How CNC Process Plans Constrain Designs of Rotational Parts: a Rigorous Approach

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ABSTRACT

The purpose of this paper is to present the use of a graph theoretic model to link designs with CNC process plans. The approach to develop process plans from design dimension trees is discussed for rotational parts. The procedures to determine datum-hierarchy tree from designs are given for direct, indirect, and pre-forming machining. This procedure is illustrated with a simple example. The approach exploits the structure of datum-hierarchy trees underlying process plans to formulate design heuristics to achieve higher machinability. The designs resulting from applying the heuristics have the fewest number of constraints on process planning and allow parts to be produced with minimal tolerance stack-ups and production costs. By using the proposed framework, it is possible to generate process plans, which are optimal in terms of minimal tolerance stacks, directly from the design specification dimensions.

Keywords: datum-hierarchy tree, process planning, tolerance stack, part variation, design heuristic.

1. INTRODUCTION

Process plans defining good manufacturing techniques are important to ensure that design specifications are met and that production is economical. Both design and manufacturing resources impose constraints on the part to be produced. A process plan that is optimal in terms of production costs may result in parts that do not meet design specifications. On the other hand, a process plan that fulfils the design specifications may not be economically viable.

It is common practice to draft process plans based on the shape of the part (i.e. machining features). Design tolerances are generally ignored in these early plans. The major disadvantage of this approach is that the developed plans have to be modified for practical production. This is because a machining strategy without consideration of design tolerances would lead to a high tolerance stack during the manufacturing process.

To overcome this problem, this paper presents an alternative approach to process planning. The paper focuses on the machining of rotational parts. The approach is based on process plans that are ideal in the sense that they have only minimal tolerances. It is argued that this process can be reversed and that design heuristics can be deduced from process plans resulting in designs with a potentially higher machinability. The essential idea is to link the design's dimensions with its ideal process plan using a graph theoretical framework. The method is applicable to all rotational part geometries, including those with prismatic features. At present the method deals only with linear dimensions, but in principle it can be extended to cover geometric dimensioning and tolerancing; the basis to do so was laid in [1-2]. The paper first introduces four classes of errors and gives an introduction on design dimension and datum-hierarchy trees. The association between the optimal datum-hierarchy trees and process plans is then discussed with respect to direct machining, indirect machining, and pre-forming. The link between machining errors and tolerances are discussed with an example. Based on the proposed approach, the work discusses on the structure of datum-hierarchy trees for formulating design heuristics to achieve higher machinability. The design dimension trees resulting from applying the heuristics are expected to constrain process plans less than others do and allow parts to be produced with minimal tolerance stack-ups and production costs.

2. ANALYSING MACHINING ERRORS

A conventional way to machine a surface is to use a surface of a design dimension to locate the part and then to machine the other. This type of machining is hereafter referred to as direct machining (relative to location). In the second approach, machining is not performed relative to a datum, but relative to a cut in the same setup (without changing the datum). S. H. Huang et al. argued that this achieves better tolerances [3]. In this approach, here referred to as indirect machining, the uncertainty of the position of the ideal datum is traded off against a tolerance stack with two machine errors. Direct machining relative to a datum or δ-machining involves setting the datum to one of the surfaces constrained by the design dimension. Prior to machining, the position of the first specified surface is measured (using a touch sensor or laser), machine-zero is reset, and then only the NC machine commences the cut. The two last-named approaches are more common to CNC machining and motivate this paper. General tolerance stacks are not considered here (see [1,3-5] for further reference).

The committed error while a certain surface is machined, is composed of the following parts:

- A predictable error that is systematic for a machine or process. Examples for this type of error are tool wear and certain dimensional inaccuracies of the machine tool. As this error is predictable, it is assumed zero hereafter.
- A setup-systematic error t_{setup}, which is common to all operations committed in the same setup. This error can be caused by an improper location and fixture problems.
- A tool-systematic error t_{tool}, which is the same for a (small number of) consecutive cuts under similar conditions (depth of cut, cutting force and speed, material removal rate, tool backlash, temperature of the tool and machine, and so on). By definition, this compromises all systematic errors except those contributing to the setup-systematic error.
- A random error t_{rand} that is different for all cuts, and is neither predictable nor systematic.

It is important to understand that the two systematic errors may be predictable, given enough resources and therefore can be eliminated. However, it is often uneconomical to do so. Furthermore, the classification is not so much concerned about the origin of the errors (in contrast to [3]), but their effect on the part's tolerances in given machining approaches. For example, tool wear includes a large predictable component and a smaller tool-systematic component (the wear is not fully predictable). It is worth noting that in tables with machining tolerances, entries are the sum of the random and the tool-systematic error. The error occurring when a surface *A* is directly machined relative to a location surface *D* is:

$$t_{\text{A-D}} = t_{\text{setup}}(D) + t_{\text{tool}}(A) + t_{\text{rand}}(A), \tag{1}$$

where $t_{\text{A-D}}$ is the tolerance of the cut resulting in surface *A*. The tolerance for δ-machining or machining from a datum *D* [6] is

$$t_{\text{A-D}} = t_{\text{tool}}(A) + t_{\text{rand}}(A), \tag{2}$$

as the setup error is eliminated by measuring the position of the datum surface. Let *A* and *B* be the finished surfaces of a design dimension. Then, the tolerance caused by machining relative to an earlier cut comprises four errors:

$$t_{\text{A-D}} = t_{\text{tool}}(A) + t_{\text{rand}}(A) + t_{\text{tool}}(A) + t_{\text{rand}}(B), \tag{3}$$

This can be preferred over direct machining from a location if t_{setup} is considerably larger than both, t_{tool} and t_{rand}. Best practices in machining seem to confirm this. However, should *A* and *B* be cut under similar conditions (the same cutting force, cutting tool, tool approach direction and so on), then $t_{\text{tool}}(A)$ is cancelled out by $t_{\text{tool}}(B)$ and the indirect machining error is reduced to

$$t_{\text{A-D}} = t_{\text{rand}}(A) + t_{\text{tool}}(A). \tag{4}$$

Figure 1 illustrates the cancellation of two tool errors (the random error is not depicted). Assumed, the two tool errors for cutting the two step surfaces are caused by an unpredicted high tool wear, which reduced the diameter of the vertical milling cutter by t_{tool}. Consequently, the two cuts are to the left of the surface that the ideal working dimensions would produce. However, both displacements are comparable and therefore the actual and the design dimensions are the same.

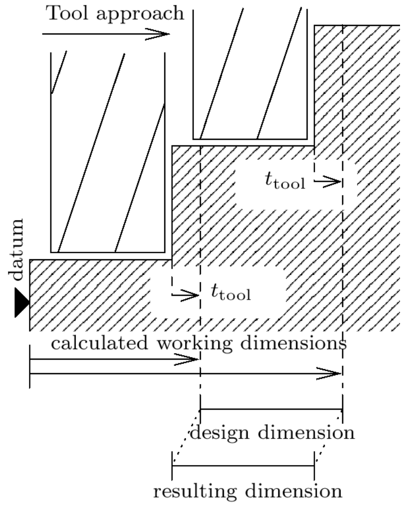

Fig. 1. Systematic tool errors may be cancelled out.

Figure 2 shows that tool errors may accumulate as well, and, as the tool error is unknown, the resulting dimension is affected by a much larger error. This demonstrates that tool-systematic errors are distinct from setup-systematic errors: the latter do not accumulate within a single setup.

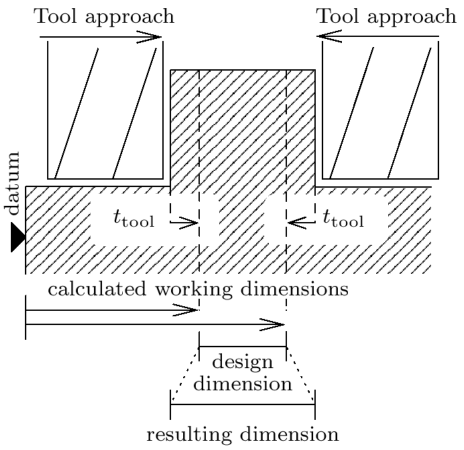

Fig. 2. Systematic tool errors can accumulate and are distinct from setup errors.

In [7], the repeatability of a turning operation - or the random error - on a NC machine is stated to be as low as 0.0038mm, which would imply that the error obtained by indirect machining can be as low as twice this amount. However, this figure certainly depends on the cutting tool, cutting speed and other parameters. Fixture errors for on a lathe were studied in [8]. Lehtihet et al. observed an average fixture error of 0.025mm for placing a part in a pneumatically activated 3-jaw chuck. In the same publication, two dimension where machined in the same setup, and the resulting dimensions from the location surface to the cut surfaces and between the cut surfaces (i.e. of direct and indirect cuts, respectively) were measured. The results showed that direct machining produces an error about 3 times higher than the indirect machining approach. But, as these figures do not apply to all processes and machining environments, the assumption $t_{\text{setup}} >> t_{\text{tool}} >> t_{\text{rand}}$ is not necessarily valid. Consequently, the optimal choice of method depends on how t_{setup}, t_{tool} and t_{rand} compare.

This paper is restricted to rotational parts and other parts with only one dimension with tolerance stacks. In rotational parts, tolerance stack-ups occur only for surfaces perpendicular to the axis of the part, only these surfaces are discussed and limited to size dimensions if not stated otherwise. Furthermore, only material removal operations, for which the datum and cut surface are indistinct stock removal sets are considered (see [9-12] for discussion of other processes).

3. DESIGN DIMENSION TREES AND DATUM–HIERARCHY TREES

A design dimension tree is the natural result of properly dimensioning a design. Figure 3 illustrates this fact: it shows on the top a part's sketch and design specification dimensions, and beneath it, the corresponding design dimensions tree. Note, that each surface has a unique label (number). Design dimension trees does not have a specified root node, in contrast to the later introduced datum-hierarchy trees.

A process plan not only includes a sequence of processes, but also the machining datums used for machining given surfaces. This results in a natural way into datum-hierarchy trees, as shown in the lower part of figure 3 (see [13] or [14]). In these trees, all machined surfaces are represented by nodes, including finished surfaces, pre-formed (rough machined) surfaces and, as tree root, a single surface of the blank. An edge of the tree corresponds to machining operations, where the parent node represents the datum surface and the child node the machined surface. Figure 3 shows an example for a part with five surfaces, which is to be made using a lathe. The node labels uniquely identify each surface created during manufacturing. For the convenience of the planer, surfaces are labelled with the stock removal set number, which is identical to the surface number in the design, followed by a 'X' and a number indicating its position in the stock removal set. The position is 1 for the first machined surface in the set (except for the surface of the blank part mentioned earlier) and is increased for each machine cut.

Datum-hierarchy trees have, in contrast to design dimension trees, a distinct root. For example, in figure 3, surface **1X1** is the root, which must be a surface of the blank in contrast to the other surfaces. Edges symbolise machining operations. The surface at the origin of an edge is the datum surface, whereas the surface it points to is the newly created surface. In the example, the surface **1X2** is the datum surface for the machining operation creating surfaces **2X1**, **3X1** and **4X1**. Although the design dimension tree's shape is not necessarily (well) reflected in the datum-hierarchy tree, a rule of thumb is that the more this is true, the smaller is the number of machine cuts per tolerance stack. Furthermore, several efficiency measures of process plans can be defined based on the shape of the datum-hierarchy tree [15]. As a matter of fact, in the absence of operations that use a surface as datum to machine it (e.g. plating, heat treatment or polishing), the optimal datum-hierarchy tree possesses as finishing subtree that is isomorphic to the design dimension tree and the isomorphism respects the correspondence of design surfaces and finished surfaces.

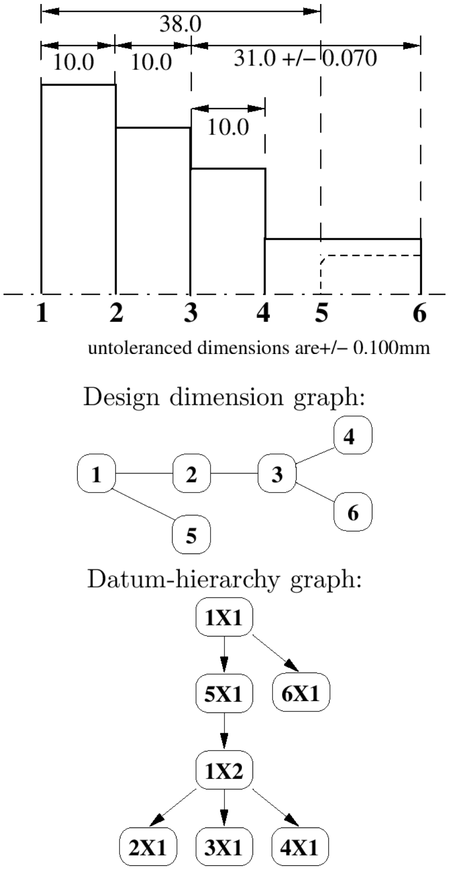

Fig. 3: A design, its design dimension tree and a possible datum-hierarchy graph.

In rotational parts, tolerance stack-ups occur only for surfaces perpendicular to the axis of the part. This paper focuses on rotational parts and only material removal operations, for which the datum and cut surfaces are in distinct stock removal sets are considered.

4. OPTIMAL DATUM-HIERARCHY TREES AND PROCESS PLANS

Any process plan possesses a unique representation as a datum-hierarchy tree, which may be shared by several plans. With respect to tolerances, these trees contain all necessary information to calculate tolerances of the machined part. On the other hand, they only constrain but not determine the sequences of processes in a plan: a surface can be machined only if the datum surface exists. A process planner may therefore decide to plan in two steps: first, to build a datum-hierarchy tree that fulfils the tolerance specifications; second, to sequence the machine cuts. Clearly, general constraints on machine cuts and a given datum-hierarchy tree may contradict each other, or a given datum-hierarchy may result in inefficient process plans. The next section presents a procedure to determine datum-hierarchy tree from given designs for direct and δ-machining.

4.1. The Optimal Datum-hierarchy Tree for Direct and δ-machining

Datum-hierarchy trees for direct and δ-machining that are optimal with respect to part tolerances, though sometimes infeasible, can be obtained using the following steps:

1. For each surface of the part, determine the number of pre-forming machine cuts.
2. Chose a pre-forming machine cut, which produces a suitable location surface for following machine operations. This surface is hereafter called the initial qualified surface.
3. Determine a surface of the blank part to serve as datum and location surface to machine the initial qualified surface. Make it the root of the datum-hierarchy tree and add the cut for the initial qualifying surface.
4. For each of the corresponding pre-formed surfaces, if such a cut is possible, add an edge from the initial qualified surface or the root to the respective surfaces. Note that the use of root of the datum-hierarchy tree as a datum or location surface for other than the initial qualifying cut is often regarded as bad practice.
5. For the remaining pre-formed surfaces, add a machine cut using any of the surfaces in the tree as a datum (while aiming at using a minimal number of datum surfaces and avoiding the root for the sake of best practices). Repeat if necessary.
6. Extract the design dimension tree and re-label to nodes such that the cut numbers follow the numbers of the surfaces already present in the tree. This creates the so-called finishing subtree.
7. Chose a suitable pair of surfaces: a datum surface among the pre-forming cuts and the first surface in the finishing subtree to be machined (the root of the finishing subtree). Then add an edge linking the two surfaces.
8. Orient the edges in the finishing subtree such that they point away from its root.

The result is a datum-hierarchy tree suitable for direct or δ-machining. All tolerance stacks are minimal in the sense that they include only the error of one machine cut. Figure 4 shows the outcomes of the various steps.

Computationally, this procedure is quite well behaved: only the choice of the roots of the datum-hierarchy and the finishing subtree are somewhat critical. The approach can be extended to other types processes such as plating, strip-plating or heat treatment - though the addition of plating and heat treatment require a modification of the algorithm (compare [9,11]).

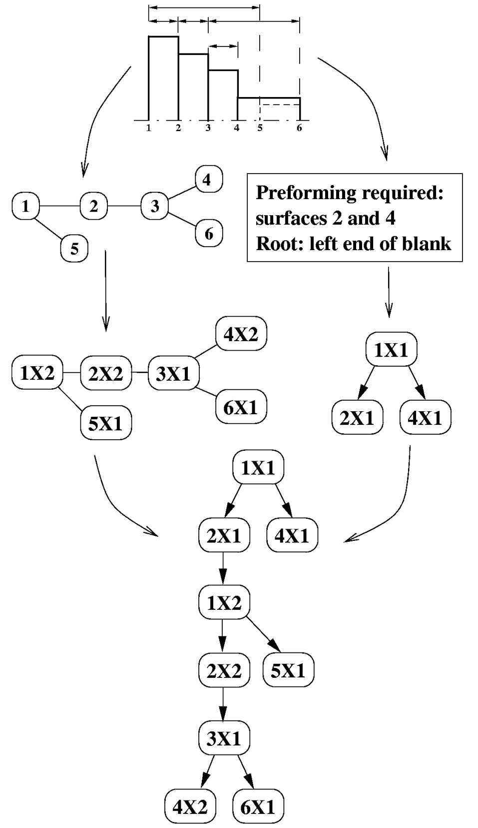

Fig. 4: Example from design to datum-hierarchy tree.

4.2. Modifying the Datum-hierarchy Tree for Indirect Machining

The second part of the procedure changes the finishing subtree such that some direct or δ-machine cuts are transformed into indirect cuts. This may be necessary to achieve a feasible and economical process plan, though this alone may not be sufficient. The following steps are repeated until the datum-hierarchy is satisfactory:

1. Chose a direct, undesired, finishing machine cut with datum surface *D* and cut surface *C*, where
   (a) *D* is not the root of the finishing subtree (this may be relaxed if the tolerance for machining this surface is sufficiently low).
   (b) *C* and *D* can be machined in the same setup (i.e. they can be produced with the same systematic error).
   (c) *C* never was a datum surface of an indirect cut.
   (d) *D* is not the result of an indirect cut.
2. Change the datum of the cut *C* to the datum used to machine *D*. The cut producing *C* is then an indirect cut.

The restrictions on the modifications enforce that no tolerance stacks besides those in indirect machine cuts are build up. The outcome depends somewhat on the sequence in which cuts are selected. Backtracking on previous choices may be necessary to reach a good result. However, as the number of undesired machine cuts using surfaces as datums produced by other undesired machine cuts can be expected to be small, this will cause only little computational load.

Figure 5A shows the finishing subtree of the original datum-hierarchy tree in figure 3, and figures 5B and 5C show the modified trees. Dotted edges in the trees indicate immutable machine cuts as defined in the algorithm. In a process plan conform to the modified tree in figure 5B, the cuts producing surfaces **4X2** and **6X1** are indirect, but not **3X1**. In figure 5C only **3X1** is indirect. In either case, no further modifications are possible.

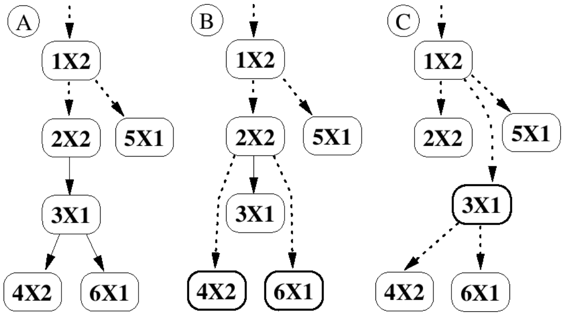

Fig. 5: Changing the datum-hierarchy tree.

4.3. Optimising Pre-forming Machining

The datum surfaces of pre-forming machine cuts may be changed to any pre-formed or finished surface. This does not impact on the resulting tolerances, as long as the constraints resulting from the datum-hierarchy tree do not contradict other constraints on the machining sequence and the pre-forming operations do not represent a risk to the quality of the finished surfaces. This may greatly improve the machinability of the part as it allows for less setups. An evolutionary algorithm as presented in [4] can achieve this easily.

4.4. Determining Tolerances

Once the systematic and random errors have been identified, the constraints can be analysed and tolerances balanced. The constraints on the tolerances can be determined as follows:

1. Identify the finished surfaces *A* and *B* corresponding to the design tolerance t_i.
2. If *A* is the datum surface for the machine cut producing surface *B*,
   (a) Decide whether direct or δ-machining should be used.

   (b) If the decision falls on direct machining, add the constraint $t_{setup}(A)+t_{tool}(B)+t_{rand}(B) \le t_i$.
   (c) For δ-machining, add $t_{tool}(B)+t_{rand}(B)\le t_i$.
3. Correspondingly, if B is the datum for machining surface A.
4. If the dimension is cut indirectly and both cuts are performed under similar conditions according to section 4.2, add $t_{rand}(A)+t_{rand}(B) \le t_i$,.
5. Otherwise, add $t_{tool}(A)+t_{rand}(A)+t_{tool}(B)+t_{rand}(B) \le t_i$.

The obtained set of inequalities is then augmented by constraints from the machining environment and solved. This is illustrated by the means of an example in section 4.5. In industrial practice, somewhat more sophisticated, automated approaches to tolerance synthesis are more appropriate. Most of these approaches for part manufacturing, possibly with minor modifications, can be used for this task; [16] provides a comprehensive review.

4.5. An Example: from Design to Process Plan

Consider the part in figure 3. Assume that t_{rand}=0.005mm and t_{setup}=0.050mm are equal for all operations. The cutting speed can be adjusted such that t_{tool} is 0.010mm, 0.020mm, 0.030mm, 0.050mm or 0.080mm. The part is fixed using a chuck for the pre-forming and finishing operations, as the use of centres is not possible given the part's shape.

The finishing subtree is as given in figure 5A. Furthermore, suppose that direct machining from a location is used whenever possible (i.e. for surfaces **5X1** and **3X1)** and δ-machining for the others. Then, the tolerance stacks for design dimensions **1-2** and **1-5** comprise the two systematic and the random error (equations (5) and (6)), whereas the others exclude the setup-systematic error (equations (7) to (9)).

$$t_{\mathbf{1\text{-}2}} \ge t_{setup}(\mathbf{1X2}) + t_{tool}(\mathbf{2X2}) + t_{rand}(\mathbf{2X2}) \tag{5}$$
$$t_{\mathbf{1\text{-}5}} \ge t_{setup}(\mathbf{1X2}) + t_{tool}(\mathbf{5X1}) + t_{rand}(\mathbf{5X1}) \tag{6}$$
$$t_{\mathbf{2\text{-}3}} \ge t_{tool}(\mathbf{3X1}) + t_{rand}(\mathbf{3X1}) \tag{7}$$
$$t_{\mathbf{3\text{-}4}} \ge t_{tool}(\mathbf{4X2}) + t_{rand}(\mathbf{4X2}) \tag{8}$$
$$t_{\mathbf{3\text{-}6}} \ge t_{tool}(\mathbf{6X1}) + t_{rand}(\mathbf{6X1}) \tag{9}$$

Replacing the variables for the random and setup systematic errors as well as the design specifications, these constraints result in the following constraints:

$$0.045\text{mm} \ge t_{tool}(\mathbf{2X2}) \tag{10}$$
$$0.045\text{mm} \ge t_{tool}(\mathbf{5X1}) \tag{11}$$
$$0.095\text{mm} \ge t_{tool}(\mathbf{3X1}) \tag{12}$$
$$0.095\text{mm} \ge t_{tool}(\mathbf{4X2}) \tag{13}$$
$$0.065\text{mm} \ge t_{tool}(\mathbf{6X1}) \tag{14}$$

Consequently, $t_{tool}(\mathbf{2X2})=t_{tool}(\mathbf{5X1})$=0.030mm, $t_{tool}(\mathbf{3X1})$= $t_{tool}(\mathbf{4X2})$=0.080mm and $t_{tool}(\mathbf{6X1})$=0.050mm. The resul-ting part tolerances are: $t_{\mathbf{1\text{-}2}}=t_{\mathbf{1\text{-}5}}=t_{\mathbf{2\text{-}3}}=t_{\mathbf{3\text{-}4}}$=0.085mm and $t_{\mathbf{3\text{-}4}}$ =0.055mm. If δ-machining is used for **2X2**, $t_{tool}(\mathbf{2X2})$ can be increased to 0.080mm, resulting in the same part tolerances. Surface **5X1** cannot be δ-machined, given the shape of the part and the choice of the root for the finishing subtree.

In the case that the finishing subtree is as shown in figure 5B, the tolerance stack for design dimension **3**-**4** is affected by the random errors occurring while cutting surfaces **3X1** and **4X2**, and correspondingly, dimension **3**-**6** is affected by the random errors of **3X1** and **6X1**. For the reasons given in the earlier example, **3X1** is machined using the δ-machining approach, surfaces **2X2** and **5X1** using the direct machining. Then, a process plan conform to the finishing subtree in figure 5B fulfils the design constraints if equations (5) to (7) as well as (15) and (16) are fulfilled.

$$t_{\mathbf{3\text{-}4}} \ge t_{rand}(\mathbf{3X1}) + t_{rand}(\mathbf{4X2}) \tag{15}$$
$$t_{\mathbf{3\text{-}6}} \ge t_{rand}(\mathbf{3X1}) + t_{rand}(\mathbf{6X1}) \tag{16}$$

Which, for the given values for the design tolerances, the random and setup error, results into the following constraints:

$$0.100\text{mm} \ge 0.010\text{mm} \tag{17}$$
$$0.070\text{mm} \ge 0.010\text{mm} \tag{18}$$

Under the given assumptions, equations (17) and (18) can be interpreted in the sense that, as long as surfaces **4X2** and **6X1** are machined under the same conditions as **3X1**, the actual precision to which these surfaces are cut, is of no importance for the tolerances of dimensions **3**-**4** and **3**-**6**. Thus, $t_{tool}(\mathbf{4X2}) = t_{tool}(\mathbf{6X1})$ = 0.080mm. Furthermore, dimensions **3**-**4** and **3**-**6** will have a tolerance of 0.010mm. Clearly, the latter is too optimistic. The weak spot of the example lies in its simplicity: the random error is simplified to a constant that is independent of the cutting speed. However, if in the example the random error for turning a surface with a tool-systematic error of 0.080mm is below 0.035mm, the given design specifications are achieved. The example shows, that depending on the relative magnitude of the random and tool-systematic error, the δ-machining of indirect machining approach may achieve a higher precision.

5. DESIGN HEURISTICS

Although having been the only consideration until here, tolerances are not the only machinability criteria. Best machining practices, constraints on the machining sequence arising from the shape of a part, and the shop floor may disallow direct, indirect, δ-machine cuts or even all approaches. Consequently, such constraints should be taken into consideration when the datum-hierarchy tree is modified according to the procedure given in section 4.2. Furthermore, the planner must consider at the same time the efficiency of the process plan - an often very complex task, which is well beyond full automation using current technology. However, the planning process can be at least semi-automated as shown in [4-5]. On the other hand, modifications to the ideal datum-hierarchy tree derived from the design are rather limited if tolerance stacks other than those in indirect cuts are to be avoided. Therefore, the design should ideally already be in accordance to the constraints. This naturally leads to the heuristics for designs based on manufacturability described below.

Given the approach described in section 4.1, it is obvious that the datum-hierarchy tree of an efficient process plan must be very similar to a part's design dimension tree. Consequently, if the functionality of the part permits, the design dimension tree should accommodate for this (see [17]). A first approach in this sense is to aim for trees, which allow as many process sequence alternatives as possible. This is achieved by aiming at compact design dimension trees (with a high branching factor [17]).

A more specific rule is deduced from the best practice: product critical surfaces should be machined late, as stated in [18]. This implies that they should be leaves of the datum-hierarchy tree, as all surfaces, which use them directly or indirectly as datum must be machined later. Consequently, if the corresponding dimension is to be machined directly or using δ-machining, product critical surfaces must be leaves in the design dimension tree. However, if indirect machining is permissible, this constraint can be relaxed somewhat: assumed, the product critical surface C is not a leaf in the design dimension tree and uses surface D as datum in the finishing subtree. Furthermore, assume that the surfaces B_i use C as datum. Then, surface C is converted into a leaf by changing the datum for all B_i to surface D, implying that surfaces B_i are then machined indirectly. This requires however, that the constraints given in section 4.2 are fulfilled and the datum-hierarchy tree can be translated into a valid and efficient process plan. As further modifications to the datum-hierarchy tree are restricted, the critical surface C and the surfaces using the B_i as datum must be cut directly or using the δ-approach, as otherwise some tolerance stacks become excessively large. For example, assume that surfaces **3** and **4** in figure 3 are product critical and the datum-hierarchy tree is as depicted in figure 4. Then, setting C=**3X1**, D=**2x2**, B_1=**4x2** and B_2=**6X1** results in the situation described above. In consequence, the following rule can be deduced:

- A product critical surface is preferably a leaf in the design dimension tree, or
- If not, and the surface is linked via a design dimension to another product critical surface, either should be a leaf.

The next rule considers part shapes and the machining environment. Suppose either requires that two design dimensions A-B and B-C have to be machined indirectly. Possible reasons are that work piece control is insufficient if the part is located using any of these surfaces, location on another surface is necessary to achieve given geometric tolerances or the shape disallows direct machining. On the other hand, during the construction of the datum-hierarchy tree according to the procedure in section 4.1, the following datum hierarchies can occur:

1. A is datum for B and B is datum for C,
2. C is datum for B and B is datum for A, or
3. B is datum for A and C. An attempt to modify the trees obtained in options 1. and 2. according to the procedure in section 4.2 reveals that it is impossible to change both dimensions.

Only option 3. allows this. Consequently:

- It should be avoided to have two design dimensions that must be machined indirectly joined at the same surface, or
- If this is not practicable, to make sure that the surface B joining them is linked to yet another surface that can be datum for the indirectly machining A and C.

6. CONCLUSION

An alternative approach to process planning for machining rotational parts using three different CNC machining approaches is presented. It exploits the relationships between design specification dimensions and process plans. Design dimensions are directly correlated with a datum-hierarchy tree, which is a by-product of conventional process planning. The proposed approach uses the design dimensions as the starting point to generate datum-hierarchy trees.

Based on the lemma that a datum-hierarchy tree must show certain similarities with the way dimension are specified in a design, in order to obtain an efficient process plan, design heuristics are proposed. These heuristics take, for example, into account that product critical surfaces should be machined late and that a part's shape disallow direct machining of some design dimensions.

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