Waste Heat Recovery in Bicycle Manufacturing Process for Specialized Bicycle Components

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Executive Summary

Specialized Bicycle Components, the third largest bicycle brand in the United States, wants to reduce the energy intensity and increase the efficiency of its bicycle manufacturing process. One way to increase efficiency is to reduce or reutilize waste heat. By increasing the efficiency of the manufacturing process, the company hopes to save money and set an example for the rest of the industry to make a commitment towards more environmentally conscious manufacturing. The main problem to be addressed in this report is how to feasibly and economically reduce or reuse waste heat. To determine if Specialized can reduce or reuse waste heat, our Duke team has calculated heat inputs and outputs of the heat treatment process, completed an exhaustive literature review of waste heat recovery technologies, and performed cost-benefit analyses of potential solutions. We also present our recommendations on how Specialized can most effectively reduce waste heat and increase overall efficiency.

The first section of this report provides a technical description and visual representation of the bicycle manufacturing process. The description explains the two necessary heat treatments for manufacturing bicycle frames, tempering and aging, and the different heat flows in and out of the oven. The data used in this description is specific to Specialized's industrial oven in Taiwan.

The second section of the report quantifies the heat treatment processes with thermodynamic calculations. Using data from Specialized's manufacturing facility, the heat inputs and outputs of the current heat treatment oven were calculated. It was found that the heat treatment process requires 507.53 MWh per year, which costs $24,921.58 per year. Of this total energy requirement, 451.60 MWh is lost as waste heat – energy that is not performing useful work. This waste heat costs the company $22,174.97 per year. Because the company is losing a substantial amount of money through waste heat, it is worth considering methods and technologies that can help reduce or recycle this waste heat. If Specialized is able to reduce or recycle waste heat, they can save thousands of dollars each year and reduce facility emissions significantly.

The third section of this report examines waste heat recovery methods and technologies that are suitable for bicycle manufacturing processes. The purpose of waste heat recovery technologies is to make use of this secondary source of energy, recognizing that utilizing the rejected or waste heat can substantially improve system efficiencies. To examine the waste heat recovery methods and technologies, a comprehensive literature review was completed. This research, based in both academic and industrial sectors, allowed us to evaluate the performance of the proposed technologies and examine how they could be added onto the existing manufacturing process. Cost-benefit analyses were also presented to determine whether the potential waste heat recovery solutions were feasible and economical for Specialized to implement. If they were not feasible and economical, they were rejected.

The fourth section of this report provides two recommendations to Specialized for feasibly and economically reducing waste heat. After literature review and cost-benefit analyses, it was concluded that Specialized could not implement commonly used waste heat recovery technologies, such as air fans, vestibules, or heat exchanges, because they were not feasible or economical. The waste heat the manufacturing process generates is not large or hot enough to reuse in an efficient way. Therefore, the recommendations focused on reducing waste heat rather than reutilizing. The recommendations include instructions on how Specialized could implement the recommended changes into their current manufacturing setting, and how much energy and money the company could save through implementation.

The first recommendation is to switch the industrial oven's fuel source from liquified petroleum gas (LPG) to natural gas. Fuel switching can save more than $600 per month and reduce emissions by 15%. Additionally, it requires minimal implementation costs because LPG equipment can easily be converted for natural gas use. The second recommendation is to replace the frame holders from steel to carbon-carbon composite. The frame holders absorb a substantial amount of heat input, which is lost to waste heat. Carbon-carbon composite absorbs less heat input during the process because of the material's lower mass compared to steel. Although there is a considerable investment cost associated with this recommendation, the materials change is prudent because the payback period is relatively short; it only takes 17 months until the company can recover its investments costs.

Introduction

Project Overview

Bicycles are one of the most ubiquitous modes of transportation around the world. While cycling has traditionally been focused on sport and recreation, the rise in bicycles as a means for commuting has been increasingly impactful. A large population of dedicated cyclists, especially in urban areas, directly reduces the number of cars on the road. Since the transportation sector is the second largest source of greenhouse gas emissions in the U.S.[1], this helps to cut net emissions and move the community towards a healthier, more sustainable environment. Although increased bicycle use is projected to lower emissions by shifting transportation away from fossil fuel powered vehicles, the bicycle manufacturing process itself has huge energy requirements. Consequently, while bicycle use may reduce emissions in the transportation sector, bicycle manufacturing is increasing emissions in the industrial sector, which represents the third largest source of greenhouse gas emissions in the U.S.[2] To address this issue, the energy intensity of the manufacturing process must be reduced. Current bicycle manufacturing processes are energy intensive because each bicycle frame must be heat-treated in an industrial oven; this energy intensive process provides a significant opportunity to improve energy efficiency through waste heat reduction or implementation of waste heat recovery technology.

In most manufacturing settings, bicycle frames are comprised of aluminum tubes that have been shaped through pressure and heat, and then welded together. Welding applies extreme temperatures to form a bond between the components of the frame. This process changes the hardness of the metal in these conjoined areas,

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[1] "Sources of Greenhouse Gas Emissions." Industry Sector Emissions. The Environmental Protection Agency (EPA). https://www3.epa.gov/climatechange/ghgemissions/sources/industry.html

[2] Ibid.

causing localized weaknesses. Therefore, the welded frame must subsequently undergo heat-treating to restore uniform strength in the bicycle frame, to prepare it for ultimate use by riders. In the heat treatment process, a rack of frames is placed in an oven and exposed to a series of heat cycles as high as 400°F for 2-10 hours. This allows each frame to reach the ideal metallurgical properties after being quenched in a glycol bath.

A previous Duke University life cycle analysis for *Specialized Bicycle Components* identified the heat treatment phase of production to be the most energy intensive. The study found that the annual requirement for heat treating the aluminum frames was 58.7 gigawatt-hours, which is equivalent to New York City's power consumption for nearly five and half days.[3] This tremendous amount of input energy is lost during several stages of the manufacturing. Heat is lost through absorption by the oven walls, the bicycle frame holders (rack) inside the oven, and the furnace itself. Input energy is also lost to the atmosphere at the end of the process when the oven doors are flung open and the rack of frames is pulled out. Harvesting this waste heat for other stages of the manufacturing process would be highly beneficial by either capturing waste heat for alternative or through waste heat reduction.

According to the National Bicycle Dealer Association[4], the bicycle market in the United States is estimated to be worth approximately 6.1 billion U.S. dollars. Globally, the cycling market size is around 42 billion U.S. dollars according to a survey on the global cycling market by the NPD Group.[5] Such a huge market indicates that even a small improvement of the bicycle manufacturing process could

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[3] Johnson, Rebecca, Alice Kodama, and Regina Willensky. "The Complete Impact of the Bicycle Use: Analyzing the Environmental Impact and Initiative of the Bicycle Industry." Master's Project, 2014. http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/8483/Duke_MP_Published.pdf

[4] National Bicycle Dealers Association. "Estimated Size of the U.S. Bicycle Market* from 2002 to 2014 (in Billion U.S. Dollars)." Statista - The Statistics Portal. Statista. 2015.

[5] Oortwijnjn, Jack. "Global Cycling Market Valued at € 38.5 Billion." Global Cycling Market Valued at € 38.5 Billion. 27 Aug. 2013.

have a significant global impact, both in profitability for manufacturers and more broadly in environmental sustainability.

Client Introduction

Our client, *Specialized Bicycle Components, Inc*., is the third largest bicycle brand in the United States, and among the largest bicycle brands in the world. Founded in 1974 with the slogan ”Innovate or Die”, they have remained dedicated to pioneering the use of new materials and methodologies for bicycle production. In 2014, Specialized commissioned Duke University Master’s students to complete a life cycle analysis for a selection of their top selling products.[6] Acting upon the results of this analysis, Specialized is now interested in a solution for greater efficiency in the heat-treatment phase of their bicycle manufacturing process. The company’s ultimate goal is to redefine this part of the manufacturing process in such a way that the entire industry may shift towards more efficient practices. This kind of commitment cements their status as a leader in innovative bicycle design and environmentally conscious manufacturing.

Objective

Our primary objective is to provide Specialized with a recommendation for changes to their heat-treatment process based on research and analysis of the current methods and technologies available for waste heat recovery and utilization. After conducting a thorough literature review of existing waste heat solutions, we carry out feasibility studies for those methods that we find most promising by order of merit. Our final analysis includes several options; highlighting capital costs, necessary changes to equipment or process design and each method's’ relative impact on efficiency. Our goal is to increase the efficiency of Specialized Bicycles’ manufacturing by recommending feasible and economical waste heat solutions.

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[6] Johnson, Rebecca, Alice Kodama, and Regina Willensky.

Methodology

In this project, we employed both quantitative and qualitative methods to understand what happens in the manufacturing process, especially the heat intensive part of the process. We then identified a potential solution to increase the energy efficiency.

First, a quantitative modeling method was adopted to determine the amount of waste heat generated in Specialized ovens. Our calculations were performed using data provided by Specialized, which included the amount of liquefied petroleum gas used, temperature of the oven, temperature of the surrounding air, temperature of the oven walls, furnace dimensions, and the mass and volume of bicycle frames and bicycle holders. This initial finding allowed us to accurately analyze potential waste heat solutions in terms of feasibility and economics.

Our initial qualitative research strategy focused on case studies. We systematically gathered information on similar projects and edge technologies applicable to waste heat recovery in manufacturing settings, similar to the aluminum frame production methods utilized by Specialized. This comprehensive research based in both academic research and the industrial sectors allowed us to evaluate the performance of the proposed technologies and examine how they could be added onto the existing manufacturing process. This examination was a multi-criteria analysis. We not only examined the technical, economic and financial feasibility, but also the operational and schedule practicability, and the environmental impact of these new technologies. The economic and financial analysis mainly focused how the proposed waste heat recovery technology would bring economic benefit to the company, and how the technology could be financed. If cost was qualitatively estimated to be equal to or greater than the benefits of increased energy efficiency, the potential solution was disregarded. Approximately six solutions were examined. In our examination process, (see *Potential Solutions Section*) we provide an overview of each potential solution, and how it would be implemented.

After forming a generalized set of promising solutions, we integrated them with our waste heat calculation and narrowed the options down to three possible solutions. At that point, we conducted an interview with an engineer from Specialized to discuss whether these solutions were feasible and whether these solutions could be integrated into other renovations that the company is already implementing. With confirmation from Specialized, our team discovered that the company could potentially reduce energy costs by switching fuel sources, changing the material of the bicycle frame holders, or employing process optimization. Deeper, quantitative analysis on these three potential solutions were carried out using a specific set of parameters provided to us by Specialized and data we retrieved from extremal sources.

We also carried out a financial analysis that can be summarized as follows: first, we determined the planning horizon of this project; then, we estimated the initial investment of the technology based on our estimations of annual energy savings, operation and maintenance costs, and other necessary cost factors; finally, we generated a cash flow so that net present value (NPV), and other common financial metrics could be adopted to measure the project's performance. We also conducted a preliminary risk analysis for each solution. By changing the fuel price, material price and other input, the change in savings was calculated and then the related financial indicators were compared.

Technical Discussion

In this discussion we review the bicycle manufacturing process, which includes tempering and aging. Although the previous Duke team provided a waste heat calculation using OpenLCA, we re-calculated this quantity using the equations listed below. This reexamination turned out to be extremely crucial for our future analysis.

Tempering and Aging Process

By consulting the plant managers, engineers, and sustainability professionals from Specialized, we summarized the tempering and aging process in Figure 1 below. The aluminum alloy frames held by a rack or frame holders are first loaded into the oven. After the door of the oven is closed, the oven heats to 520-550 °C and is maintained at this temperature for about 100 minutes. This heat treatment rearranges the molecular structure to strengthen the aluminum alloy. This process is called T4, a commonly accepted aluminum alloy heat treatment temper designation. In most manufacturing settings, T4 solution heat treats aluminum alloy, and naturally ages it to a substantially stable condition[7] (the T4 only refers to the heating here). After T4, the oven door opens and the bicycle frames are quenched in a glycol bath to capture the new molecular structure. After the glycol bath, the frames are aged in the T6 process. T6 is similar to T4 as it is also a solution heat treatment, but differs because it artificially ages the bicycle frames to further stabilize the aluminum alloy. Specifically, the frames are re-heated in the oven to 160-180 °C for 10 hours.

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[7] "Aluminum Alloy Heat Treatment Temper Designations" http://www.matweb.com/reference/aluminumtemper.aspx

Figure 1: Energy Intensive process: T4 and T6 treatment

Unlike the process described in the 2014 Duke LCA Report [3], which cited electricity as the oven fuel source, Specialized's oven is in fact heated by liquefied petroleum gas (LPG). This difference leads to a huge discrepancy between our team's findings and the 2014 Duke report on how much energy these processes consume. The 2014 report estimated the amount of waste heat produced to be 58.7 gigawatt-hours. Our analysis using liquefied petroleum gas proved this value to be a huge overestimate. We found that T4 and T6 together generate 1,625,752,704 kilojoules per year, or 0.508 gigawatt-hours per year. This finding was pivotal in forming opinions and recommendations on the feasibility and economics of waste heat solutions for Specialized.

Waste Heat Calculations

To estimate whether it is feasible and economical to recover waste heat, our team first estimated the amount of the waste heat from each part of the manufacturing process. This calculation allowed us to accurately analyze the possible technological solutions by their potential to reduce energy requirements and meet cost targets.

The energy flow of each heat treatment process is summarized in Figure 2. Waste heat is generated as a by-product of LPG combustion, and is then transferred to all the elements in the oven. The only useful heat is that which is absorbed by the bicycle frames. Waste heat is absorbed into the walls of the oven, the bike holders, and the air. There is also loss during combustion.

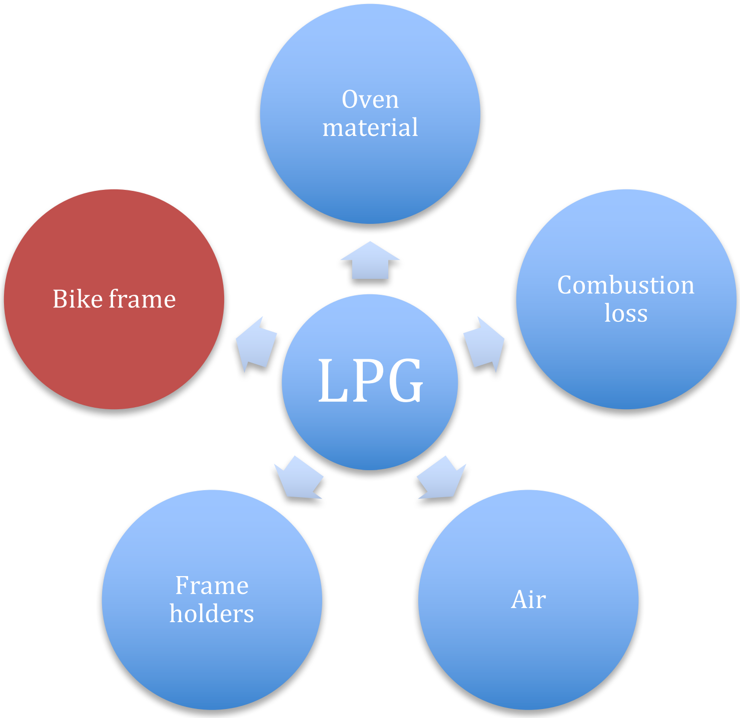

Figure 2: Energy flows in heating process

Frame Holders

The heat absorbed by frame holder is calculated in Equation 1.

Equation 1

$$\mathrm{Q}_{ab,i} = \mathrm{m}_i * \mathrm{C}_i * \Delta\mathrm{T}_i$$

Where

$\mathrm{Q}_{ab,i}(\mathrm{J})$— Heat absorbed by material i

$\mathrm{m}_i, (\mathrm{kg})$— Mass of the material i

$\mathrm{C}_i, (\mathrm{J\ kg}^{-1} K^{-1})$— Heat capacity of the material i

$$\Delta T_i\,(K) \text{– Temputure increased before and after heating of material i}$$

$$i = 1{,}2;\ \text{1 represnets for frames and 2 for holder}$$

Liquefied Petroleum Gas

The heat generated by the LPG combustion is calculated in Equation 2.

Equation 2

$$Q_{in} = V * LHV$$

Where

$$Q_{in}\ , (MJ)\text{— Heat generated by LPG}$$

$$V, (m^3)\text{— Volume of LPG consumed}$$

$$LHV, (MJ/m^3)\text{— Low Heating value of the LPG}$$

We estimated the economic value of the waste heat based on the retailing price of LPG in Taiwan, where the manufacturing plant is located. The economic value of the waste heat is calculated in Equation 3.

Equation 3

$$P = \left(Q_{in} - Q_{ab,1}\right)/LHV * p$$

Where

$$P\ , (\$)\text{— Value of the waste heat}$$

$$p, (\$/m^3)\text{— Price of the LPG in Taiwan}$$

With the data provided by the manufacturing plant, we calculated that the T4 heat treatment process requires 91,310 MJ per month and T6 process consumes 60,950 MJ per month. Only 6.10% of the heat input is useful in the T6 heat treatment process. Efficiency in the T4 process is marginally higher, as the bicycle frames absorb 14.31% of the heat input. Based on our calculations, the value of total waste heat for Specialized in both the T4 and T6 could be as high as $22,200 U.S. dollars per year. All the inputs and outputs are summarized in **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.** in the Appendix.

Waste heat distribution

Despite the high value of the total waste heat, it is impossible to recover all the waste heat without substantial costs. To recover the heat from air and solid material requires additional costs. Therefore, we need to first identify how much heat is wasted during the entire heat treatment process, and the value of the waste heat from each component. Then we can determine which part of the waste heat might be valuable to recover or to reduce.

Waste heat absorbed by holders

The frame holders are the rack that supports the bicycle frames in the oven during T4 and T6. The heat absorbed by the holders, calculated in Equation 1 as $\mathbf{Q}_{ab,2}$, is 23,430 MJ per month during T4 and 6,662 MJ per month during T6. The waste heat absorbed by the holders is almost twice the amount of the useful heat, valued at $4,925.42 U.S. dollars per year for the company. For that reason, adopting holders with a lower specific heat capacity or a reduced mass may be a cost-effective path to improved efficiency and help to reduce the long-term fuel cost.

Due to the lack of data on the property of the walls of the oven, we cannot calculate the heat absorption by the walls and or the heat that escapes from the walls. However, we expect that the thermal conductivity of the oven walls is low, making the heat escaping through the walls negligible. Even if the heat escaping through the walls is not negligible, it won't affect our calculation for other parts of waste heat.

Waste heat absorbed by air

Calculating the waste heat absorbed by the air is more complicated. To simplify this calculation, we divided the heat into two parts: heat input needed to increase the temperature of the air in the oven, and the heat input that escapes by oven ventilation during the heating process. In addition, another significant portion of the heat input escapes to the air through convection when the door of the oven is opened.

Waste heat absorbed by air within the oven

The pressure in the oven is constant, at one standard atmosphere. This is because the oven is connected to outside air at all times through ventilation. Therefore, we used the heat capacity of air under constant pressure for our calculations. Since this rapid heating process is relatively short, and the vent on the oven is small, we ignored the convection of air through ventilation. Based on these assumptions, we calculated the heat absorbed by the air ($dQ_{air,h}$) in Equation 4.

Equation 4

$$\mathrm{dQ}_{air,h} = \mathrm{V}_o * \rho_o(T) * \mathrm{C}_p(\mathrm{T}) * \mathrm{dT}$$

Where

$\mathrm{Q}_{air,h}$— the heat absorbed by air during the heating process

V_o— constant, volume of the air which is the volume of the oven, $17.67\mathrm{m}^3$

$\rho_o(T)$— the density of the air, a function of T

$\mathrm{C}_p(\mathrm{T})$— heat capacity of the air under constant pressure, a function of T

T— the temperature in unit of K

For an ideal gas, the density and temperature have the relationship demonstrated in Equation 5.

Equation 5

$$\rho_o(T) = \frac{P_{air}}{R_s * T}$$

Where

$$P_{air} - \text{the sea level standard atmospheric pressure}, 1.01 * 10^5\,\text{Pa}$$

$$R_s - specific\ gas\ constant;\ for\ dry\ air, it\ is\ 287.058\, J * kg^{-1}K^{-1}$$

To demonstrate the relationship between the heat capacity and temperature, we adopted an empirical approximation[8] shown in Equation 6.

Equation 6

$$\mathrm{C}_p(\mathrm{T}) = 1.9327 * 10^{-10} * T^4 - 7.9999 * 10^{-7} * T^3 + 1.1407 * 10^{-3} * T^2 - 0.4489 * T + 1057.5$$

We calculated the heat absorbed by the air within the oven in Equation 7, using Equation 5 and Equation 6.

Equation 7

$$\mathrm{Q}_{air,h} = \mathrm{V}_o \int_{T_0}^{T_1} \rho_o(T) * \mathrm{C}_p(\mathrm{T})\mathrm{dT}$$

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[8] Liu, Shuli. "A novel heat recovery/desiccant cooling system." PhD diss., University of Nottingham, 2008.

Our calculations generated the following results in **Error! Reference source not found.** in the Appendix:

This estimation may be exaggerated because the heat treatments are conducted one after the other, with little to no break in between. The oven does not need to be heated from room temperature to operating temperature for each new batch of bicycle frames because the temperature is not likely to drop dramatically between batches. Despite the operating schedule, our calculation provides a reasonable, worst-case estimate of heat absorbed by the air. The estimation reveals the opportunity for Specialized to recover the waste heat by the technology, which has an annual Operation and Maintenance cost lower than $0.29 million dollars if the government is willing to invest. However, the company itself, might not have enough incentive to recover the waste heat in air since the value is as low as $120.91 per month.

Heat escaped from vents

Since we assumed the material of walls of the furnace is good thermal insulator, the sole manner in which heat exchanges with the outside environment during the heat treatment process is through the vent. As we can see from Figure 3, depicting ventilation from T4 and T6, the vent is a metal cylinder with two small irregular holes at the top. Figure 4(a) illustrates the ventilation model. Ventilation is a natural convective heat transferring process, which can be described by the Newton's law of cooling, shown in Equation 8. To simplify the estimation, we assumed the top surface of the vent is sealed with a thin metal layer. This top layer serves as a constant heating source because we assumed it would contribute considerably to heat transfer, even without the holes. This simplified model is depicted in Figure 4(b). This simplification might lead to 50%~150% of error comparing to the exact heat escapes, based on our experience.

Figure 3: Ventilation of the oven during T4 and T6

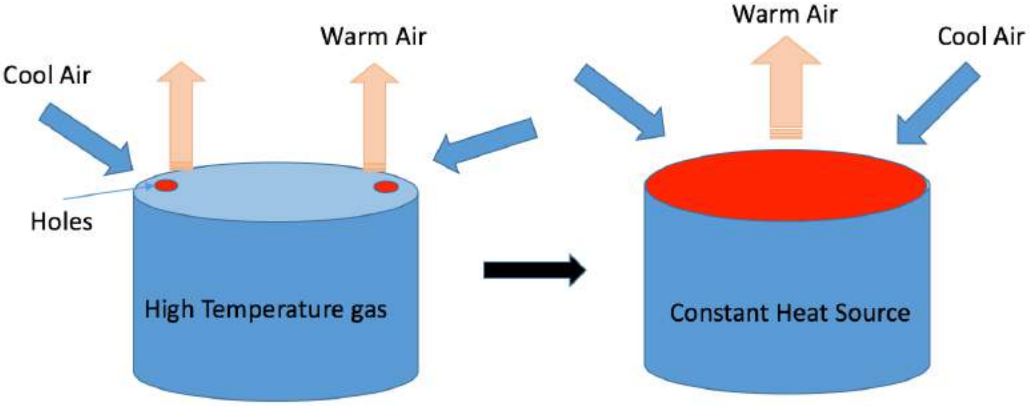

Figure 4: Ventilation (a) model, (b) simplified model

Equation 8

$$q_{air} = h_c * A * dT$$

Where

$q_{air}, (W)$— heat transfer per time

$h_c, (Wm^{-2}K^{-1})$— heat transfer coefficient

$A, (m^2)$— the area of the heat transfer surface

$dT, (K)$— the temperature difference between the surface and the surrounding fluid

The heat transfer coefficient is calculated in Equation 9 for top metal surface.

Equation 9

$$h_c = N_u * \frac{k}{L} \quad Eq.9$$

Where

$$N_u\text{— } Nusselt\ number$$

$$k, (Wm^{-1}K^{-1})\text{— } thermal \text{ conductivity}$$

$$L\text{— } Characteristic\ length, for\ a\ circular\ disk, \text{it is } \frac{\text{Diameter}}{4}$$

Nu, calculated in Equation 12, is dependent on the Rayleigh number (Ra). Ra is the product of Prandtl number (Pr), calculated in Equation 10, and Grashof number (Gr), calculated in Equation 11.

Equation 10

$$Pr = \frac{c_p * \mu}{k}$$

Equation 11

$$Gr = \frac{\Delta\rho g L^3}{\rho v^2}$$

Equation 12

$$Ra = Gr * Pr$$

Where

$$c_p\text{— } heat\ capacity\ under\ constant\ pressure$$
$$g\text{— } acceleration\ due\ to\ Earth's\ gravity, 9.80665\ m/s^2$$
$$\mu\text{— } dynamic\ viscosity$$
$$v\text{– kinematic viscosity}$$
$$\Delta\rho\text{— } density\ difference\ between\ the\ boundary\ layer\ fluid\ and\ that\ far\ away$$

In this case, Ra is smaller than 10^9, based on common practice in such calculation, so we use:

$$N_u = 0.54 * Ra^{0.25}$$

We considered the air constant at a room temperature of 33°C. The top metal surface of the vent is considered a stable heat source with the same temperature as the hot air in the oven. Therefore, with the input shown in Table 4, we can estimate the heat escaped through the ventilation in T4 and T6. The input of this calculation is shown in Table 5 and the result is shown in Table 6 in Appendix.

The waste heat through ventilation is relatively small, only 92 MJ/month compared with the waste heat absorbed by the air (8,864 MJ/month) or absorbed by the holders (30,092 MJ/month). Therefore, improving the ventilation does not appear to be an attractive solution in terms of improving energy efficiency.

Conclusion and discussion from the waste heat calculation

Based on these calculations, we identified that the value of the waste heat is $22,174.97/year, with the assumption that the oven requires a similar amount of LPG each year as they consumed during the data collection period. Among the identifiable waste heat, the major source of waste heat is the frame holders, which absorb 30,092.15 MJ/month, worth \$4,925.42/year. Hence, the frame holders should be targeted for maximum waste heat recovery.

There are two main limitations our waste heat calculations. The first limitation is that our team could only identify less than 50% of the heat generated during manufacturing. This means that the frame holders may not actually be the largest source of heat loss. Despite the lack of data, our analysis is still reasonable and practical for reducing waste heat. With on site detection, flow meters, and other data collection methods, we can expect to get more precise estimations for the waste heat generated during this process. Another limitation is the uncertain value of the LPG. The price of LPG we found from a local retailer (\$1.57/m^3) is much cheaper than the price we found online for the commodity market in Taiwan (\$380/m^3). We conjecture the reason behind that is the considerable subsidy on fossil fuels in Taiwan. In 2013, the subsidy on oil, gas, electricity and coal was 0.6 billion dollars in Taiwan and the subsidy per capita was 24.3 dollars, which is much higher than Mainland China (\$15.5/person) and South Korea (\$3.6/person).[9] Therefore, the real value of the waste heat, which excludes the subsidy, should be much higher than we estimated. Due to subsidy offerings, we believe the local government should also participate in waste heat reduction and recovery projects as well as Specialized and other bicycle manufacturing companies.

Potential Solutions

To recommend an effective solution for Specialized, waste heat recovery technologies that are suitable for bicycle manufacturing processes were examined.

According to the laws of thermodynamics, an energy system must reject heat as a byproduct of operations and processes. A wide variety of academic researchers,

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[9] International Energy Agency, *World Energy Outlook 2014*, Paris.

engineers, and inventors have set their efforts on devising methods and technologies that make use of this secondary source of energy, recognizing that utilizing the rejected or waste heat can substantially improve system efficiencies. Several strategies exist to limit or make use of waste heat; however, each strategy is generally tailored to a specific application or has limiting requirements and tradeoffs. In order to identify the most effective potential solutions for Specialized's processes, we considered the energy requirements of heat transfer within the oven and its operation.

The baseline model, demonstrating heat transfer during oven operations, has been created using data provided by Specialized, supplemented with the previous Duke LCA[10]. This model has allowed for an estimation of the percentage of usable waste heat energy. One important characteristic of Specialized oven operations that will affect the feasibility of waste heat recovery solutions is the relatively low temperature of heat. Although low temperature heat (below 450°F [232°C]) "has less thermal and economic value than high temperature heat", it can be valuable if it is "ubiquitous and available in large quantities".[11] Therefore, waste heat recovery solutions that can be implemented effectively using lower temperature heat, such as the Organic Rankine Cycle, will be considered.

While hot air escaping the opened oven doors is expected to be an important source of energy losses and provides the potential for waste heat recovery according to client's estimation and previous LCA report, our model indicates that the greatest energy losses are found in heat absorption by the rack that holds the bike frames during both phases of heat treatment. Bearing these factors in mind, we have identified a variety of solutions that are potentially applicable to Specialized

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[10] Johnson, Rebecca, Alice Kodama, and Regina Willensky.

[11] "Waste Heat Recovery: Technology and Opportunities in the U.S. Industry." Industrial Technologies Program, United States Department of Energy. P. xii.

processes, and have ranked them by order of merit in terms of feasibility. They generally fall into four broad categories:

1. Material changes made to equipment used in the heat-treating process to reduce the percentage of energy lost due to non-useful heat absorption;

2. Heat retention strategies for minimizing losses to the atmosphere;

3. Use of waste heat as a means to produce electricity; and

4. Change the heating source, for instance, electricity or natural gas.

Waste Heat Recovery Strategies

Material Changes

The primary focus of our improvement strategy will be on the effect of changing the material of the rack that holds the bike frames during the heat treatment process. Based on the mass and specific heat capacity data provided, we are under the assumption that the rack is currently made of steel. Replacing the steel racks with racks made from a material that has a lower specific heat capacity or reduced mass may have a pronounced effect on the amount of energy lost to the racks. The mechanical properties of steel represent an ideal mix for this application due to a low heat capacity, general durability and resistance to thermal shock, and so any replacement also needs to meet these criteria. The working temperatures of the T6 process and/or cost of many materials with lower heat capacities than steel render them infeasible, but several alternatives have been developed to good effect. Molybdenum is an alloy of titanium, zirconium and carbon that is used in commercially available heat treatment racks.[12] Although more dense and more expensive than a comparable steel rack, molybdenum's thermal conductivity is

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[12] Davis, Joseph. *ASM Specialty Handbook: Heat-Resistant Materials*. Materials Park, OH: ASM International, 1997.

higher than that of steel, allowing it to reach working temperature more quickly. Reinforced carbon composite racks offer even higher thermal conductivity and have the beneficial property of strengthening as temperatures increase.[13] An experimental comparison of RA330 (a steel alloy), molybdenum and reinforced carbon composite demonstrated that the carbon composite test article reached working temperature 29% faster than the molybdenum test article, and 76% faster than the RA330 test article.[14] Ultimately, each of these materials will be compared on a cost per unit energy saved based.

Vestibules and Air Curtains

Heat retention strategies aimed at limiting thermal losses to the environment have been explored for decades, and are most commonly applied to buildings in order to reduce the energy requirements of HVAC systems.[15] Adopting this idea into building energy codes, the Department of Energy requires any commercial space greater than 3,000ft^2 to have a vestibule for this direct purpose.[16] In the absence of a vestibule, every time a person opens the door(s) to a building, there is unimpeded airflow between the interior and exterior of the building, which is amplified by differences in temperature, pressure, and wind. A vestibule functions like an airlock, which heavily impedes airflow in and out of the building since the entry is effectively always closed. While not a perfect barrier, the vestibule's small interior space is effective in reducing the volume of heated or air-conditioned air lost to the environment.

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[13] Rogers, Kirk A. Leist, and Jon R. "Heat-Treat Rack Material Selection Based on Thermal Performance." *Industrial Heating*, December 1, 2015.

[14] Ibid.

[15] Maxwell, Patrick, Faisal Durrani, and Mahroo Eftekhari. "Investigating Heat Loss through Vestibule Doors for a Non-Residential Building." *Sustainability in Environment*1, no. 1 (2016): 25.

[16] United States. Department of Energy. Energy Efficiency & Renewable Energy. *Vestibule Requirements in Commercial Buildings*. 2012.

Generally, vestibules are installed to keep rooms at a more stable temperature, which reduces energy requirement of the HVAC system. The same principles of vestibules can be adapted to the heat-treating processes in an industrial manufacturing setting. A vestibule placed on the opening of the heat treatment oven would have an impact on heat losses when the oven doors are opened.[17] One of the major variables, which determine vestibule's effectiveness is the frequency in which the doors are opened.[18] A vestibule used in an industrial setting, such as Specialized bicycle manufacturing processes, in theory has the potential to be more effective than in a commercial building setting because building doors open more often than industrial oven doors.

The oven doors would need to open every time a T4 or T6 process is completed. The T4 process takes approximately 100 minutes and the T6 process takes approximately 10 hours – this frequency would be far lower than most commercial buildings.

Air curtains can also be used as a heat retention strategy. There are two types of air-curtains: recirculating and non-recirculating.[19] A recirculating air curtain is installed above an opening and uses a high-powered fan to channel air through a shaped duct that is at least as wide as the entryway, creating a "blade" of high velocity air to act as a barrier to airflow. The air curtain either continuously blows over an opening that is required to be open, or automatically turns on when the door is opened. This air curtain is expensive to buy and install. These expenses coupled with the increased energy expenses make this option extremely unpopular.[20] Non-recirculating air curtains for manufacturing processes are simply

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[17] Talbert, Rodger. "Heat From Ovens." Suppliers, Technical Resources, News and Events for the Finishing Industries: Products Finishing. January 11, 2011. http://www.pfonline.com/articles/heat-from-ovens.

[18] United States. Department of Energy. Energy Efficiency & Renewable Energy..

[19] Johnson, David A. "What are some Benefits of an Air Curtain?" *ASHRAE Journal* (09, 1998): 40. http://proxy.lib.duke.edu/login?url=http://search.proquest.com/docview/220484442?accountid=10598.

[20] Ibid.

installed below and above an opening, and serve to prevent or slow down the transfer of heat between the oven and the ambient air.[21] Despite the lower cost of the non-recirculating air curtain, the efficiency is significantly lower.

In terms of reducing thermal losses, air curtains have been shown to be more effective than vestibules when the difference between the interior and exterior temperatures is high, but require energy input to power the fan(s) in recirculating ovens and the lower efficiency in non-recirculating ovens can make these solutions uneconomical.[22] However, the scale of impact and logistics of a vestibule in an industrial setting are not without complications. The major reason vestibules are not widely utilized on industrial ovens is that they require a lot of space. The recommended vestibule length for an oven of similar size to that used in the T6 process is roughly 10ft – any amount less than this results in very little impact.[23] Without a means to make this space requirement available for a retrofit, a vestibule becomes impractical. Additionally, there is very little available data on the actual amount of energy savings that a vestibule, applied in this way, yields. Therefore the investment is risky. To lower investment risk, an inexpensive pilot test with cheap materials is recommended to test the feasibility. This could later be adapted into a more advanced vestibule design.

Overall, we find either of these solutions viable for Specialized, but they are not considered preferred solutions due to the fact that our baseline model indicates that the energy losses from opening the oven doors are relatively small. However, since these energy losses are not insignificant over time, we find it warranted to conduct cost-benefit analyses for scenarios of each of the strategies at variable percentages of heat retention to determine feasibility in a range of performance levels.

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[21] Johnson, David A.

[22] "Air Curtains: a Proven Alternative to Vestibule Design." Berner International Corporation 2008. 3-4

[23] Talbert, Roger.

Waste Heat to Power Strategies

The most common waste heat to power strategy is the use of heat exchangers.[24] Heat exchangers are "used to transfer heat from combustion exhaust gases to combustion air entering the furnace."[25] This use of waste heat in this strategy reduces the amount of fuel needed to power the process.

Heat exchangers generally make use of waste heat to generate electricity. These strategies are more complicated to implement in Specialized processes because the company uses liquid petroleum gas (LPG) to fuel the industrial ovens. In a process using electricity, a heat exchanger can utilize waste heat to boil water in order to create steam for electricity production. Therefore, the use of waste heat reduces the amount of fuel that would be used to create steam. In a process using LPG, a heat exchanger could capture waste heat and transfer the heat back into the oven to maintain oven temperature.

While heat exchangers are technically feasible options in a manufacturing setting, their substantial capital costs and long payback periods makes them uneconomical.[26] The issue is amplified by the fact that there is not a large amount of usable heat output. For these reasons, we would not recommend waste heat to power strategies for Specialized.

Traditional Rankine Cycle

The Rankine Cycle is a process that utilizes waste heat to generate pressurized steam, which is then expanded through a turbine, ultimately moving a drive shaft for a generator to produce electricity. The temperature, pressure and flow rate of

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[24] United States. Department of Energy. Industrial Technologies Program. *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. Washington, D.C.: United States. Dept. of Energy. Office of Energy Efficiency and Renewable Energy, 2008. 12

[25] Ibid.

[26] Ibid,11.

the input steam are the primary variables in how much power the system can put out. The most common application of this type in terms of waste heat utilization can be found in a cogeneration system, or combined heat and power plant (CHP). Within the last few years, many hospitals, industrial firms and universities (including Duke) that operate a steam plant for heating and/or other uses have initiated a CHP conversion.

A standard steam plant generally uses natural gas boilers to make process steam, with a system efficiency around 33%.[27] By replacing one or more of these boilers with a gas turbine and heat exchanger connected to the turbine exhaust, the CHP can generate both power and all or a significant portion of the operators steam requirements. A CHP configuration typically runs at a system efficiency of 60-80%, granting substantial savings in overall energy costs.[28] Even though Specialized does not have an established need for process steam, a smaller scale Rankine system may have a similar effect.

The majority of capital investment and operational costs of a CHP are tied to the gas turbine, but Specialized can avoid some of this cost with a less expensive steam turbine. Since the T6 ovens reach a stable, high working temperature, a heat exchanger could be built into the oven wall. Steam would be produced as water is pumped through pipes in the oven walls, running an appropriately sized turbine/generator set. There is a clear benefit in producing electricity on site, and steam's versatility as an energy carrier makes it generally useful for multiple end-uses. Exhaust steam from the turbine could be used to heat water or air for the manufacturing facility, or grant modest pre-heating for the feed water going into the oven.[29]

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[27] United States. Environmental Protection Agency. Combined Heat and Power Partnership. *Catalog of CHP Technologies*. 4-9

[28] Ibid.

[29] Ibid.

The major barrier for Specialized’s employment of a traditional Rankine Cycle is that they have generally been designed around access to a fairly undiluted energy source, such as the exhaust of a natural gas turbine. Since there is little focus on heat absorption within a turbine, the majority of the energy exits the system as high-flow, hot exhaust. This flow of hot exhaust makes the attachment of a heat exchanger to the system very effective in generating steam for other purposes from energy that would otherwise be rejected. Since the heat treatment process has an implicit goal of using the minimum amount of energy required for a high-quality frame, the heat exchanger stands as an additional outlet for heat absorption, thereby increasing the overall energy input requirement of the process. This substantially limits the net energy savings that the turbine may provide, and so it is unlikely that this system would reach the efficiency of a similarly sized cogeneration system. For this reason, in addition to the fact that Specialized would need to conduct extensive experimental design studies to make it function as intended, we feel that this strategy should not be among the first pursued.

Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is nearly identical to the traditional Rankine cycle, but uses an organic working fluid as its prime mover. The fluid has a boiling point lower than water, which allows the system to utilize a much lower temperature waste heat stream. This makes ORC units ideal in industrial settings due to the fact that there is generally an abundance of low to moderate temperature waste heat available.[30] The other advantage of the ORC is that the working fluid can be formulated to work efficiently with many different types of waste heat streams.[31]

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[30] Tchanche, Bertrand F., Gr. Lambrinos, A. Frangoudakis, and G. Papadakis. "Low-grade heat conversion into power using organic Rankine cycles – A review of various applications." *Renewable and Sustainable Energy Reviews*15, no. 8 (2011): 3963-979.

[31] Ibid.

This flexibility, along with the fact that ORC units are generally modular and automated, make this strategy much more viable for Specialized than a steam driven system. The T6 process would likely see the most benefit from integrated ORC units since the processing time is so much longer. Rankine turbines are most efficient in near-constant operation, and so without a fairly steady stream of heat input, the net generation from the units will suffer from relatively poor start-stop performance.[32] Although it is likely that costs will outweigh energy savings with an ORC, this strategy still warrants cost-benefit analysis, as well as a deeper consideration of how to coordinate the exhaust of multiple ovens into a fairly constant waste heat stream.

Thermoelectrics

The final set of waste heat technologies that we find applicable to a heat treatment process are units that make use of the thermoelectric effect in order to produce electricity. While there is a considerable range in how the devices may be built and applied, the umbrella term for them is "thermoelectrics". Their solid-state design and near-zero emissions operation are major advantages for power generation in terms of ease of use and maintenance costs. A thermoelectric generator (TEG) is comprised of an array of modules that have physical and electrical properties such that when exposed to a temperature gradient, they produce voltage. In order to produce a current, a thermoelectric module must be comprised of both an n-type (negatively charged) material and a p-type material (positively charged), which is achieved by connecting the n-type material to the p-type material in series with conductive strips. The modules are then placed together in parallel so that one surface is exposed to a source of heat, while the opposite surface is exposed to a lower temperature. Multiple modules are also connected electrically in series due to

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[32] United States. Environmental Protection Agency.

their low output (usually in the millivolt range), which allows for scalable power output by the array.[33]

Most commercially available TEG setups require a temperature gradient in the order of several hundred degrees to be economically viable, as the voltage output of the unit correlates approximately linearly with the change in temperature.[34] Although in most cases experimental or proof-of-concept, they have been installed on the exhaust from boilers and gas turbines in utility scale power plants; usually only providing modest auxiliary power to the plant itself. However, alternatives for lower temperature waste heat stream do exist. Since there is a considerable variety of thermoelectric materials with different conductive properties, there is a lot of flexibility in the design of a thermoelectric array. The efficiency of any given thermoelectric material is often variable as temperature changes, and as a result, TEGs can theoretically be customized to nearly any heat source by utilizing materials that are most efficient at the given hot-side temperature.[35] This is sometimes achieved by developing 'segmented modules' that are comprised of layers of several different thermoelectric materials. Materials that are more efficient at high temperatures are placed closer to the hot side of the module, while materials with higher efficiency at lower temperatures are place towards the cold side – increasing efficiency as temperature changes through the module.[36]

An experimental study focused on the role of thermoelectrics in waste heat utilization was conducted in 2011 that tested a commercially available TEG in operating conditions similar to a T6 oven. They captured waste heat from an

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[33] "Thermoelectrics." Caltech Materials Science. http://www.thermoelectrics.caltech.edu/thermoelectrics/engineering.html.

[34] Hsu, Cheng-Ting, Gia-Yeh Huang, Hsu-Shen Chu, Ben Yu, and Da-Jeng Yao. "Experiments and simulations on low-temperature waste heat harvesting system by thermoelectric power generators." *Applied Energy*88, no. 4 (2011): 1291-297.

[35] Tritt, Terry M., and M. A. Subramanian. "Thermoelectric Materials, Phenomena, and Applications: A Bird's Eye View." *MRS Bulletin*31, no. 03 (2006): 188-98.

[36] "Thermoelectrics."

industrial furnace using a fluid heat exchanger to generate a hot-side flow at 150C (302F). Without any supplementary cooling, the cold side temperature was 30C (86F), which resulted in a maximum power output of 145.6W and a 4.44% conversion efficiency.[37] The output and conversion efficiency can be increased by finding the ideal balance of input temperature and flow rate, but in practice, this is complicated by the variation in the properties of thermoelectric materials described above. Our overall conclusion is that thermoelectrics do work, and are certainly very promising as a means to capture waste heat, but simply are not yet economically viable in a manufacturing setting. While we consider a TEG to be the least feasible solution for Specialized, we also feel that it is definitely something to be revisited in the future. As more efficient, cheaper materials are identified and tested, and economics of scale can take hold in the TEG market, it is likely that utilizing thermoelectric units will a feasible waste heat energy harvesting solution.

Table 7 shows a summary of our findings after examining all of the potential waste heat recovery methods and technologies. Only changing the material of the bicycle frame holders is recommended.

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[37] Niu, Xing, Jianlin Yu, and Shuzhong Wang. "Experimental study on low-temperature waste heat thermoelectric generator." *Journal of Power Sources*188, no. 2 (2009): 621-26.

Table 1: Summary of Potential Waste Heat Solutions

Potential Solutions		Recommended
Material Changes in Bicycle Frame Holders		Yes
Vestibules and Air Curtains		No
Waste Heat to Power Strategies	Traditional Rankine Cycle	No
	Organic Rankine Cycle	No
	Thermoelectrics	No

Recommendations:

Through a literature review of potential technologies for implementation, our team has concluded that none of the proposed solutions would be feasible and economical for Specialized, except the implementation of material changes (Table 1). Furthermore, we recommend, based on Specialized oven and heat treatment characteristics, fuel switching and material changes to reduce waste heat. These two recommendations are discussed in more detail below.

Fuel Switching

Baseline

Because Specialized does not have a flow meter measuring the exact amount of LPG consumption per year by the manufacturing oven, our team needed to create a close estimate for our calculations. We estimated the cost of Specialized's fuel consumption by using natural gas consumption data and the retail value of LPG, which was 21.45 TWD[38]/kg.[39] If we consider that the density of the LPG is 2.34kg/m^3, we can convert the price of LPG from TWD per kilogram to dollars per kilogram, which is \$1.57/m^3. With the consumption and price data, we calculated that the price of LPG per month is \$2,076.80. This is used as the baseline in the following discussion where we explore the cost-benefit of changing the fuel from LPG to natural gas or electricity. If Specialized can change their fuel source, the overall cost could be reduced.

Natural Gas

Natural gas is a widely used fuel to power turbines, heat pumps, vehicles, and more. While the gas is mainly composed of methane, it can also contain propane, butane, pentane, carbon dioxide, and hydrogen. Different concentrations of methane result in different heating values and prices. The low heating value of natural gas varies from 850 Btu/ft^3 to 1050 Btu/ft^3.[40] The price of natural gas in Taiwan, where the manufacturing facility is located, is between 9.7006-10.5726 TWD/m^3 for industrial users and 9.28 - 10.11 TWD/m^3 for public users.[41] For the purposes of this analysis, we made two assumptions. The first assumption is that the natural gas has higher heating value and the higher price. The second assumption is that the price increases linearly with the net heating value. For reference, the exchange rate between USD and TWD is 1USD= 32.142 TWD. Therefore, the net heating value is calculated using the following equation:

$$Net\ heating\ value\left(\frac{Btu}{ft^3}\right) = 154.73 * price\left(\frac{USD}{m^3}\right) - 585.87$$

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[38] Taiwanese dollar

[39] "'Liquefied petroleum gas' reference price list." CPC Corporation, Taiwan. http://new.cpc.com.tw/division/mb/oil-more1-11.aspx

[40] "Fuel Gases Heating Values." The Engineering ToolBox. http://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html.

[41] "'Gas' reference card. http://new.cpc.com.tw/division/mb/oil-more1-10.aspx

Accordingly, the net heating value calculated for natural gas prices of 9.7006 TWD/m^3 and 10.11 TWD/ m^3 are 34,132.41 kJ/m^3 and 36,495.19 kJ/m^3. For our analysis, we use four samples of natural gas, shown in Table 2, which represent high and low prices.

Table 2: Natural Gas Samples

	NG1	NG2	NG3	NG4
Low heat value (kJ/m^3)	31,705	34,132	36,495	39,165
Price ($/m^3)	0.2895	0.3026	0.3154	0.3299

The cost of purchasing enough natural gas to generate the heat required for the manufacturing process ranges from $1,282.4 /month to $1,390.47/month. As shown in Figure 5, changing from LPG to natural gas will reduce the fuel cost by about 33%-38%.

We performed a sensitivity analysis to determine the possible range of savings Specialized could earn by switching from LPG to natural gas. The total savings from fuel switching could be as high as $794/month if high quality natural gas is used. If we use the highest quality natural gas (NG4), the savings would only equal zero if the price of natural gas increases 61.95% and the price of LPG remains the same. If we use the lowest quality natural gas (NG1), the saving will be zero when the price of natural gas increases by 49.36%. For all four types of natural gas, the savings will be higher than $600/month as shown in Figure 6. It is evident that the savings from fuel switching are significant.

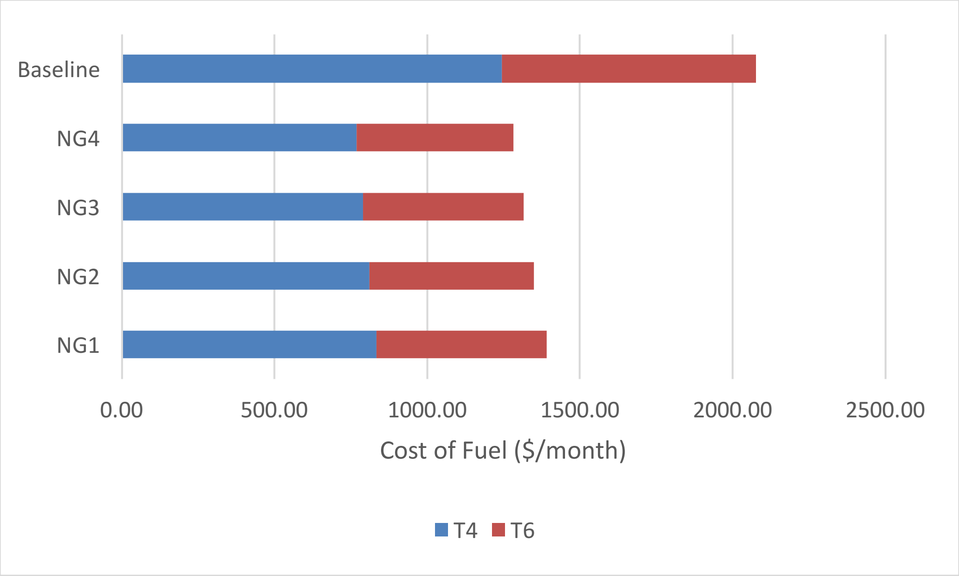

Figure 5: Monthly Cost of Fuel for Different Natural Gas Samples

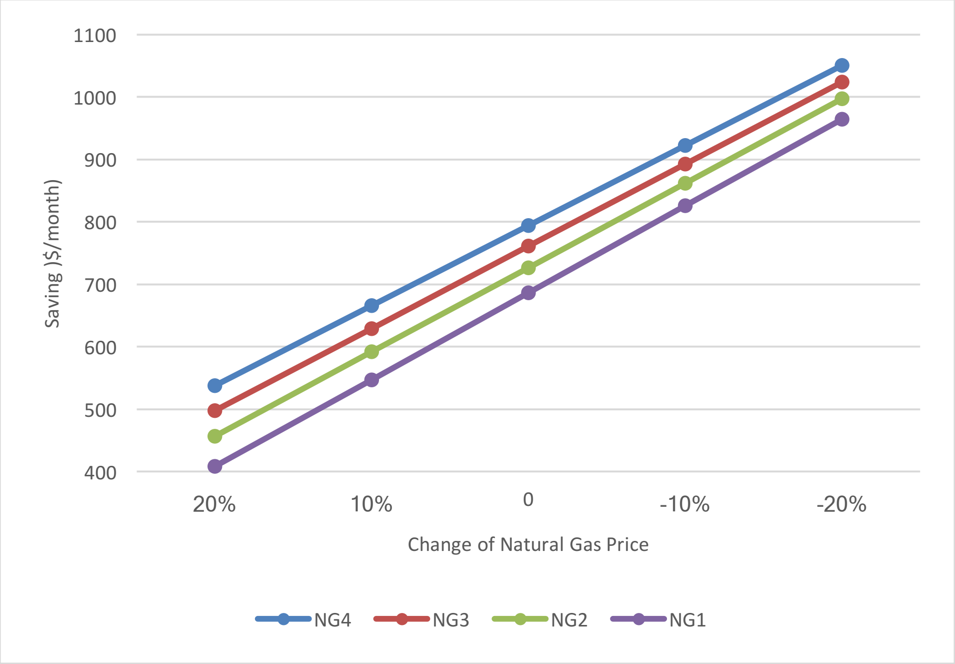

Figure 6: Monthly Savings by Switching from LPG to Natural Gas

Another benefit of fuel switching is a reduced carbon footprint. Natural gas is expected to have lower carbon emissions compared to LPG. LPG is mainly composed of propane and butane, while natural gas is mainly composed of methane. The Energy Information Administration reports that a propane and butane substance emits 64.01 kg CO_2 per million Btu and natural gas generates between 53.07-54.70 kg CO_2 per million Btu.[42] Hence, we can calculate the monthly carbon emissions for both LPG and natural gas. As shown in the Figure 7, if Specialized uses LPG as a fuel source, it will emit 9.24 ton of CO_2 each month. If the company uses natural gas it will only emit between 7.66-7.89 ton of CO_2 monthly, reducing CO_2 emissions about 15%. Although Taiwan is not a participant of the carbon market of China, we estimate the value of the CO_2 emissions based on the carbon price in a nearby carbon market, the carbon market of Guangdong Province in China. The carbon price in August, during peak production, is around 11 CNY/ton in 2016.[43] Hence, we estimated the value of this this reduction at \$2.13-\$2.50 per month, when 1 CNY =0.1439 USD.

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[42] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." Environment - U.S. Energy Information Administration (EIA) - U.S. Energy Information Administration (EIA). https://www.eia.gov/environment/emissions/co2_vol_mass.cfm.

[43] "China's seven major carbon market K-line chart." http://www.tanpaifang.com/tanhangqing/

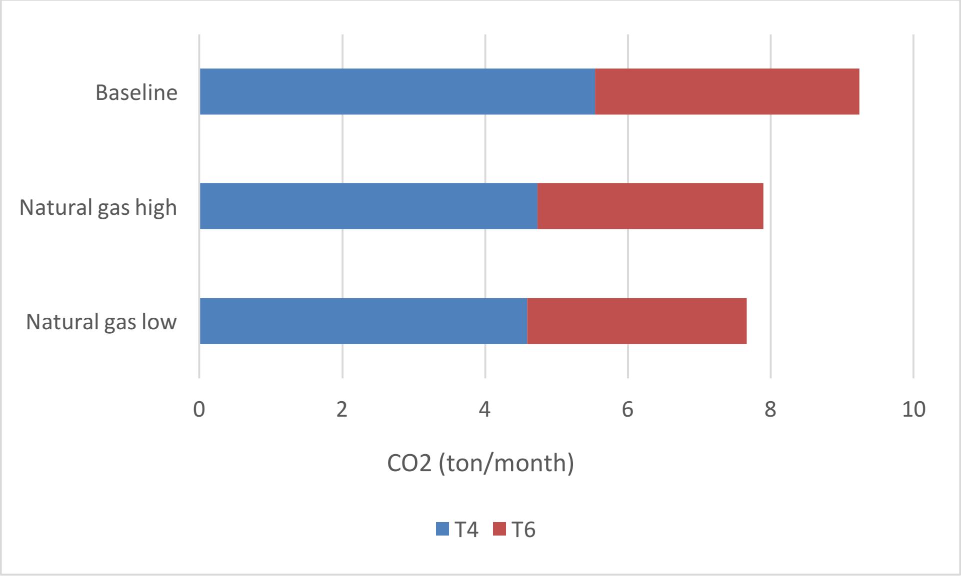

Figure 7: Monthly CO2 Emissions

There are few costs associated with fuel switching from LPG to natural gas. Natural gas and LPG are very similar and a manufacturing facility that uses LPG could easily start using natural gas without replacing any equipment or retrofitting the facility. Costs of fuel switching may include the time and effort to find another fuel supplier and to build the supply chain. This cost is difficult to estimate within the scope of the report. However, we believe these costs are relatively low compared to the estimated saving of switching to natural gas in the long term. Therefore, we recommend changing the fuel from LPG to natural gas based on our estimations and calculations above.

Electricity

Electricity is a high quality and widely used energy source in today's world. When electricity is converted into heat, it can achieve almost 100% efficiency. Using electricity to generate heat for Specialized's oven is another option worth considering. The utility in Taiwan provides several options for pricing. It generally includes time of use rate and non-time-of-use rate, and low tension and high tension.[44] Due to its complexity, we use the highest non-time-of-use rate, 6.15 TWD/kwh, the average rate of industrial use in 2015, 2.7641 TWD/kwh, and the lowest rate 1.63 TWD/kwh to generate three electricity price scenarios for our sensitivity analysis.[45] The cost of electricity is shown in the Figure 8 below. Even when the lowest rate of electricity is adopted, the cost, $2150.93/month, is still more expensive than the baseline cost of $2076.80/month. Moreover, if electricity is adopted for this heating process, a new furnace is necessary, leading to a higher implementation cost.

Figure 8: Monthly Electricity Costs

The amount of carbon emissions generated from electricity is determined by the portfolio of generators. According Taiwan Power's Sustainability Report on the sustainability of the local utility in 2012, the carbon intensity of power generation in

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[44] "Taiwan power company-Rate Schedules." Taipower. http://www.taipower.com.tw/e_content/content/rate/rate01.aspx.

[45] "Comparison of national electricity prices." Taipower. http://www.taipower.com.tw/content/new_info/new_info-d16.aspx?LinkID=14

Taiwan is 0.508 CO_2e/kWh.[46] Therefore, if the plant uses electricity for both the T4 and T6 processes, the carbon emissions from the T4 process are 12.88 tons/month and 8.60 ton/month from the T6. The emissions from both the T4 and T6 processes are higher than the baseline value of 9.24 ton/month. Because of the higher CO_2 emissions and the higher operation cost, we do not recommend the manufacturer to switch the fuel from LPG to electricity.

Frame Holders Material Change

The frame holders absorb a substantial amount of heat during T4 and T6. Specifically, the holders absorb 25.66% of the heat input in T4, and 10.93% of the heat input in T6. If Specialized replace the material of the frame holders with another material that absorbed less heat, manufacturing costs will be reduced. Characteristics of the current frame holders can be found in Table 3. Pictures of the frame holders can be found in the

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[46] "Taiwan Power Company Sustainability Report." 2013. 20. http://www.taipower.com.tw/UpFile/CompanyENFile/2013Taipower_English_EBook.pdf

Appendix.

Table 3: Current Frame Holders Information

T4/T6	
Material	Steel
Mass (kg)	671.4
Specific Heat (J/(Kg * K)	450

T4		T6	
Heat absorbed by frame holder (kJ/month)	23,430,181.50	Heat absorbed by frame holder (kJ/month)	6,661,966.50
Heat absorbed by frames/total Heat input	25.66%	Heat absorbed by frames/total Heat input	10.93%

Carbon Composites

The frame holders are currently made of steel. In many industries a popular steel replacement is carbon composite. Some carbon composite applications include aerospace, medical, renewable energy, electronic, racecar, and bicycle technologies. Industries are switching to carbon composite because of its several advantages over steel. Carbon composite is cheaper, lighter, and up to twice as strong as steel.[47]

"A composite is a structural material which consists of combining two or more constituents. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The reinforcing phase may be in the form of fibers,

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[47] Das, Sujit, Josh Warren, Devin West, and Susan M. Schexnayder. *Global Carbon Fiber Composites Supply Chain Competitiveness Analysis*. National Renewable Energy Lab. Oak Ridge National Laboratory. Golden, CO. 2016. 2.

particles, or flakes."[48] There are several types of carbon composites available on the market. The two types of composites we examined were polymer matrix composites and carbon-carbon composites.

Carbon Fiber Polymer Matrix Composites

"The most common advanced composites are those with polymer matrix composites (PMC). These composites consist of a polymer (e.g., epoxy, polyester, urethane) reinforced by thin-diameter fibers."[49] Advantages of PMCs include "high strength", and "low viscosity and low flow rates, which allow good wetting of fibers and prevent misalignment of fibers during processing."[50] Epoxy is the most commonly used resin in a polymer matrix composite. This is because of its relatively low cost and its high resistance to corrosion.[51]

Although PMCs are the most popular composite, they are only suitable for low operating temperature conditions.[52] Polymer matrix composites cannot withstand high temperatures because of "degradation…to thermal stress resulting from thermal expansion mismatch between the polymer matrix and the fibers."[53] One study revealed that visible degradation began to appear after 30 minutes in an environmental temperature between 340°C -450°C.[54] Therefore, carbon polymer matrix composites could not be implemented in the T6 heat treatment cycle. Even though this material could be implemented in the T4 cycle, after several cycles thermal degradation would likely occur and material replacement would be necessary.

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[48] Kaw, Autar K. Mechanics of Composite Materials. London: CRC, 2006. 2.

[49] Kaw, 16.

[50] Kaw, 24.

[51] Chung, Deborah D. L. Composite materials: functional materials for modern technologies. London: Springer, 2003. 18.

[52] Ibid, 17.

[53] Ibid, 5.

[54] Wolfrum, J., S. Eibl, and L. Lietch. "Rapid evaluation of long-term thermal degradation of carbon fibre epoxy composites." *Composites Science and Technology*69, no. 3-4 (2009): 523.

Carbon-Carbon Composites

Carbon-carbon composites consist of a reinforcing phase in the form of carbon fibers in a carbon matrix. Therefore, "The carbon fibers in a carbon-matrix composite (called carbon-carbon composite) serve to strengthen the composite, as the carbon fibers are much stronger than the carbon matrix owning to the crystallographic texture in each fiber."[55]

In the absence of oxygen, "Carbon-carbon composites are used in very high temperature environments of up to 6000°F (3315°C)."[56] A major drawback of carbon-carbon composites is that in the presence of oxygen, they degrade at a fairly low temperature. Above 320°C, carbon-carbon composites degrade due to the oxidation of carbon.[57] Specialized needs a material than can withstand around 180°C for T4 and 550°C for T6. Although carbon-carbon composites cannot withstand these conditions, there are industrial coatings that may be applied to composites to improve this issue.[58] With coatings, carbon-carbon composites can withstand up to 1700°C.[59]

Carbon-carbon composites would be most suitable for Specialized's needs. Not only can they withstand the temperature of the T4 and T6, but they also have high thermal conductivity and low thermal expansion.[60] These characteristics allow the carbon-carbon composite to exchange the heat the frame holders absorbs back into the air within the oven. Carbon-carbon composite would be extremely useful for Specialized's ovens because the material would decrease the amount of waste heat absorbed by the holders, and help to heat the oven faster.

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[55] Chung, 16

[56] Kaw, 42.

[57] Chung, 17.

[58] Chung, Deborah D. L.*Carbon Fiber Composites*. Boston, MA: Butterworth-Heinemann, 1994. 159.

[59] Ibid.

[60] Chung, Deborah D. L. Composite materials: functional materials for modern technologies. 16

We recommended the carbon-carbon composites over the carbon fiber polymer matrix composites. Our team believes that the implementation of carbon-carbon composite frame holders will allow Specialized to reduce waste heat, and save a substantial amount of money each month on fuel costs for heat input. To calculate the estimated savings, we perform a cost-benefit analyst, comparing estimated savings to initial implementation costs.

Saved Energy Estimation

To determine if this material replacement could lower manufacturing costs, our team performed a cost-benefit analyst. First, we determined how much heat would be absorbed in frame holders made of carbon fiber. This calculation was performed using Equation 1. Results can be found in Table 3. In order to estimate the heat absorbed by carbon fiber frame holders using this equation, our team made several assumptions about the weight and volume. The mass of the current steel frame holders, provided by Specialized manufacturing plant, is 671.4 kg. Because steel weights 8.1 grams per cubic centimeter[61], we assumed that the volume of the frame holders is 82,888.89 cubic centimeters. If 82,888.89 cubic centimeters of steel is replaced with carbon fiber composite, the new weight of frame holders is 147.54 kg, assuming carbon fiber weights 1.78 grams per cubic centimeter.[62]

Carbon composite frame holders reduced the amount of heat absorbed because the mass of carbon fiber is significantly lower than the mass of steal. Despite the higher specific heat capacity, the absorption of total heat input was reduced from 25.66% in to 10.40% in T4, and from 10.93% to 4.43%.

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[61] Das, Sujit, Josh Warren, Devin West, and Susan M. Schexnayder. 1

[62] Ibid.

Table 4: New Frame Holders Information (Estimation)

T4/T6	
Material	Carbon Fiber
Mass (kg)	147.54 kg
Specific Heat (J/(Kg * K)	1015.43[63]

T4		T6	
Heat absorbed by frame holder (kJ/month)	9,496,776.45	Heat absorbed by frame holder (kJ/month)	2,700,243.98
Heat absorbed by frames/total Heat input	12.72%	Heat absorbed by frames/total Heat input	5.42%

Purchase Cost

We based our purchase cost estimations from the price of carbon fiber in Japan, $23/kilogram, which is also the estimated carbon fiber price for all regions by 2020 due to increases in demand in technological advances.[64] The frame holders are 147.57 kilograms. Therefore it would cost $3,394.11.

Estimated Energy Savings

We estimated the new cost of waste heat absorbed by frame holders after switching from steel to carbon composite frame holders. Equation 3 was used to calculate the cost of the waste heat. We then compared the cost of waste energy using steel and carbon composite frame holders and carbon to estimate the monthly savings from the materials change. Monthly savings estimates are found in Table 5.

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[63] Alghamdi, A., A. Khan, P. Mummery, and M. Sheikh. "The characterisation and modelling of manufacturing porosity of a 2-D carbon/carbon composite." *Journal of Composite Materials*48, no. 23 (2013): 2828. doi:10.1177/0021998313502739.

[64] Das, Sujit, Josh Warren, Devin West, and Susan M. Schexnayder. 23.

Table 5: Monthly Savings

	Steel		**Carbon**	
	T4	T6	T4	T6
Cost of waste heat absorbed by frame holders (LPG) ($/month)	319.58	90.87	158.47	45.06
Savings ($/month)	0	0	161.11	45.81
Cost of Implementation ($0)	0		3393.42	

By replacing the steel frame holders with carbon composite frame holders, Specialized could save an estimated $206.92/month. The payback period of this material changing project could be less in 2 years (17 months) and it will generate net saving in future operation.

Carbon composites are widely used, but cost is still a significant barrier to adoption. The manufacturing process of composites is extremely energy intensive which drives the cost up.[65] The choice to use composites presents a "tradeoff between cost and performance.[66] For Specialized, this tradeoff does not exist because switching to carbon composite improves performance of their ovens and saves money. The

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[65] "Carbon Fiber Composites." Carbon Fiber Research. http://web.ornl.gov/sci/manufacturing/research/carbon-fiber/.

[66] N., Shama Rao, T.G.A. Simha, K. P. Rao, and Ravikumar G.V.V. *Carbon Composites are Becoming Competitive and Cost Effective*. Report. Infosys, 2015.2. https://www.infosys.com/engineering-services/white-papers/Documents/carbon-composites-cost-effective.pdf,

savings during the first month of implementation is greater than the purpose price of carbon composite.

Process Optimization

In addressing Specialized's energy losses during the heat treatment process, we find that the best first step should be a robust process analysis and optimization. This strategy alone can yield substantial energy savings with little to no capital cost, but also allows for several of the other waste heat technologies described below to be applied to the optimized process.[67] The EIA reports that globally, the industrial sector accounts for about 54% of the world's delivered energy, and that in most industrial applications, anywhere from 15-85% of this energy goes towards heating materials.[68] The sheer magnitude of this energy requirement has placed heavy focus on cost minimization, which is a natural driver for overall process efficiency. In many cases, however, the individual components of an energy-intensive process, such the working state of a heat treatment oven, have not been fully optimized.[69]

While there are various analysis frameworks and approaches to process optimization for different industry applications, the goal is to establish settings for a given part of an overall manufacturing process that result in a metered energy input level that is as close as possible to a calculated theoretical minimum energy input without sacrificing operational safety or product quality.[70] One of the favored approaches to reach this end is some variation of the Six Sigma DMAIC Process Improvement

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[67] Apostolos, Fysikopoulos, Papacharalampopoulos Alexios, Pastras Georgios, Stavropoulos Panagiotis, and Chryssolouris George. "Energy Efficiency of Manufacturing Processes: A Critical Review." *Procedia CIRP*7 (2013): 628-33. doi:10.1016/j.procir.2013.06.044.

[68] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." International Energy Outlook 2016-Industrial sector energy consumption - Energy Information Administration. https://www.eia.gov/forecasts/ieo/industrial.cfm.

[69] Friedler, Ferenc. "Process integration, modelling and optimisation for energy saving and pollution reduction." *Applied Thermal Engineering*30, no. 16 (2010): 2270-280. doi:10.1016/j.applthermaleng.2010.04.030.

[70] Pask, F., J. Sadhukhan, P. Lake, S. Mckenna, E.b. Perez, and A. Yang. "Systematic approach to industrial oven optimisation for energy saving." *Applied Thermal Engineering*71, no. 1 (2014): 72-77. doi:10.1016/j.applthermaleng.2014.06.013.

Methodology applied to thermal systems.[71] Under this framework, the optimization project is divided into the distinct phases of definition, measurement, analysis, improvement and control. The definition phase of process optimization is dedicated to understanding the purpose of each part of the overall process, as well as an identification of binding constraints related to factors such as operational safety and product quality. For example, in the T6 heat treatment process, the working temperature of the oven or product exposure time would serve as primary constraints, meaning that any alterations to the process may not affect these values. The measurement phase serves to establish the working parameters for the process before optimization. This consists of identifying all input and output streams in the process in order to derive a mass balance. This information is then used to calculate a theoretical minimum energy requirement based on project constraints. Comparing the process theoretical energy requirement to the actual amount of energy consumed, as indicated by metering, reveals an estimate of possible energy savings.[72] It is also important to divide the input and output streams into sets of variables. Variables can be defined differently depending on how the optimization analysis is conducted, but the generalized sets are input factors, such as fuel pump speed and thickness of oven insulation, factors that are affected by input factors, such as oven temperature and exhaust flow, and output factors, such as fuel consumption and product metallurgical state.

The analysis and improvement phases are distinct, but represent the actual optimization of the process. The primary goal of analysis is to conduct experiments on the process itself either by running trials of the actual process or a simulation under different input conditions. These trials should reveal the sensitivity and/or level of control an input factor has on the process. This information is then used in

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[71] "Six Sigma DMAIC Roadmap." ISixSigma. https://www.isixsigma.com/new-to-six-sigma/dmaic/six-sigma-dmaic-roadmap/.

[72] Pask, F., J.

the improvement phase to establish an optimized input configuration which minimizes input factors that have a strong effect on energy related output, while meeting all project constraints. The configuration can usually be calculated manually in simpler processes, but when there are many important secondary effects found in the analysis phase, it is likely warranted to construct either a linear or nonlinear optimization problem.[73]

An applied systemic process optimization to one of 3M's curing ovens for masking tape production utilized this framework to demonstrate an estimated energy savings of 29% by only altering dampers that control oven air flow and pressure.[74] While it is likely that Specialized's ovens are already fairly well optimized, we feel that a similar process optimization analysis is the most cost effective strategy for reducing energy use, and does not alter the feasibility of implementing further waste heat technologies. Due to the fact that the accuracy of the results of a process optimization study often require direct experimentation and/or complex thermodynamic simulations, our execution of the method may turn out incomplete or inconclusive, in which case we would recommend Specialized to pursue a more specialized analysis within the field.

Conclusion

Specialized Bicycle Components, Inc. is interested in increasing the efficiency of its bicycle manufacturing process, especially to reduce or reutilize waste heat generated from the process. After careful examination of the heat treatment process, we recommend reducing rather than reusing waste heat. This is because waste heat recovery technologies are too expensive and inefficient in this manufacturing setting. Our team provides two recommendations on how Specialized can feasibly

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[73] Herrmann, Christoph, and Sebastian Thiede. "Process chain simulation to foster energy efficiency in manufacturing." *CIRP Journal of Manufacturing Science and Technology*1, no. 4 (2009): 221-29. doi:10.1016/j.cirpj.2009.06.005.

[74] Pask, F., J.

and economically reduce waste heat and increase overall efficiency. First, we recommend that Specialized reduce waste heat by switching their fuel source from liquefied petroleum gas to natural gas. This measurement is expected to save more than $600 per month. Second, we recommend that Specialized replace the steel frame holders with carbon-carbon composite holders. This investment will pay back in 17 months and save more than $200 per month thereafter.

Appendix

Table 1: Inputs of Heat Treatment

General Input Values	
M_1 (kg per batch)	187.2
M_2 (kg per batch)	671.4
C_1 ($J*kg^{-1}*K^{-1}$)	900
C_2 ($J*kg^{-1}*K^{-1}$)	450
Lower Heating Value (LHV) (MJ/m^3)	115
Number of frames per month	15,000
Number of frames per batch (average)	100
LPG Retailing Price ($/L)	0.0016

Table 2: Inputs for the T4 and T6 Heat Treatment Process

T4		T6	
V (m^3 per month)	794	V (m^3 per month)	530
ΔT1 (K) and ΔT2 (K)	517	ΔT1 (K) and ΔT2 (K)	147

Table 3: Outputs for the T4 and T6 Heat Treatment Process

T4		T6	
Q_{in} $(MJ/month)$	91,310	Q_{in} $(MJ/month)$	60.950
$Q_{ab,1}$ $(MJ/month)$	13,065	$Q_{ab,1}$ $(MJ/month)$	3,714
Overall Energy Efficiency	14.31%	Overall Energy Efficiency	6.10%
Waste Heat Economic Value	1.07	Waste Heat Economic Value	0.78

(k$/month)	(k$/month)

Table 4: Heat Absorbed by the air in T4 and T6

T4		T6	
T0 (K)	306.15	T0 (K)	307.15
T1 (K)	823.15	T1 (K)	453.15
$Q_{air,h}$ (MJ/month)	6,409.60	$Q_{air,h}$ (MJ/month)	2,454.90
Value of $Q_{air,h}$ ($/month)	87.43	Value of $Q_{air,h}$ ($/month)	33.48

Table 5: Inputs Waste Heat from Ventilation

General Inputs			
D (m)	0.08	Ambient Air Temperature (^oC)	33
Air density (kg/m^3)	1.1534	Dynamic Viscosity (kg/(m*s))	1.8821*10^{-5}
Specific Heat (J/(kg*K))	1006.6	Thermal conductivity (W/(m*K))	0.026562
T4		**T6**	
Surface Temperature (^oC)	550	Surface Temperature (^oC)	180
Time	100 minutes	Time	10 hours

Table 6: Outputs Waste Heat from Ventilation

T4	T6

Pr	0.71324	Pr	0.71324
Gr	$4.97729*10^5$	Gr	$1.4152*10^5$
Ra	$3.55003*10^5$	Ra	$1.0094*10^5$
Nu	13.181	Nu	9.6252
h_c ($Wm^{-2}K^{-1}$)	17.506	h_c ($Wm^{-2}K^{-1}$)	12.783
$q_{air}(W)$	45.493	$q_{air}(W)$	9.4455
Q_{air} (MJ/month)	40.943	Q_{air} (MJ/month)	51.006
Economic Value of waste heat ($/Month)	0.56	Economic Value of waste heat ($/Month)	0.70

Figure 1: T4 Racks

Figure 2: T6 Racks