improve the overall performance of the system.

The location of the air compressor in a facility plays a critical role in ensuring an energy efficient air compressor system. By optimizing the air compressor location, the distance to the highest demand and pressure zones is minimized, total pressure drop and number of air leaks is reduced, and compressed air distribution system (piping) is improved. According to Scott Foss, President of Plant Air Technology, "The concept design or redesign [of air compressor systems] should be to minimize the highest amount of air mass or volume of air and the distance that the air must flow to support any part of the system from supply to demand [2]". In essence, the goal

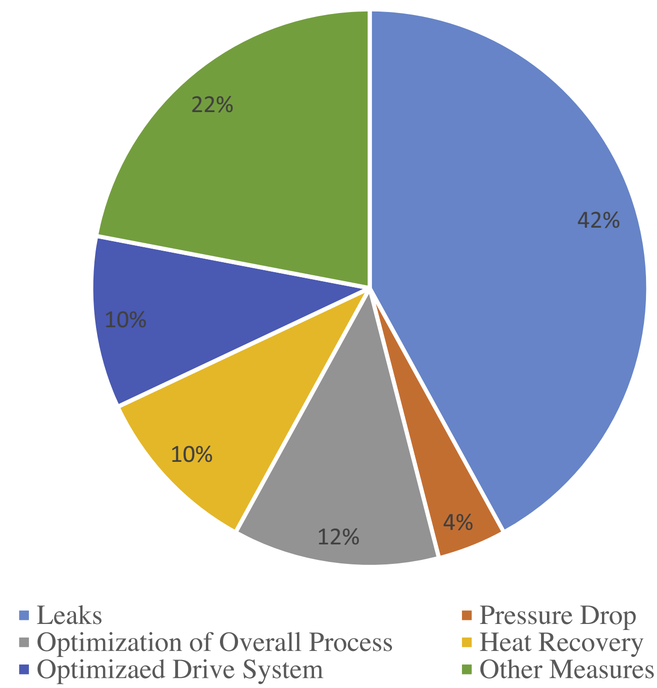

Fig. 2. Energy savings opportunities in air compressor systems [25].

is to get the compressed air from the supply side to the demand side in the most efficient and cost effective manner to minimize losses in the system (air leaks and pressure drop).

The rate of pressure drop in a system is directly correlated to the distance compressed air must travel to air demand areas. Poorly designed air compressor systems can experience up to a 60% drop in pressure at the point of use of air [22,29]. Corrective actions must be taken on the air compressor system to improve pressure drop across the system.

Air leaks are the single greatest cause of energy loss in manufacturing facilities with compressed air systems and account for 20–50% of compressed air losses [14,29,30]. The majority of air leaks occur in air leaks, occur at the joints, flange connections, elbows, reducing bushes, sudden expansions, valve systems, filters, hoses, check valves, relief valves, extensions, and the equipment connected to the compressed-air lines [29]. The amount of air lost to leaks is dependent on the line pressure of the pipe and the temperature of the air at the point of the leak [29]. By minimizing distance to the highest pressure and volume locations, the goal is to minimize the number of joints in piping and the distance air must travel to the highest pressure and volume equipment.