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Production System Optimization, Automation and Sustainability in Manufacturing of Crankshaft

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Abstract: A multistage automated production system for crankshafts under sustainability considerations is presented. The advanced methodologies presented here will reduce cost and improve productivity. The optimum parameters for operations are calculated for the minimum cost of operation. The manufacturing automation is illustrated through a production system design showing the specification of machine tools, total energy consumption and total carbon dioxide emission.

Key words: Automation, autonomous manufacturing system, sustainability, energy consumption, carbon dioxide emission.

1. Introduction

An automated integrated production system recognizing the value of environment, economics and sustainability is presented. It is a multi-station computer-assisted system with serial operations and automated transfer of work units between stations. It is assumed that the demand is large and supposed to last for several years to offset the huge investment. The automated system is likely to increase the production rate and thereby reduce the cost. A fully automated production line for manufacturing of crankshafts is described which is to integrate all the processing centers, buffers and transfer systems. Automation is expected to enhance quality and lower cost of the crankshaft.

The CO_2 emission in manufacturing the 6-cylinder crankshaft of a large sedan is estimated. It depends on energy consumption which is a central feature of environmental concerns. The embodied energy of the material is also estimated. However, carbon emission also depends on the fuel source producing energy presented below [Ashby]. However, the energy from grid is a mix of energy and the CO_2 emission is approximately 3.6 MJ/kW·h. It has been reported in literature that approx. 3 times more energy is produced at the source and carbon dioxide emission is three times more [Gutoswaki].

Further downstream of the supply chain average passenger vehicle emits about 404 grams of CO_2 per mile and a typical passenger vehicle emits about 4.6 metric tons of carbon dioxide per year. Automation increases energy consumption in manufacturing equipment. The manufacturing of crankshaft starts with removal of the excess material at the ends by facing and a center is drilled in the forged crankshaft. Then turning operation is further divided into pin turning and journal turning operations. These pin and journal turning operations are carried out on the same machine or at different centers which is highly recommended to reduce setup time. After these operations, oil holes are drilled on them by a special purpose operation called peck drilling where the tool is withdrawn from the work after a known interval for the removal of the chip. The crankshaft is then subjected to induction hardening to relieve the stresses. Finally, pin grinding and journal grinding operations are performed where these operations are carried out at different stages. For the journal grinding operation, $_2$. grinder can be used, whereas for the pin grinding, a special-purpose machine must be used. All these operations consume lot of energy and emit lot of CO_2

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Fig. 1 The flow-type manufacturing of crankshaft.

during manufacturing. Forged-steel crankshafts have higher impact strength, better fatigue resistance and longer life. The crankshafts have to last for millions or billions of revolutions throughout the lifetime of an engine. Due to these developments smaller six-cylinder engines can replace current eight-cylinder engines. The design for environment (DfE) concept of reduction in energy consumption, minimization of waste and increasing reuse & recycle, including reduction in energy are presented in this research. Jeswiet 2008 advocates more sustainable car with lower cost, better fuel efficiency, and most of all less CO_2 emission or more environmentally friendly sedan. The schematic representation of flow-type [8-10] machining system of the crankshaft is presented in Fig. 1. The objective is to find the manufacturing parameters at different stages to minimize the cost of production. The total cost (*TC*) equation is developed below, where f_1 = cost of facing and centering operation, f_2 = cost of journal turning, f_3 = cost of the pin turning, f_4 = drilling cost, f_5 = induction hardening cost, f_6 = journal grinding cost, f_7 = cost of pin grinding. The optimization model is formulated as a standard geometric programming (GP) problem.

$$TC = f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7 + f_8 \qquad (1)$$

The function $h_m(t)$ is called posynomial function. Duffin et al. [2] have shown to maximize the dual. Minimize $h_0(t)$, $t_j > 0, j = 1,2,..,r$ s.t. constraints: $h_m(t) \le 1,$ m = 1, 2, …, where $h_m(t) = \sum_{k=1}^{I(m)} C_{mt} \Pi_{j=1}^{r} t_j^{a_{mkj}}$, m = 0, 1, 2, … And $C_{mt} > 0$ and a_{mkj} are real numbers. The coefficient $C_{mk,}$ the exponent a_{mkj} , and I (m) are all known.

2. Formulation of Objective Function and Constraints for the System

Before developing the mathematical model, factors such as type of operation performed, machinability of the material, desired surface quality, standard parts and availability must be considered. After forging the journal diameter = 67.955 mm, pin length = 54.72 mm, and the total length = 651.09 mm.

2.1 Mathematical Modeling of Facing and Centering Operation

The objective of the facing and centering operation is to remove the excess material. The mathematical model is as follows.

Minimize

$$f_1 = M_1.(4.2511\,10^{-4} f_f^{-1} v_f^{-1} + 2.28) + 3.171 * 10^{-4} \qquad (2)$$

s.t. constraints:

$$300\ m/\min \le v_f \le 3000\ m/\min \qquad (3)$$

$$0.15\, mm/tooth \le f_f \le 0.5\, mm/tooth \qquad (4)$$

$$1.1948 v_f f_f \le 7.5\ KW \qquad (5)$$

2.2 Mathematical Model for Journal Turning Operation

There are a total of 7 journals for a 6-cylinder IC engine. After forging operation journal diameter is 67.955 mm which means that there is a total of 0.32 mm of material in excess on the journals which need to be removed in 4 steps. All 7 journals are turned successfully covering about 1,270 mm. Insert of type K cubic boron nitride (CBN) is recommended. The mathematical model is:

Minimize:

$$f_2 = 5.4315.v_{jt}^{-1}.f_{jt}^{-1} + 1.78585 \qquad (6)$$

under constraints:

$$27\,m/\min \le v_{jt} \le 70\,m/\min \quad (7)$$

$$0.2\,mm/rev \le f_{jt} \le 0.55\,mm/rev \quad (8)$$

$$0.01688 v_{jt} f_{jt} \le 15\,KW \quad (9)$$

2.3 Mathematical Modeling of Pin Turning Operation

For the pin turning operation, rapid traverse by the tool is about 535 mm, the total length of 6 pins is about 160 mm and the diameter of the pin before the beginning of the pin turning operation is about 58 mm substituting these values in the equation, the mathematical model for pin turning is:

Minimize

$$f_3 = 14.3784.v_{pt} \cdot f_{pt} + 1.772 \quad (10)$$

s.t. constraint

$$27\,m/\min \le v_{jt} \le 70\,m/\min \quad (11)$$

$$0.2\,mm/rev \le f_{jt} \le 0.55\,mm/rev \quad (12)$$

$$0.01688 v_{jt} f_{jt} \le 15\,KW \quad (13)$$

2.4 Mathematical Modeling of Drilling Operation

The cost of performing the drilling operation on the crankshaft is developed as:

Minimize

$$f_4 = 0.1467.v_d^{-1}.f_d^{-1} + 1.9110 \quad (14)$$

s.t. constraint

$$30\ m/\min \le v_d \le 200\ m/\min \quad (15)$$

$$0.3166 v_d f_d \le 15\ KW \quad (16)$$

2.5 Grinding Operation Model

Grinding of crankshaft pins and journals is a high precision machining operation, surface finish of 8 m is assumed on 6 pins and 7 journals. For the journal grinding:

Minimize

$$f_5 = 0.36855.f_g^{-1}.v_{wg}^{-1} + 2.3 \quad (17)$$

s.t. constraints

$$531.69.v_{wg}^{\frac{-3}{19}} \cdot f_g \le 647.105 \quad (18)$$

$$0.291.v_{wg}^{-\frac{3}{27}} \cdot f_g^{\frac{19}{27}} \le 0.02789.\mu m \quad (19)$$

$$6.7 * 10^5 v_{wg}^{-3/19} f_g \le 20 \quad (20)$$

$$1.\frac{m}{\min} \le v_{wg} \le 500.\frac{m}{\min} \quad (21)$$

$$0.000001.\frac{m}{s} \le f_g \le 10.\frac{m}{s} \quad (22)$$

For the pin grinding operation:

Minimize

$$f_5 = 0.89976.f_g^{-1}.v_{wg}^{-1} + 5.5275 \quad (23)$$

s.t. constraints

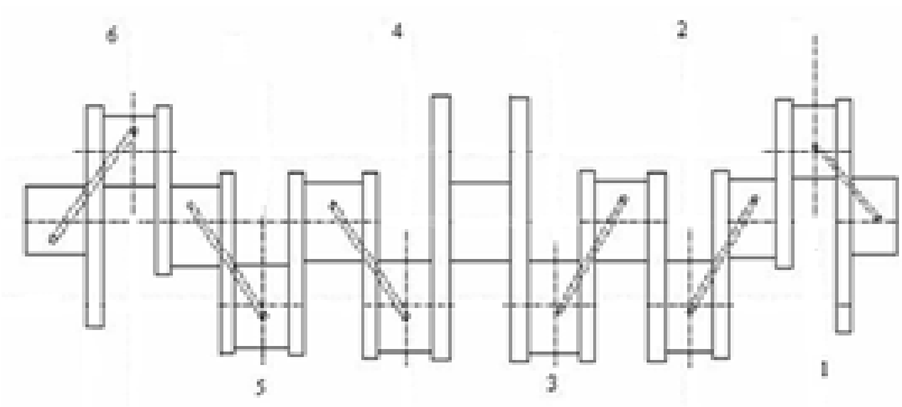

Fig. 2 Six throw crankshaft oil ways.

$$0.000001.\frac{m}{s} \le f_g \le 10.\frac{m}{s} \quad (24)$$

$$182.2.v_{wg}^{\frac{-3}{19}}.f_g \le 664.05 \quad (25)$$

$$0.007014.v_{wg}^{-\frac{3}{27}}.f_g^{\frac{19}{27}} \le 0.02789.\mu m \quad (26)$$

$$4.441*10^5 v_{wg} f_g \le 20 \quad (27)$$

$$1.\frac{m}{\min} \le v_{wg} \le 500.\frac{m}{\min} \quad (28)$$

The optimization problem is converted to standard geometric programming format and solved. The cost for individual operations on crankshaft is: facing = \$2.10, journal turning = \$3.30, pin turning = \$3.25, drilling = \$2.75, induction hardening = \$3.50, journal grinding = \$20.25, pin grinding = \$18.25. The optimized cost of the multistage system is:

$$M = \sum_{i=1}^{I} \left\{ m_i^{\frac{1}{\tau}} \right\}^{\tau} \quad (29)$$

where, I = number of subsystems in the manufacturing process; $\tau = 1 - \sum_{j=1}^{I} \delta_j^*$ is called the recomposition coefficient, δ_j^* = 1, and $\tau = 0.3$. For the crankshaft, the optimum cost is given by

$$M = \left(2.1^{\frac{1}{\tau}} + 3.3^{\frac{1}{\tau}} + 3.25^{\frac{1}{\tau}} + 2.75^{\frac{1}{\tau}} + 3.5^{\frac{1}{\tau}} + 20.25^{\frac{1}{\tau}} + 18.25^{\frac{1}{\tau}} \right)^{\tau} \quad (30)$$

The δ_j values will depend on the expertise of the engineer. The graph of recomposed value of system cost is shown in Fig. 5.

3. Energy Consumption Estimation

Over the life cycle of crankshaft the consideration of environmental impact of design and user's safety should be included into crankshaft design. The reduction of hazardous waste, reduction in embodied energy and increase in recycle & reuse of materials need to be increased.

3.1 Facing Operation

Speed = 122.835 mpm, feed = 0.01533 mmm, depth of cut = 0.5 mm.

The cutting parameters were presented in Table 1.

Using the specific energy data (from Table 20.3 Groover), 4.4 J/mm^3, we calculate the facing operation consumes 4,143 J for steel.

3.2 Turning Operation

Journal length = 33.4 mm, and journal diameter = 67.635 mm. The optimum cutting parameters obtained in the Table 1: speed = 686 mpm, f = 0.03 mm/s, depth of cut = 1.133 mm. The specific energy for forge steel is 4.4 J/mm^3 (Groover).

3.3 The Energy Consumed in Pin Grinding

Pin = Vfd (specific energy) = 97 J.

The energy consumed in turning the pin: length = 26.4 mm, pin dia. = 60.9 mm, and speed = 686 rpm, feed = 0.035 mm, and the cutting parameters presented in Table 3 are speed = 686 rpm, feed = 2.2 mm/rev, feed rate (f_r) = 14.5 mm/min, rate of metal removal = 48,731 mm^3/min, time to drill = 5.73 min, energy consumed in drilling a hole = 2,809 J, and the total energy consumed in drilling 6 holes = 78,826 J.

3.4 Energy Consumed Grinding Operation

Grinding energy provides a further valuable measure of the ability of a grinding wheel to remove material. The grinding energy required to remove a volume of material is given by the grinding power *P* divided by the removal rate *RMR*. This quantity is generally known in manufacturing technology as the specific cutting energy *U*. Since we are considering the grinding process, it will also be known as the specific grinding energy or simply as specific energy. The removal rate is 50 mm^3/s. The value of specific energy depends particularly on workpiece hardness and wheel sharpness.

Table 1 Optimum production parameters.

Type of machining	Limiting range	Optimal parameters			
		Lower	Upper	Feed (mps)	$1.543*10^{-4}$
Facing	Feed (mps)	$1.525*10^{-4}$	$5.4*10^{-4}$	Speed (mpm)	122.835
	Speed (mpm)	32	235	Power (KW)	8^{+}
		Lower	Upper	Feed (in)	$3.05*10^{-4}$ +
Journal turning	Feed (mps)	$1.016*10^{-4}$	$5.385*10^{-4}$	Speed (mpm)	686^{+}
	Speed (mpm)	600	686	Power (KW)	4.5
		Lower	Upper	Feed (in)	$3.5*10^{-4}$ +
Pin turning	Feed (mps)	$1.02*10^{-4}$	$3.85*10^{-4}$	Speed (mpm)	686^{+}
	Speed (mpm)	600	686	Power (KW)	4
		Lower	Upper	Feed (mps)	$2.29*10^{-4}$
Drilling	Feed (mps)	$7.65*10^{-5}$	$2.29*10^{-4}$	Speed (mpm)	120
	Speed (mpm)	58	120	Power (KW)	9.5
		Lower	Upper	Feed (mps)	$934 * 10^{-5}$
Journal grinding	Feed (mps)	10^{-6}	10	Speed (mpm)	500^{+}
	Speed (mpm)	1	500	Power (Kw)	1.4
		Lower	Upper	Feed (mps)	$1.196 * 10^{-4}$
Pin grinding	Feed (mps)	10^{-6}	10	Speed (mpm)	500^{+}
	Speed (mpm)	1	500	Power (KW)	19^{+}

A high value is typical of a difficult-to-grind material and a low value of an easy-to-grind material. Specific energy values reduce with increasing removal rate as found by many researchers in Fig. 3.

The energy consumed during grinding of one pin = 50 * 50 = 2,500 J. There are 6 journals and 6 pins and so the total energy consumed during grinding of crankshaft is, Total Grinding Energy consume = 12 × 2,500 = 30,000 J.

3.5 The Total Energy

The total energy for complete crankshaft manufacturing of the crankshaft is, total energy consumed = energy in facing = energy consumed in turning the pin + energy consumed in turning the journal + energy consumed in drilling + energy consumed grinding of both pin & journal = 30,080 J + 78,826 J + 30,000 J = 138,906 J. However, the energy consumed during manufacturing of crankshaft separated into energy consumed in manufacturing plus the energy for ancillary operations. The ancillary energy consumed by supporting equipment such as hydraulic pumps which run continuously while manufacturing operation is not even performed. Gutowski et al [16].

3.6 Induction Hardening

The surface hardening plays an important role in keeping geometrical dimensions as small as possible and boosting the component's resistance to ever-increasing loads at the same time. Later, an appropriate Induction hardening equipment is selected in Section 4. The CFW-Automatic Crankshaft Hardening Machine [15] is the best. The 6-cylinder crankshaft for a sedan will need 3 set-ups and it would take roughly 2 minutes to complete the hardening process. The specification of the power consumed by GFW induction hardening machine is about 205 W/h. Roughly it approximates to 12.1 kW·h and it translates to 0.5 kW or is equivalent to 2,000 J. The total energy consumed in manufacturing a crankshaft in the production system presented in Section 4 is updated to 140,906 J.

4. Carbon Dioxide Emission during Manufacturing Operations

Now we proceed to estimate the Carbon Dioxide Emission during the manufacturing of the crankshaft.

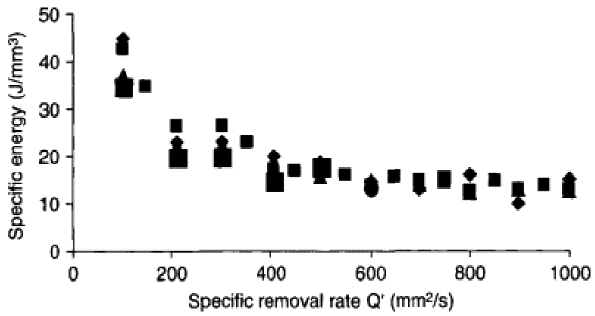

Fig. 3 Specific energy vs. metal removal rate.

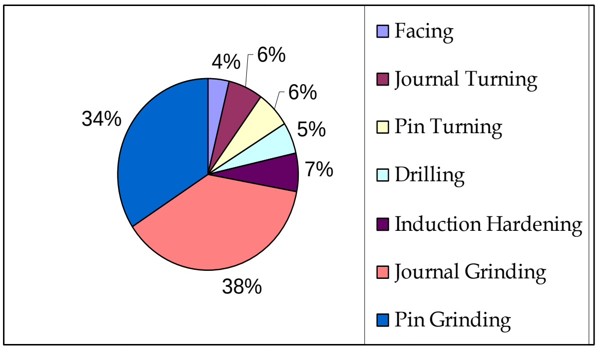

Fig. 4 Subsystem cost chart.

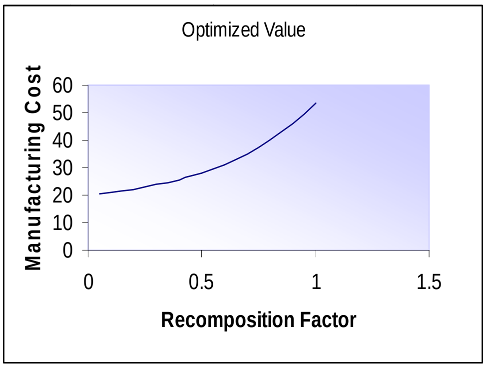

Fig. 5 Recomposed cost.

The grid power in US is essentially 50% from coal. The CO_2 emission is about 667 kg/MW·h. In US the transmission line efficiency is approximately about 36% (which is better than many other countries) and so at the power generation point the power generated to power the manufacturing of the crankshaft is approximated to 0.5 MW·h and the carbon dioxide emission is about 335 kg. It is huge but if you look the downstream of this product to be used in every car and every typical passenger car emits about 4.6 metric tons of carbon dioxide per year. Then for every MJ of electricity consumed also emits: 0.76 g of SO_2, 0.31 g of NO_x, 6.24 g of CH_4, 0.0032 mg of mercury (Hg). Then we have not estimated the embodied energy for a crankshaft material. Every section of crankshaft is about 5 kg of forged steel and for a 6-cylinder and total weight is 30 kg. The embodied energy can be estimated [Ashby] as 30 kg × 50 MJ/kg = 1,500 MJ, which should be added to the total energy consumed = embodied energy + manufacturing energy = 15.25 MJ. All other energy and carbon dioxide emission can be updated and we can visualize the total energy consumed and the resultant carbon dioxide emission in the air along with other toxic gases.

5. Cost Analysis of Proposed Production System

From Table 1 it can be noticed that there the turning operation utilizes about 5.5 hp out of 20 hp and a machine with less horsepower could be used. For other machining operations, the power used for the operation is realized very close to the upper limit of the available power. The range of manufacturing cost is between $23.379 and $53.4.

It can also be seen that the grinding operations (both journal and pin) are very critical operations, constituting about 75% of the total manufacturing cost. It was also noticed that the total cost for loading and unloading constituted about 30% of the total machining cost and more study is needed for automation of material handling to reduce these costs.

6. Production System Design: Selection of Equipment

Now the configuration of the production system is presented. All the optimum process parameters obtained above will be loaded into the machine tools before manufacturing process starts. The vendors were thoroughly vetted and then selected as follows.

In the final configuration, the automated crankshaft production line conducts the main turning operations on two identical cells. Raw material is first transferred to facing and turning operation. The George Fisher facing and turning machine looks the best after examining various other machine tools. A George Fisher Model ZM80 [11, 12] has double ends and is equipped with facing, centering and forming spindles. It has universal vices with replacement inserts which make it preferable to others in the category. The specifications are presented below:

Maximum work length 31.49 in. (800 mm), minimum work length 1.96 in. (50 mm), clamp diameter with loader 4.52 in. (120 mm), clamp diameter without loader 0.62 in. (16 mm), max. workpiece diameter 25.20 in. (640 mm), travel of spindle quills 4.33 in. (110 mm), spindle horsepower 10, spindle speed 180-2,360 rpm, feed rates 0.31-15.7 ipm (8-400 mm/min), rapid traverse 98.42 ipm (2,500 mm/min). There is one cell in each of the parallel production lines. Both cells on the two lines are built around eight ROTURN 320 lathes that face each other in pairs on opposite sides of the moving parts conveyor.

Roturn 320 CNC Lathe: max turning diameter 13 in., travel z-axis 8.2 in. 6-station tool turret, speed range 200-4,500 rpm. After examining Motoman, KUKA, and FANUC robots of various specifications, we came to conclusion that FANUC M-4 10iB [13] is the best. It has long been recognized in industry that use of robot to load, unload and transfer crankshaft increases productivity by as much by 25%. It lowers the direct labor cost and position work to an accuracy of 0.004 in. (0.1 mm). It has five axes of motion corresponding to human waist, shoulder, elbow rotation, wristband and hand motions. The specification of FANUC M4 10 IB robot is given below.

FANUC M4 10iB;

Reach 3,143 mm, payload 160 kg;

Motion 5.24 rad/s, motion range ± 270 degrees;

A floor-mounted FANUC M4 10iB robot is positioned in the middle of each pair of lathes, but lockout safety fencing allows the cells to be isolated into single-machine zones. This allows each cell operation to continue while one of the machines is sequestered for maintenance.

The twin-turret design allows both ends of the crankshaft to be machined simultaneously in one fixturing, whereas these ends were machined separately on the former lines. These machines are equipped with ball screw-driven, servo-actuated doors that have 1-second open and close time, which minimizes load and unload cycle times.

More importantly, these lathes are able to hold the 0.0005-inch tolerances as specified for turned features of the crankshafts. The rotary encoders on the ballscrews read 1,296,000 pulses per revolution. Such a high resolution allows the machine to adjust infeed commands in 0.0001-inch increments, based on the feedback from the gaging stations. This capability is the key to effective closed-loop control.

The high accuracy of these turning operations should be normally required in the entire rough grinding operation. Rough grinding is a particularly troublesome bottleneck on the production lines and a persistent source of errors and loss of productivity. Just by eliminating this rough grinding step, the efficiencies and productivity should increase tremendously. Obviously, the automated gaging stations play a key role in each cell. It gives low scrap rate of the turning operations and it is mainly attributed to the closed-loop feedback provided by these stations. The scrap rate is less than 1%; the gaging stations are designed by Edmund Gages [14]. All gaging stations are installed in parallel to the workstations.

Each gaging station simultaneously can measure five dimensions of every crankshaft machined in the cell. The gage’s data processor should be able to track every crankshaft and offset any one or all of these dimensions. Feedback to the lathe’s CNC should be able to compensate for these deviations. If a turned crankshaft exceeds the tolerances on any of the dimensions, then the part is placed on the conveyor for transport to the pin turning and griding cells. The drilling machine is stationed right after turning lathe. The specifications of the drilling machine tool [12, 13] are given below.

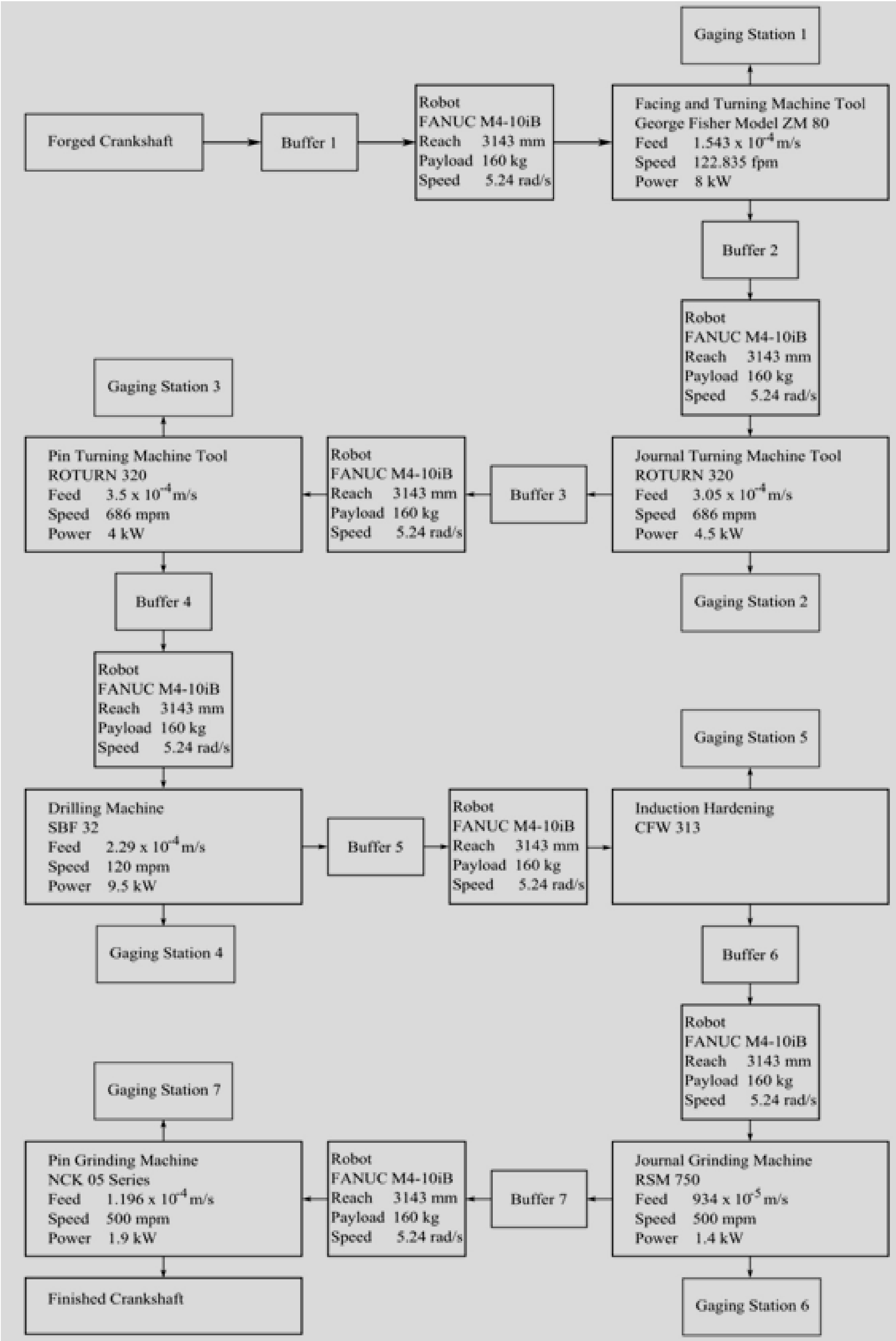

Fig. 6 Automated production system design.

SBF 32

SBF 32; drilling thread-cutting and light machine operations, tavel distance (X/Y/Z) 15 in. × 7 in. × 5 in., drilling capacity 1.26 in., spindle mount MT4.

Speed range 75-3,200 rpm, SBF 32 is suggested due to its versatility and according to drilling operation for the crankshaft it seems the best.

Next in the production line is Induction Hardening. After examining various induction hardening machines, it was decided that CFW-Automatic Crankshaft Hardening Machine [15] is the best. Fully automatic CFW can harden the crankshaft as little as 40 seconds. It has 3 heating stations, 2 for hardening pins and 1 for hardening journals. Two 400-Kw power supplies enable simultaneous hardening of 5 journals and 4 pins. The model CFW-313 automatically identifies the specifications of the crankshaft to be hardened. It is one of the most important characteristics of CFW hardening machine.

CFW 313-Specifications

Power 400 Kw power supplies (2).

Frequency 10-15 Hz, production 89 parts/hr or 40.5 sec/part, maximum part length 700 mm.

It should be recognized that low frequency gives better quality of hardness. CFW 313 has frequency of 10-15 Hz. After induction hardening the crankshaft is transferred to journal grinding station. The grinding machine selection was based primarily on the grinding length and RSM 750 [11, 12] seems to be best suited for the job. The specification is presented below.

RSM 750

Maximum grinding diameter 0.31 in.-7.87 in. Maximum grinding length is 30 in.

Maximum part weight is 110 lbs.

The next pin grinding selection poses a problem. This operation needs high speed, high accuracy and flexibility of operation. The ultra-speed crankshaft pin profile machine NCK 05 series was selected. It should significantly enhance flexibility in grinding crankshaft due to high-speed, high-accuracy profile control technology embedded in NCK 05 series. Specifications of NCK 05 series [12] are presented below. Two of NCK 05 series are shown here.

N FT08 NCK05 FNo.6

Swing over table 220 mm, distance between fixtures 800 mm, 600 mm grinding wheels 550 × 50 × 50 CBN wheel peripheral velocity 120-160, wheel hand rapid traverse 40 m/min, floor space 6,100 × 6,500 mm, 2,500 × 3,000 mm. Machine main body weight 19,000 kgf. From space and weight considerations, it seems NCK05 FNo6 is better.

7. Conclusion

An investigation of manufacturing automation of crankshaft under sustainability conditions is presented. A new mathematical model for the multistage machining system comprising of several machine tools sequenced in the production-technological order developed in an attempt to determine machining parameters for each stage under sustainability consideration is presented. A new decomposition algorithm was developed to solve the subsystem and finally the results were recomposed to find the optimal results. The optimal results point in the direction of the stage where lowering the cost of automation and environmental impact of the crankshaft is the most desirable. The total energy consumed during the manufacturing of crankshaft including the embodied energy is estimated and it shows the resultant carbon dioxide emission in the air. The cost of the crankshaft on the production system designed seems to be reasonable. The sustainability estimation of cost and energy consumption along with CO_2 emission is very interesting. Final configuration of automated production system is shown in Fig. 6. Jha [14] presented a simpler version of this paper at IMECE, ASME 2013.

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