Design For Existing Lines: Part and Process Plan Optimization to Best Utilize Existing Production Lines

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This paper presents a method for modifying the design of the new part for the maximum utilization of existing production lines dedicated to other products. The method takes as inputs a nominal part design and the process information of the (potentially multiple) existing line(s), and produces a modified part design and a process sequence of the new part that maximizes the utilization of available manufacturing processes in the existing lines or equivalently minimizes the addition of new processes dedicated to the new product. The problem is formulated as mixed discrete-continuous multiobjective optimization. A multiobjective genetic algorithm is used to generate Pareto optimal designs for the optimization analysis. A case study on the production of a new machine bracket considering two available production lines is presented. [DOI: 10.1115/1.2720886]

1 Introduction

Ever-increasing trends for more product varieties and shorter lead times are pressuring manufacturers more than ever to investigate ways to minimize production costs and maximize earnings. Because of the large capital cost for setting up a new production line, many manufacturers opt for the reuse of the existing production lines as an effective way of reducing the cost of introducing a new product into the market. Although a lower cost can be achieved by utilizing the existing production resources, undesired compromise in the product function due to the utilization of existing resources would result in quality loss and/or a longer design cycle due to unnecessary redesign at a later stage. Therefore, a systematic design method is desired that facilitates the optimal "casting" of a new product design into the existing production resources without affecting the intended product function.

As an illustration, consider the simple machined products shown in Fig. 1, where Fig. 1(*a*) shows the part currently produced in an existing production line (Fig. 2) and Fig. 1(*b*) shows the new part under consideration. Assuming no flexibilities in fixturing size and tool motion, the fixtures of the existing line cannot hold a 2×2 stock, which is a minimum size stock for the new product. If a 2×2 stock is to be utilized, the new part must be manufactured without utilization of the existing processes, for instance, the sequence shown in Fig. 3.

On the other hand, careful examination of the critical dimensions of the existing and new products (indicated by circles in Fig. 1) reveals that, with some material waste, a 2×3 stock can be utilized to enable the use of existing processes without compromising an intended function of the new product. Figure 4 shows such an example process sequence of the new part, with two of the existing processes and one new process. In Fig. 4(*e*), the part width is kept as 3 since it was not indicated as a critical dimension in Fig. 1(*b*). This means, for better utilization of the existing manufacturing processes, the initial part design in Fig. 1(*b*) can be modified to a width of 3 without compromising the intended part function.

If the reduction of part width is desired, an additional new process can be added at the end to cut off the extra width. The additional part width in Fig. 4 was added merely to facilitate the fixturing by the existing fixtures with no other functions. Such geometric features, which we refer to as *fixturing features*, can greatly enhance the utilization of the existing processes.

This research aims at developing a method for modifying the design of a product, considering the in-progress part geometry and manufacturing process sequence, for the maximum utilization of existing production lines dedicated to other products. The method takes as inputs a nominal part design and the process information of the (potentially multiple) existing line(s), and produces a modified part design and a process sequence that maximizes the utilization of available manufacturing processes in the existing lines or equivalently minimizes the addition of new processes dedicated to the new product. The problem is formulated as mixed discrete-continuous multiobjective optimization. A multiobjective genetic algorithm is used to generate Pareto optimal designs for the optimization analysis.

The method, which we shall refer to as design for existing lines (DFEL), is highly effective during the introductory phase of a new product into a product portfolio, when increasing volume of new products must be accommodated in an economical fashion while maintaining the high production volume of existing products [1]. The successive application of DFEL during the transition of an old product to a new product would facilitate the incremental changes in the production facilities from the one dedicated to the old product, eventually to the one dedicated to the new product. Also, DFEL provides an alternative to the use of flexible manufacturing cells [2] for small batch, custom-made products, for which building a dedicated line cannot be justified.

Sections 2–4 provide a brief review of the relevant literature, a problem formulation, and a case study on the production of a new machine bracket considering two available production lines. The paper concludes with a discussion.

2 Literature Review

DFEL belongs to a general area of Design-for-X (DFX) methods, where X can be manufacturing, assembly, environments, etc., depending on the purpose for which a product design is improved. Design for manufacturing (DFM) [3–5] and design for assembly (DFA) [5,6] provide generic design guidelines to modify part designs for lower manufacturing and assembly cost. Although the guidelines are specific to the type of production processes, eg.,

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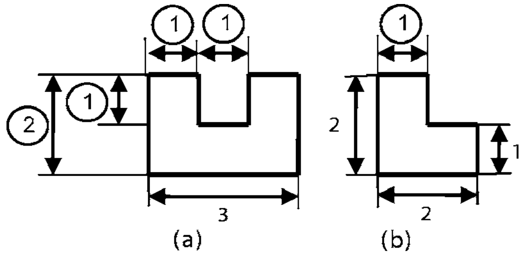

Fig. 1 (*a*) Part manufactured by an existing line and (*b*) new part. The critical dimensions, for which both of the end faces are milled, are indicated by circles.

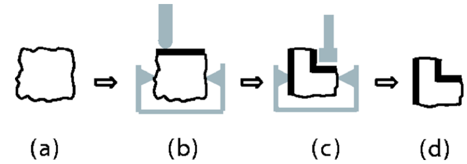

Fig. 3 A possible process sequence of the new product without utilizing processes in the existing line: (*a*) stock, (*b*) left face milling, (*c*) slot milling, and (*d*) finished part

machining and manual assembly, they are still generic to assure the applicability to various situations. Also, the guidelines are process oriented rather than systems oriented. Although effective as genetic methods, both of these characteristics makes DFM and DFA fall short for enhancing the reuse of a specific production facility. On the other hand, design for existing environment (DFEE) [7] and design for production (DFP) [8] provide means for evaluating a product design based on the system-level information specific to the target production facility, such as process plans, cycle time, and production capacity. Although key system-level issues are considered, however, they do not explicitly deal with part geometry that is essential to determine the reusability of a production process [9–13]. For this reason, these methods cannot effectively address the partial utilization of existing facilities based on in-process part geometries nor synthesize a modified part geometry as an end result.

Since the reusability of an existing process depends on the similarity of the current part and new part, a system for measuring similarity of part geometry is relevant. Group technology (GT) [14–18] serves this very purpose. Although GT provides a system for classifying parts based on the similarity of their manufacturing processes, it is merely a coding system without an explicit consideration of process sequence and therefore in-process geometries. Computer-aided process planning (CAPP) [19–24], on the other hand, explicitly deals with both process sequence and in-process geometries to synthesize the process plan best suited for a given part geometry, through either modifying an existing process plan for a similar part or searching among the feasible plans that satisfy the process precedence imposed by the part geometry. Although GT and CAPP attempt to link part geometry and production system design, they regard part geometry as a given input, with no consideration of redesign for better utilization of existing facilities as addressed in the proposed method.

Dissimilar to other DFX methods stated above, DFEL assumes the existence of specific production lines and synthesizes (rather than evaluates) the modified product design for improved utilization of the existing lines, by simultaneously considering in-process part geometries and process sequencing as CAPP. Focusing on machined parts, the demonstration in this paper in essence extends the design for fixturability [25] method into multiprocess, dedicated production lines. Since the reusability of an existing process is determined based on the fixturing envelope and the in-process part geometries, both partial and total utilization of the existing lines can be seamlessly addressed.

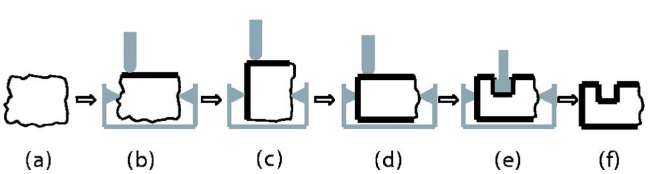

Fig. 2 Process sequence of the existing line: (*a*) stock, (*b*) bottom face milling (p_1), (*c*) left face milling (p_2), (*d*) top face milling (p_3), (*e*) slot milling (p_4), and (*f*) finished part

3 Approach

Given the design of a new part and the process information of the existing lines (potentially multiple), DFEL outputs a modified part design and a process sequence that maximizes the utilization of available manufacturing processes in the existing lines. The outputs are obtained by solving the multiobjective optimization problem described in Sec. 3.4. Although the concept of DFEL is applicable to many domains, this paper focuses on the geometric aspect of machined parts and assumes (i) single parts, not assemblies; (ii) linear production line with no branching, consisting of machining processes only; (iii) no part deformation during fixturing and machining; and (iv) no machine reconfiguration in the existing production lines.

3.1 Definition of Inputs. For simplicity of notation, a nominal part geometry, either in-process or finished, is represented in this section as a subset three-dimensional (3D) space $\mathbf{R}^3$ and a production line is represented as a mapping from $\mathbf{R}^3$ to $\mathbf{R}^3$. A problem-specific parametrization of the part geometry should be adopted in the actual implementation of the DFEL method, such as the one in the case study.

Geometry $s \subset \mathbf{R}^3$ of a new part consists of critical and noncritical design features, which are specified as a set of value ranges (or single values) of part dimensions as illustrated in Sec. 1. Although the out-of-range noncritical features do not affect the intended function of the part, the critical features within the acceptable range must be present in the part geometry for the part to be functional. The part geometry is also indirectly represented by $MF=\{mf_1, mf_2, \ldots, mf_l\}$, a partially ordered set of l machining features (MF) that are minimally required to machine all critical design features, starting from a material stock.

A production line $\boldsymbol{p}=\langle p_1, p_2, \ldots, p_m\rangle$ is a linear sequence of m machining operations $p_j=(r_j, o_j, E_j^{\min}, E_j^{\max})$; $j=1,2,\ldots,m$, where function $r_j: 2^{\mathbf{R}^3} \mapsto 2^{\mathbf{R}^3}$ is the relocation of incoming part,[2] function $o_j: 2^{\mathbf{R}^3} \mapsto 2^{\mathbf{R}^3}$ is the actual machining operation, and set $E^{\min} \subset \mathbf{R}^3$ is the minimum and $E^{\max} \subset \mathbf{R}^3$ is the maximum fixturing envelope of the operation, respectively. At process p_j, an incoming part $s_{j\text{-}1}$ is first relocated and fixtured, and then machined to produce an outgoing part $s_j = o_j(r_j(s_{j\text{-}1}))$, as illustrated in Fig. 5. Starting with a material stock s_0, a production line sequentially transforms the part geometry $s_1, s_2, \ldots$ to finally produce a finished part s_m. Multiple production lines are differentiated by an additional (preceding) subscript, where $\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n$ denote the n existing production lines. The subscript 0 is reserved for the production line of the new product.

3.2 Definition of Design Variables. The design variables are as follows:

- Stock geometry $s_{00} \subset \mathbf{R}^3$ of the new part

[2] $2^{\mathbf{R}^3}$ is a power set (set of subsets) of $\mathbf{R}^3$.

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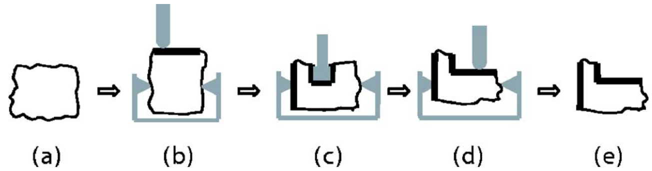

Fig. 4 Alternative process sequence for new part utilizing two processes in the existing line: (*a*) stock, (*b*) left face milling (p_2), (*c*) slot milling (p_4), (*d*) face milling (new process), and (*e*) finished part. Part width is not reduced to 2 since it is not indicated as critical.

- Number of machining operations $m_0 \in \mathbf{Z}_+$ in the production line of the new part
- Sequence of machining features $\boldsymbol{e}=\langle e_1, e_2, \ldots, e_l\rangle$ to produce the new product, where $e_j \in \{1,2,\ldots,l\}$ is the ID of the machining feature $mf \in MF$ machined at the ith operation in the production line of the new part
- Machining operations $\boldsymbol{q}=\langle q_1, q_2, \ldots, q_{m0}\rangle$ for the machining features of the new part, where q_k is the machining operation for the kth machining feature $mf_k \in MF$. Each operation q_k can either be the one chosen from the existing lines $\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n$, or a newly created operation. It is assumed that newly created operations can accommodate the machining of any desired features since they are custom made.

For a set of values of m_0, $\boldsymbol{e}$, and $\boldsymbol{q}$, the production line $\boldsymbol{p}_0$ of the new product is uniquely specified as $\boldsymbol{p}_0=\langle p_{01}, p_{02}, \ldots, p_{0m0}\rangle$, where $p_{0j}=q_{ej}$ for $j=1,2,\ldots,m_0$. Although the problem can be formulated with a given minimum stock size obtained from the nominal part geometry, the inclusion of stock shape and size s_{00} in design variables is essential to exploit the potential benefit of the fixturing features as illustrated in Sec. 1.

3.3 Definition of Constraints. The constraints are as follows:

- Each machining feature is machined exactly once

$$e_j \neq e_k \quad \text{for any} \quad j \neq k; \quad j,k = 1,2,\ldots,l \tag{1}$$

- Sequence of machining feature conforms the precedence

$$mf_{e_j} \prec mf_{e_k} \quad \text{for any} \quad j < k; \quad j,k = 1,2,\ldots,l \tag{2}$$

- Each machining feature is machined by the operation with the compatible type

$$\text{machinable}[mf_k, type(q_k)] = \text{true} \tag{3}$$

  where machinable $[mf_k,\ type(q_k)]$ returns true if machining feature mf_k can be machined by the type of machining operation q_k (denoted as $type(q_k)$), and false otherwise.
- Finished new part must be functional

$$\text{functional}(s_{0m_0}) = \text{true} \tag{4}$$

  where functional (s_{0m_0}) returns true if finished part geometry s_{0m_0} has all critical geometric features within the acceptable ranges, and false otherwise.
- Relocation is done by rigid-body translation and/or rotation

$$r_{0j} \in \text{TR}; \; j = 1,2,\ldots,m_0 \tag{5}$$

  where TR is a set of rigid-body motions that yield a feasible fixturing configuration (eg., translation and rotation at 90 deg increments).
- In-process geometry is fixturable at each process

$$E_{0j}^{\min} \subseteq \boldsymbol{r}_{0j}(s_{0j-1}) \subseteq E_{0j}^{\max}; \quad j = 1,2,\ldots,m_0 \tag{6}$$

- Material is removed by machining at each process

$$o_{0j}[r_{0j}(s_{0j-1})] \subset r_{0j}(s_{0j-1}); \quad j = 1,2,\ldots,m_0 \tag{7}$$

In addition, any problem specific constraints, such as process capacity and prohibition to utilize certain existing processes, can be imposed and written in a generic form as

$$\boldsymbol{g}(s_{00}, \boldsymbol{p}_0) = \textbf{true} \tag{8}$$

3.4 Definition of Objective Functions. The primary objective of DFEL is to obtain a modified part design s_{0m_0} and its process sequence $\boldsymbol{p}_0=\langle p_{01}, p_{02}, \ldots, p_{0m_0}\rangle$ with the minimum length, which maximize the utilization of available manufacturing processes in the existing lines $\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n$. These correspond to the following two objectives to be minimized (written in symbolic forms for simplicity):

- Number of new manufacturing operations in $\boldsymbol{p}_0$ that do not match any operation in $\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n$

$$f_1 = \text{nomatch}(\boldsymbol{p}_0, \boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n) = m_0 - \text{match}(\boldsymbol{p}_0, \boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n) \tag{9}$$

  where the function match() returns the number of manufacturing operations on the line p_0, whose machines are picked from those available in the lines $p_1, \ldots, p_n$ For a manufacturing operation to be considered a *match*, the machinery and fixturing must abide simultaneously to the in-progress part geometry manufacturing and size requirements.
- Number of manufacturing operations in $\boldsymbol{p}_0$

$$f_2 = m_0 \tag{10}$$

  Also, the addition of new material transfer lines should be avoided by minimizing the following objectives:
- Number of switching in $\boldsymbol{p}_0$ among available manufacturing lines $\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n$

$$f_3 = \text{switch}(\boldsymbol{p}_0, \boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n) \tag{11}$$

- Number of manufacturing operations on the same line but out of sequence:

$$f_4 = \text{out-of-seq}(\boldsymbol{p}_0, \boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_n) \tag{12}$$

  Finally, unnecessary material waste should be avoided by minimizing the following objectives:
- Stock volume

$$f_5 = \text{volume}(s_{00}) \tag{13}$$

- Volume to be machined from the stock

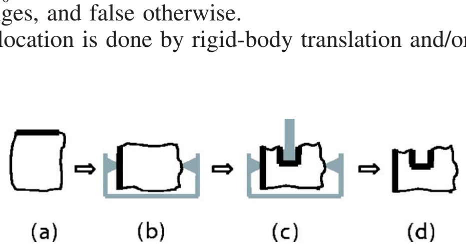

Fig. 5 Representation of the *j*th operation p_j in a production line: (*a*) incoming part s_{j-1}, (*b*) relocation r_j, (*c*) machining operation o_j, and (*d*) outgoing part $s_j=o_j[r_j(s_{j-1})]$

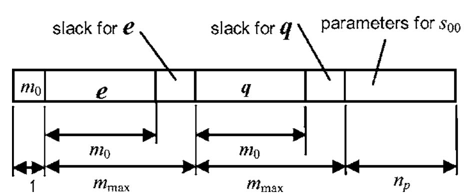

Fig. 6 Encoding of the design variables in a chromosome. Slacks for *e* and *s* are to accommodate their variations in length as specified by the value of m_0.

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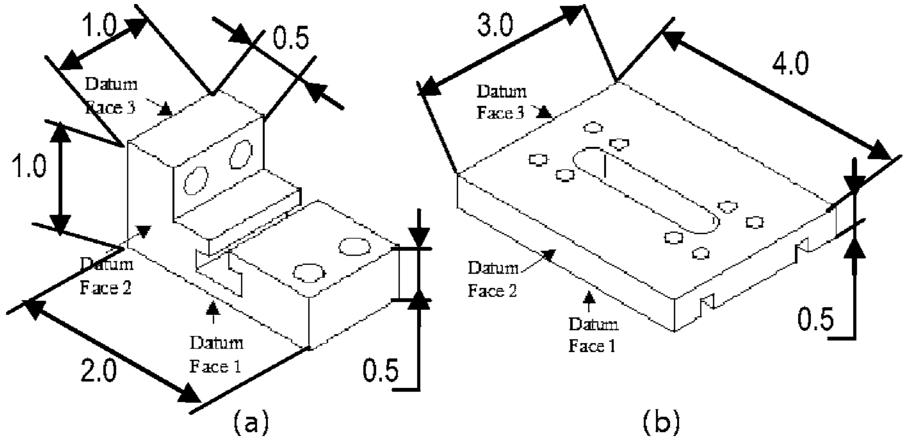

Fig. 7 Products with existing production lines: (*a*) product A and (*b*) product B. All specified dimensions are in inches.

$$f_6 = \text{volume}(s_{00}) - \text{volume}(s_{0m_0}) \quad (14)$$

Since a six-dimensional Pareto set is very difficult to interpret, the following case study aggregates some of these objectives as weighted sums, in order to reduce the dimension of the resulting Pareto set.

3.5 Optimization Algorithm. Because of a combinatorial nature of the stated optimization problem and the existence of multiple objectives, a multiobjective genetic algorithm [26,27] is utilized that can efficiently compute near-Pareto-optimal solutions of mixed discrete-continuous optimization problems. A variant of NSGA-II [26] is implemented for the following case study, which is outlined as follows:

1. Create a population Q_{main} of n_q chromosomes (an encoded representation of the design variables) and evaluate their values of objective functions.
2. Rank each chromosome c in Q_{main} according to the number of other chromosomes dominating c (rank 0 is Pareto optimal in Q_{main}). Store the chromosomes with rank 0 into set O.
3. Create an empty subpopulation Q_{new}.
4. Select two chromosomes c_i and c_j in Q_{main}.
5. Crossover c_i and c_j to generate two new chromosomes c_i' and c_j' with a certain high probability.
6. Mutate c_i' and c_j' with a certain low probability.
7. Evaluate the objective function values for c_i' and c_j' then store them in Q_{new}. If Q_{new} contains less than n_q new chromosomes, go to 4.
8. Let $Q_{\text{main}} \leftarrow Q_{\text{new}}$.
9. Delete Q_{new}.
10. Update the set O and increment the generation counter. If the generation counter has reached a prespecified number, terminate the process and return O. Otherwise, go to 3.

Figure 6 shows a schematic of the chromosome that encodes the design variables m_0, $\boldsymbol{e}$, $\boldsymbol{q}$, and s_{00} described in Sec. 3.2. It is simply a concatenation of m_0, $\boldsymbol{e}$, $\boldsymbol{q}$, and the part dimensions to represent s_{00}, with slack locations for $\boldsymbol{e}$ and $\boldsymbol{q}$ to allow the variations in length up to $m_{\max}$, an upper bound of m_0. Each segment of the chromosomes is subject to the following crossover and mutation operators:

- m_0 segment: no crossover or mutation
- $\boldsymbol{e}$ segment: substring swap and path relinking [27,28], known as effective for variable-length permutations
- $\boldsymbol{q}$ segment: uniform crossover [28] with random mutation
- s_{00} segment: heuristic and arithmetic crossovers [28] with random mutation

Upon the termination of a GA run at step 10, set O contains near Pareto optimal solutions. For each of these Pareto solutions, a local optimization is performed by examining the one-swap neighborhood of $\boldsymbol{e}$, followed by gradient search along the continuous dimensions for s_{00}, while keeping the discrete variables constant. The new solution replaces the old one only if the former dominates the latter.

To solve the case study presented bellow, a program coded in visual basic was developed to evaluate the chromosomes that the GA optimizer generated. The GA optimizer was coded in C++.

4 Case Study: Machine Bracket

4.1 Problem. This section describes a case study on the production of a new machine bracket considering two available pro-

Table 1 Machining operations for existing product A, where *fm*=face milling, *em*=end milling, *d*-2=drilling 2 holes.

Operation	Type	Feature	$E^{\min}$ (in)	$E^{\max}$ (in)
p_{11}	*fm*	Datum 1	1.0×2.2	2.0×3.3
p_{12}	*fm*	Datum 2	1.0×2.2	2.0×3.3
p_{13}	*fm*	Datum 3	0.875×1.125	0.875×1.125
p_{14}	*fm*	L-shape	1.2×2.2	2.3×3.3
p_{15}	*em*	Middle slot	1.2×2.2	2.3×3.3
p_{16}	*em*	T-slot	1.2×2.2	2.3×3.3
p_{17}	*d*-2	Hole set 1	1.2×2.2	2.3×3.3
p_{18}	*d*-2	Hole set 2	0.875×1.125	0.875×1.125

Table 2 Machining operations for existing product B, where *fm*=face milling, *em*-2=end milling 2 slots, *em*=end milling, *d*-4=drilling 4 holes, and *d*-2=drilling 2 holes

Operation	Type	Feature	$E^{\min}$ (in)	$E^{\max}$ (in)
p_{21}	*fm*	Datum 1	2.25×3.25	3.2×4.2
p_{22}	*fm*	Datum 2	0.25×1.2	3.0×4.2
p_{23}	*fm*	Datum 3	0.25×1.2	3.0×4.2
p_{24}	*em*-2	Bottom slot	2.25×3.25	3.2×4.2
p_{25}	*em*	Center slot	2.25×3.25	3.2×4.2
p_{26}	*d*-4	Hole set 1	2.25×3.25	3.2×4.2
p_{27}	*d*-4	Hole set 2	2.25×3.25	3.2×4.2

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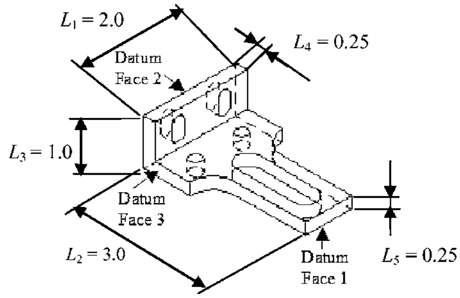

Fig. 8 Shape and main dimensions of the new product. All specified dimensions are in inches.

duction lines $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ (i.e., $n=2$) considering products A and B, respectively. The shape and main dimensions of products A and B are shown in Fig. 7. Both products are machined from a rectangular block. Tables 1 and 2 list the information on the machining operations in $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$, respectively, where type *fm*, *em*, and *d* denote face milling, end milling, and drilling, respectively.

Figure 8 shows the shape and main dimensions of the new part to be introduced. Assuming that the new product is machined from an L-shaped stock, dimensions L_1 through L_5 are adopted as the parameters to describe the stock geometry s_{00}. Table 3 shows the seven critical design features of the new product. Assuming exactly one machining operation is required to complete each design feature, the features in Table 3 can also be regarded as the minimally required machining features in MF. Table 3 also lists the compatible operation types, for which *machinable* in Eq. (3) is true. Among the machining features in Table 3, the datum faces 1–3 must be machined before the other features, namely,

$$mf_1,mf_2,mf_3 \prec mf_4,mf_5,mf_6,mf_7 \tag{15}$$

There is no other precedence assumed among the machining features.

Table 4 shows the acceptable ranges of L_1-L_5 along with their current values. Since dimensions L_1-L_5 of the L-stock may be larger than the acceptable range in Table 4 of the finished part, it is assumed there can be up to 3 additional face milling operations for each dimensions L_1-L_5 for size reduction. Since $l=7$, this yields $m_{\max}=7+3\times 5=22$.

To facilitate the interpretation of the resulting Pareto-optimal solutions, the six objectives of Eq. (9)–(14) are aggregated into three objective functions, all to be minimized,

$$f_1' = w_1 f_1 \tag{16}$$

$$f_2' = w_2 f_2 + w_3 f_3 + w_4 f_4 \tag{17}$$

$$f_3' = w_5 f_5 + w_6 f_6 \tag{18}$$

where w_i, $i=1,2,\ldots,6$ are weights. All original objectives $f_1,\ldots,f_6$ are assumed as equally important, and therefore, the weights are simply scaling factors such that the added terms have same order of magnitude. If an accurate process cost model exists, these weights can be selected to reflect their relative importance. In the example presented here, the weights used in the analysis are 1, 1, 0.25, 0.4, 0.5, and 1 for $w1-w6$, respectively.

Table 3 Critical design features of the new part, each of which corresponds to the minimally required machining feature mf_i, and the compatible operation types

Feature Id	Name	Machinable operation type
1	Datum-1	*fm*
2	Datum-2	*fm*
3	Datum-3	*fm*
4	Middle slot	*em*
5	Face slots	*em*-2
6	Side profile	*em*
7	Hole set	*d*-2

Table 4 Dimensions of the new part in Fig. 8 and their acceptable ranges

Dimension	Value (in)	Min (in)	Max (in)
L_1	2.00	2.00	2.500
L_2	3.00	3.00	3.500
L_3	1.00	1.00	1.500
L_4	0.25	0.25	0.375
L_5	0.25	0.25	0.375

4.2 Results and Discussion. Being a stochastic search algorithm, the results produced by GA are typically slightly different every time it is run. It is therefore a common practice to perform several runs for each considered problem. In this study, ten GA runs were performed. All runs used an overall crossover probability of 0.9 and mutation of 0.1. The population size and number of generations are listed in Table 5. For this study, a typical run requires ~10 min on 3.2 GHz PC. It is noted that the total number of model simulations for all the runs combined, is only a very tiny fraction of the search space, whose size is in the order of $22! \times 15^{22}$ for discrete variables.

Figure 9 shows the Pareto solutions obtained by combining the results of all ten GA runs (indicated with filled circles), and their improvements via the subsequent local search (indicated with filled squares). In Fig. 9, objectives f_1', f_2', and f_3' are normalized to the interval of $[0, 1]$.

Table 6 lists the solutions 1–4 labeled in Fig. 9, obtained by GA and local search. All solutions have the smallest possible number of operations ($m_0=l=7$). No design modification was made in solutions 1–3, whereas L_1 and L_2 are made slightly larger in solution 4 as follows:

- Solution 1 uses new operations for all machining features (hence worst in f_1'), which allows the use of a minimal size stock with no jumps between production lines or out of sequence steps (hence best in f_2').
- Solutions 2 and 3 also use a minimal size stock, and make use of some of the existing manufacturing operations. Consequently, there is one line jump in solutions 2 (from $\boldsymbol{p}_0$ to $\boldsymbol{p}_1$), and two line jumps in solution 3 (from $\boldsymbol{p}_2$ to $\boldsymbol{p}_0$, and from $\boldsymbol{p}_0$ to $\boldsymbol{p}_1$).
- Solution 4 realizes a maximum number of existing operations among all, by taking advantage of fixturing features: Larger L_1 and L_2 in the starting stock allow the in-process part geometry to be fixturable at operation p_{23}. Consequently, the final part is larger than the initial design. It is, however, considered functional since all dimensions fall within the acceptable ranges in Table 4.

It is noted that size reduction of to the original dimensions could have been achieved in solution 4 by adding one (or two) more

Table 5 Parameters for genetic algorithm for different runs

Run ID	Population size	Number of generations	Number of model simulations
1, 2	400	50	20,000
3, 4	200	80	16,000
5, 6	150	120	18,000
7, 8	200	150	30,000
9, 10	400	100	40,000

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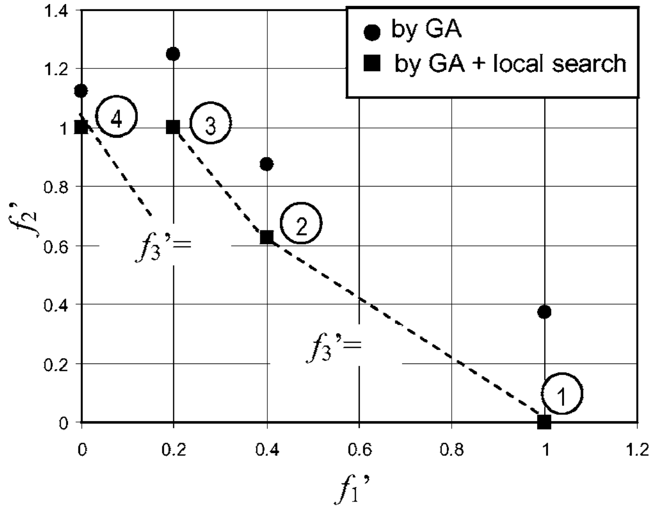

Fig. 9 Pareto solutions obtained by ten GA runs (circles) and their improvements via the subsequent local search (squares). All objectives are normalized to the interval of [0,1].

manufacturing processes at the end of the line. Although doing so would improve f_3' (stock and machined volumes), it would add too much penalty on f_2' (extra process and out of sequence step), resulting in the domination by solution 2.

5 Conclusion and Future Work

This paper presented a new design method, design for existing lines (DFEL), to reduce the cost of introducing a new product into the market via the effective utilization of existing production facilities. The method takes as inputs a nominal part design and the process information of the existing lines, and produces alternative product designs and process plans with a multiobjective genetic algorithm. A case study on a new machine bracket considering two existing production lines demonstrated a success in efficiently generating alternative product and process designs with varying utilization of existing processes.

Future work would include case studies on more complex parts and the method application to assemblies, additional analysis of process sharing, machine capacity, and production cost. Future work could also include consideration of part deformation under the manufacturing and fixturing loads, exploration of part deformation, net shape, and material adding manufacturing processes, as well as consideration of partial reconfiguration of machines and/or fixtures in the existing production lines.

Table 6 Solutions 1–4 in Fig. 9

	Solution 1	Solution 2	Solution 3	Solution 4
f_1'	1.000	0.400	0.200	0.000
f_2'	0.000	0.625	1.000	1.000
f_3'	0.000	0.000	0.000	1.000
L_1	3.00	3.00	3.00	3.25
L_2	2.00	2.00	2.00	2.25
L_3	1.00	1.00	1.00	1.00
L_4	0.25	0.25	0.25	0.25
L_5	0.25	0.25	0.25	0.25
m_0	7	7	7	7
e	1,2,3,4,5,6,7	1,2,3,6,4,5,7	3,2,1,4,5,6,7	1,2,3,4,5,6,7
p_{01}	(new)	(new)	p_{22}	(new)
p_{02}	(new)	(new)	(new)	(new)
p_{03}	(new)	(new)	(new)	p_{23}
p_{04}	(new)	(new)	(new)	p_{24}
p_{05}	(new)	p_{15}	p_{15}	p_{15}
p_{06}	(new)	p_{16}	p_{16}	p_{16}
p_{07}	(new)	p_{17}	p_{17}	p_{17}

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