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On the Automatic Generation of Set-Ups Given a Feature-Based Design Representation

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Summary:

A design methodology has been developed which takes manufacturing restrictions into account in the geometric design phase. This has been accomplished by defining Manufacturable design transformations. A Manufacturable design transformation is a design operation which has one or more manufacturing operations as counterpart. The applied design operations are recorded in a Design Tree which is an integral part of the product model. Process planning converts this Design Tree, given the available manufacturing machines, fixturing tools and machining tools, into a Manufacturing Tree. The Manufacturing Tree consists of one or more set-ups with per set-up a collection of basic manufacturing operations. This paper deals with the automatic generation of set-ups given a design representation based on Manufacturable design transformations. The main advantage of this approach is a faster generation of set-ups. Furthermore, the generated set-ups and the collection of basic manufacturing operations per set-up can be used for automatic generation of NC code.

Keywords: Optimisation, process-planning, computer integrated manufacturing (CIM).

1. Introduction.

The current market requires a greater product range, shorter production runs, 'right first time' products and a reduction in throughput time. A mean to accomplish these requirements is integrating design, process planning and manufacturing. This paper deals with one aspect of integrating design and manufacturing namely the automatic generation of set-ups given a feature-based design description, as implemented in the *IDM* (Integration of Design and Manufacturing) software package which is being developed at the Eindhoven University of Technology [Del 89, 91].

2. The basics of *IDM*.

The purpose of design is to generate an unambiguous and complete representation of the product to be manufactured. The representation must lead to a product that can be manufactured and that realises the desired product functionality. The first requirement necessitates the enforcement of manufacturing restrictions while designing. The second requirement necessitates design validation approaches such as simulation or Finite Elements Analysis methods. The second requirement will not be dealt with any further in this paper.

Two main approaches can be used in order to be able to check for Manufacturability while designing. The first one is called 'feature recognition'. With this approach the completed design is checked for the presence of manufacturing features. The other approach is very often called 'feature-based design'. This approach allows to check the design in progress continuously for Manufacturability. It is based on the assumption that only design operations that are in principle Manufacturable, are allowed to be applied to a design in progress. The latter approach is being used for the research described in this paper.
The approach developed is based on a hybrid solid modeller. The design representation consists of a combination of a so-called Boundary representation and a Constructive Solid Geometry representation. The first representation is a method for describing a physical solid model in terms of its topological boundary. The Constructive Solid Geometry representation is based on the concept that a physical solid object can be represented as a series of design transformations, such a subtract-solid, being applied to various simpler solids.
These design transformations are recorded in and represented as a CSG tree of design operations, the so-called *Design Tree*. The design transformations defined for this approach are in principal Manufacturable design operations. These design transformations are called: *apply a Manufacturable Object*, or *ApplyMO* for short. The *Manufacturable Object* (*MO*) part of the design operation is an in principle Manufacturable shape. A *Manufacturable Object* consists of a combination of one or more Manufacturable shapes.

While applying each design operation the Manufacturability of the design is being checked. First of all the Manufacturability of the design operation being applied is checked by generating a so-called *micro process plan*. Secondly, the Manufacturability of the design operation is checked for reachability. This is carried out in order to make sure that the *ApplyMO* can be manufactured by the manufacturing machine and cutting tools without undesired removal of material or collision. The third way of Manufacturability checking of design operations is checking whether the specified tolerances and surface roughnesses can be achieved with the available set of manufacturing machines and tools.
As mentioned before the first Manufacturability check generates a *micro process plan*. A *micro process plan* is a sequence of basic manufacturing processes which, when combined, are able to manufacture the *ApplyMO* design operation according to its specification. Besides internal parameters of the *MO*, such as surface roughness or length diameter ratio, the micro process planning process takes relations with other *ApplyMO* design operations such as position and orientation tolerances into account while generating a *micro process plan* for this *ApplyMO*. Furthermore, the manufacturing machine models, which are models of the available machine types, are consulted to check if the needed manufacturing processes, as generated by the micro process planning, can be used. For the generation of a *micro process plan* manufacturing logic is being used.
The second way of checking Manufacturability, the reachability check, uses *tool(s)volumes*. A *tool(s)volume* is the volume generated by the movements of the complete tool(s) while manufacturing the *Manufacturable Object* [Del 91]. These *tool(s)volumes* can also be used, as will be shown, for the generation of precedence graphs for set-ups.

3. *Design Tree*.

All applied design operations are recorded in a kind of CSG tree called the *Design Tree*. The *Design Tree* records the initial state and all design operations successively applied to the design as shown in *figure 1*. The initial state also contains the specified tolerances, such as planarity and perpendicularity. For each design operation such as *ApplyMO*, the *Design Tree* contains information like nominal shapes, tolerances, surface-roughnesses, nominal position, nominal orientation, but also position- and orientation tolerances. The tolerance information is split into two parts; *internal tolerances* and *external tolerances*. *Internal tolerances* are tolerances on the nominal shape of the *MO*. *External tolerances* are position and orientation tolerances relative to a reference item such as an edge, vertex or face of another *ApplyMO* or an edge, vertex or face of the current intermediate design state. *External tolerances* are modelled using so-called Implicit Locatings in the *IDM* system. The tolerances and their reference items are of special importance for the automatic generation of set-ups. Tolerance relation graphs can easily be generated given the *Design Tree*, as will be shown later on.

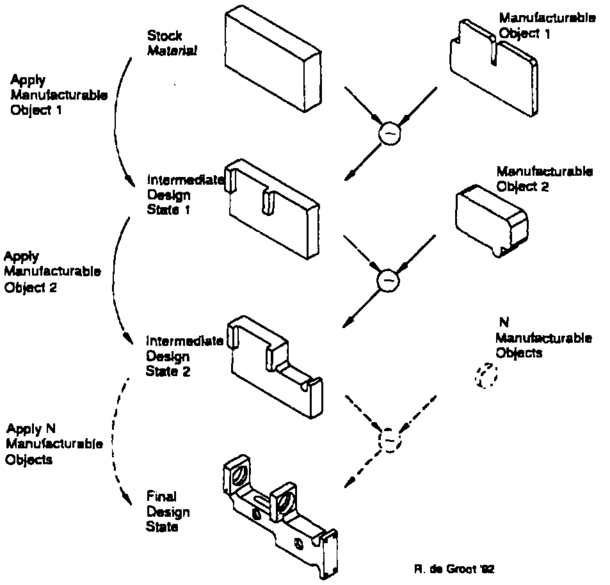

Figure 1: *Design Tree*

4. Mapping from *Design Tree* onto a *Manufacturing Tree*.

The *Design Tree* contains, in combination with the description of the manufacturing resources, enough information to manufacture the design. The information however has to be reordered, made accessible and usable for manufacturing. In terms of the *IDM* system a *Manufacturing Tree* has to be generated. In conventional terminology a process plan has to be generated. Some of the steps that have to be carried out in conventional process planning, such as part understanding, process selection and micro process planning [Fer 90], are left out here, as the output of these processes has already been recorded or generated in the design phase of *IDM*. The mapping of the *Design Tree* onto a *Manufacturing Tree* that remains, consists of five dependent processes:

- machine tool type selection,
- set-up planning,
- fixture planning,
- manufacturing operation sequencing, and
- output preparation and generation.

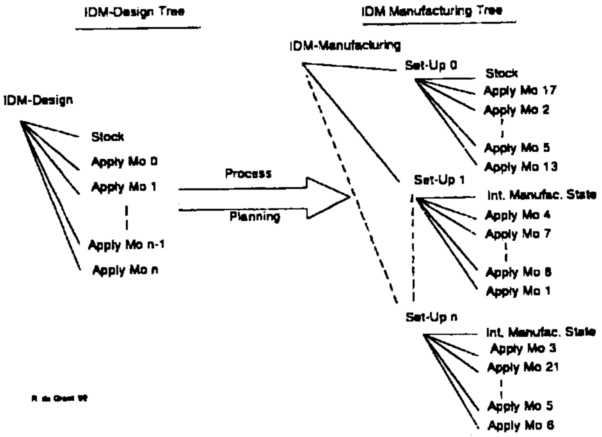

Figure 2: *Design-Tree* to *Manufacturing-Tree* mapping.

The first process in the *IDM* process planning mentioned is the selecting of the candidate sets of machine tool for each operation. The next process groups all *ApplyMOs* into one or more set-ups. A set-up is the description of the position and orientation of the raw stock material or pre-machined workpiece on the selected manufacturing machine plus the *ApplyMOs* to be machined in that alignment. When all *ApplyMOs* have been assigned to set-ups the manufacturing processes will be rescheduled within the set-up.

Subsequently, a fixture has to be designed for every set-up. The fixture must perform the functions of positioning, supporting and clamping the part in a predefined position and orientation and keeping it in that position and orientation under the forces of the manufacturing process. Deformations of the workpiece due to manufacturing- and fixturing forces have to be taken into account while generating the set-up.

Every *ApplyMO* will be machined by means of one or more manufacturing processes. The manufacturing processes have already been determined in the design phase, by the micro process planning. As soon as the lay-out of the fixtures has been defined or changed, the manufacturing processes will be rescheduled within the set-up. For this rescheduling several criteria can be applied, such as tool change minimisation, tool travel minimisation or minimisation of tool axes changes.

Finally, all the data needed to generate the NC-code are prepared to be sent to a post-processor. Sketches of the fixtures are made available, a list of the required tools and the specification of the raw stock material are generated.

The processes mentioned are not necessarily executed sequentially. To get optimal results feedback loops are needed.

5. Set-up planning.

In the *IDM* system a set-up is considered to be a data-structure consisting of:

- The configuration of the translation, rotation and machining axes of the candidate manufacturing machine.
- The initial shape and dimensions of the stock or pre-machined workpiece.
- The orientation of the stock or pre-machined workpiece on the candidate manufacturing machine.
- The group of *ApplyMOs* that have to be machined in this set-up.
- The precedence- and tolerance relations of the *ApplyMOs* that have to be machined in the set-up.

5.1. Characteristics.

Some of the characteristics of the designed part need special attention when planning a set-up. All of these characteristics are either represented in the *Design Tree* or can be generated from the data in the *Design Tree*. Two of these characteristics will be discussed here; the required accuracy of the geometry and the reachability of the *ApplyMO* operations with respect to the cutting tools.

Tolerances, to start with, greatly influence the distribution of the *ApplyMOs* over individual set-ups. As explained earlier there are two types of tolerances in the *IDM* system: *internal tolerances* and *external tolerances*. Although it may seem unusual, set-up planning is not influenced by *internal tolerances*. Deviations in the orientation or position of the workpiece on the manufacturing machine do not influence the quality of, for instance, the surface properties of an *MO*. In contrast to *internal tolerances*, *external tolerances* play a major role in planning set-ups. An *external tolerance* is defined in the *IDM* system as the maximum deviation on the spatial relation, either translational or rotational, between (entities of) two *ApplyMOs*. Any error in orientation or position of the workpiece during machining causes a deviation on the defined spatial relation, which might exceed the tolerance field. However, modern NC-controlled manufacturing machines are able to reduce the influence of mis-positioning by means of an off-set on the programmed workpiece reference point. Reduction of mis-orientation, on the other hand, cannot be done by NC-control. Therefore, the required workpiece position and orientation accuracy on the manufacturing machine base plate are determined by a smallest allowable deviation on rotation [Boe 89].

Preferably a tolerance relation between two *ApplyMOs* leads to both *ApplyMOs* being put in the same set-up. Sometimes this cannot be realised for instance due to the reach of the candidate manufacturing machine. So the tolerance relation must be broken when this machine will be used. When it concerns an accurate tolerance relation this means that the design specification will not be achievable or will only be achievable at higher cost, due to the effort needed to generate the accurate orientation of the workpiece relative to the machine tool. *ApplyMOs*, belonging to tolerance relations most sensitive to workpiece misorientation, are preferably planned together in one set-up. To be able to discriminate sensitive from less sensitive tolerance relations, the tolerance relations in the *IDM* system are expressed in terms of maximum allowable workpiece rotation.

The second characteristic of the designed part, which has to be mentioned here, is the reachability of the individual *ApplyMOs*. When machining each individual *ApplyMO* , it must be reachable for the machine tools in order to prevent tool - and workpiece damage. Reachability during manufacturing is analogous with availability while set-up planning. Availability of *ApplyMO* operations for set-up planning is represented, as will be shown, by precedence graphs.

Reachability of an *ApplyMO* is mainly influenced by four factors. First of all the shape of the *MO* influences the accessibility of an *ApplyMO* operation for machining tools. The position and orientation of the *ApplyMO* with respect to other *ApplyMOs* or the current intermediate manufacturing state also effects its reachability [Del 91]. The position and orientation reach of the machine tool is another major factor. The latter is determined by its geometrical configuration consisting of:

- The number of linear axes (mostly 3).
- The configuration of the linear axes (C-frame, arch-frame).
- The number of rotation axes (0,1,2,..).
- The configuration of the rotation axes.
- The number and orientation of the tool spindles.
- The orientation of the machine table (horizontal, vertical)

A large positional - and orientational reach often reduces the number of set-ups needed to machine the workpiece and therefore the need to break tolerance relations of *ApplyMOs*.

Lastly the reachability of *ApplyMOs* is influenced by the shape and size of the manufacturing tools. When the shape and size of manufacturing tools are not tuned to the shape, size, position and orientation of the *ApplyMO* or the intermediate manufacturing state this leads to tool-workpiece collisions. [Del 91].

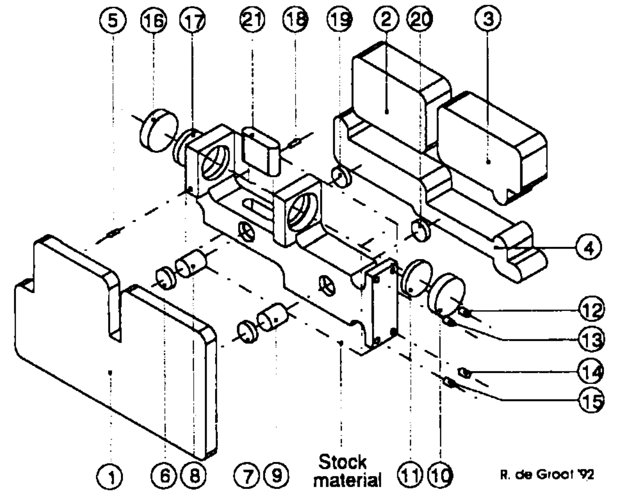

Figure 3: Exploded view bearing seat.

5.2. Inputs to the set-up planning process.

The data needed for planning set-ups will be described in the next paragraphs. The data are either generated by the *IDM* system or have been entered while designing the product. First of all the *ApplyMO* operations. The designer instantiates the *ApplyMO* operation by specifying its geometry-parameters (e.g., length width, depth, etc.) and its position and orientation. Every parameter mentioned above holds a tolerance, which is defaulted by the system or is specified by the designer. The order in which the *ApplyMOs* are instantiated is recorded in the *Design Tree* (see figure 1).

Figure 3 shows a part, modelled with the *IDM* system. The block, which enfolds the modelled part (dotted lines), is the stock material. The indexed volumes are the shapes of the *ApplyMOs*.
As mentioned before, an *ApplyMO* consists of a functional geometry and one or more *tool(s)volumes*. Because most of the MOs available in the *IDM* system are 2 1/2 D shapes, the number of machining directions is at least two. At least one of the *tool(s)volumes* should not interfere with the previous Intermediate Design State to be sure there is at least one direction available from which the *ApplyMO* can be machined without undesired removal of material. Even if, at a later stage of part-design, the removal of material releases a previously restricted machining direction the valid machining direction vectors are automatically updated. While set-up planning the *IDM* system records the currently valid machining direction vectors of the *ApplyMOs* .

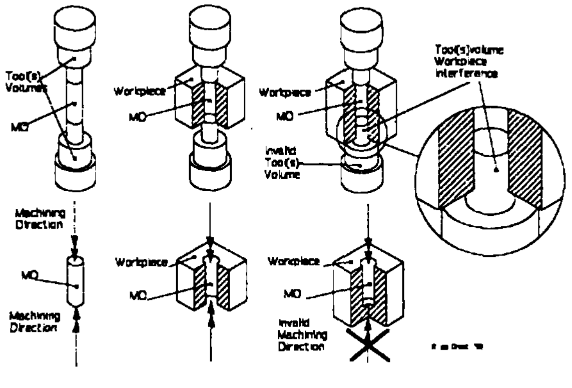

Figure 4: Machining direction vector.

During set-up planning every *ApplyMO* needs to be assigned to a set-up. For instance due to optimisation reasons very often *ApplyMOs* aren't machined in the sequence they were applied in the design phase. Nevertheless while set-up planning, like in the design phase, the necessity remains that at least one *tool(s)volume* should not interfere with the previous manufacturing state in order to prevent tool-workpiece collisions while manufacturing. The order in which the *ApplyMOs* become reachable for machining, and therefore the order in which they become available for set-up planning, is recorded in a precedence graph. During set-up planning the precedence graph is continuously updated by the *IDM* system. For a better understanding of these precedence graphs two examples are included (see also the figures 5 and 6).

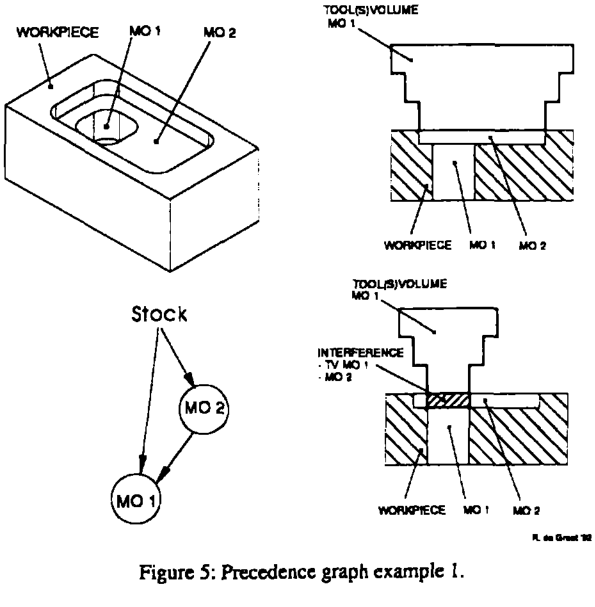

Figure 5: Precedence graph example 1.

Example 1: The workpiece in figure 5 consists of stock material and two *ApplyMOs*; *ApplyMO*1 and *ApplyMO*2. *ApplyMO*2 has only one valid machining direction. The *tool(s)volume*, that belongs to the valid approach direction of *ApplyMO*2, doesn't coincide with the geometry of any other *ApplyMO*, therefore *ApplyMO*2 is available for set-up planning straight away. *ApplyMO*1 also has an approach direction which doesn't coincide with the geometry of any other *ApplyMO* so again this *ApplyMO* is available for set-up planning. *ApplyMO*1 has another valid approach direction. As *ApplyMO*1 and *ApplyMO*2 share equal machining directions and the corresponding *tool(s)volume* of *ApplyMO*1 coincides with the geometry of *ApplyMO*2, *ApplyMO*1 is only available for planning from this direction after *ApplyMO*2 has been planned.
The convention is that in precedence graphs an arrow points from *ApplyMO*i to *ApplyMO*j, if *ApplyMO*j is reachable after machining of *ApplyMO*i. So *ApplyMO*i (in figure 5 *ApplyMO*2) is the parent of *ApplyMO*j (in the figure *ApplyMO*1). The root of the graph is the stock, as it has no parents. The leafs of the precedence graph are *ApplyMOs* with no children. The figure shows that the number of parents of an *ApplyMO* in the precedence graph equals the number of valid machining direction vectors of that *ApplyMO* .

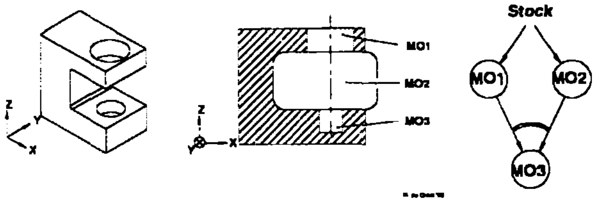

Figure 6: Precedence graph example 2.

Example 2: Figure 6 depicts another precedence graph. *ApplyMO*1 and *ApplyMO*3 can be machined along the z-axis and *ApplyMO*2 along the y-axis. The single valid *tool(s)volume* of *ApplyMO*3 coincides with the geometry of *ApplyMO*1 and *ApplyMO*2. *ApplyMO*3 and *ApplyMO*2 however, do not share the same machining direction. Machining *ApplyMO*2 is not sufficient to render *ApplyMO*3 reachable and thus plannable. *ApplyMO*1 on the other hand has the same machining direction as *ApplyMO*3 and the *tool(s)volume* of *ApplyMO*3 coincides with the geometry of *ApplyMO*1. The geometry of *ApplyMO*1 and *ApplyMO*3 however are not in contact with each other. So, both *ApplyMO*1 and *ApplyMO*2 need to be planned before *ApplyMO*3 in order to make *ApplyMO*3 available for set-up planning. This is represented in the precedence graph by the arch between the two precedence arrows. A set of *ApplyMOs* as mentioned here is called a "multiple parent". So the conclusion of the previous example must be extended: the total number of single - and multiple parents of an *ApplyMO* equals the number of valid machining direction vectors that *ApplyMO* has in the precedence graph .

In the design phase *ApplyMOs* can be positioned and oriented in two ways. It is either positioned or oriented relative to the initial design state or relative to another previously defined (entity of an) *ApplyMO* . Every position- and orientation-relation holds a tolerance. Similar to precedence graphs, position- and orientation-relations can be captured in tolerance-graphs. The only difference is that every node of a tolerance-graph has only one parent . The parent is either the reference object or the initial design state. Every tolerance-graph relation holds an attribute that registers the value of the tolerance on the relation (i.e. the maximum allowable misalignment). As the reference item of an *ApplyMO* is either (entities of) the initial design state or (entities of) an *ApplyMO* with a smaller *ApplyMO*-index (per definition), it is impossible to encounter circular tolerance chains in tolerance-graphs.

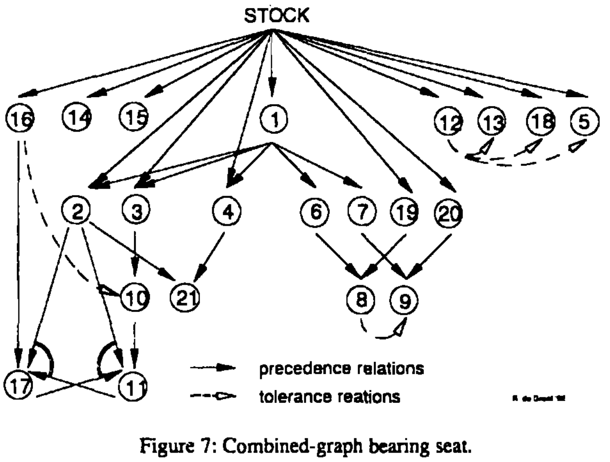

Figure 7: Combined-graph bearing seat.

For the purpose of set-up planning the tolerance-, and precedence-graph are merged together into a combined graph. Hence the combined graph captures the tolerance and precedence relation for every node. Figure 7 depicts the combined graph of the bearing seat of figure 3.

While planning the set-ups of a part, groups of *ApplyMOs* are generated, based on tolerance- and precedence relations. Whether a group of *ApplyMOs* can be machined in a single orientation of the workpiece depends, among other things, on the geometrical configuration of the manufacturing machine. Therefore it is important to be aware of the capabilities of the manufacturing machine. Manufacturing machine models describe the workspace and reach (i.e., geometrical configuration) of the manufacturing machines. In the *IDM* system, a manufacturing machine model takes the machining direction vectors of a group of *ApplyMOs* as input. The manufacturing machine model evaluates the machining direction vectors and reports whether a valid orientation of the workpiece can be found in which all the *ApplyMOs* of the group can be machined using the methodology developed by Woo[Woo 90].

5.3. Implementation.

The most important criterion when planning set-ups is to meet the design specifications after manufacturing. The design contains the information which specifies when *ApplyMO* operations become reachable for machining and thus become available for set-up planning. This information is gathered in the precedence-graph. The precedence-graph must always be obeyed because *ApplyMO* operations are unavailable for set-up planning because they cannot be reached for machining. Tolerance relations, as specified in the design by Implicit Locatings, should be obeyed whenever possible. The tolerance values have to be reached even when the tolerance relation is broken because separate set-ups need to be used. The importance of a tolerance relation is influenced by the orientation accuracy of the workpiece on the machine table of the manufacturing machine.

There are two major kinds of set-up planning strategies: forward planning and backward planning. Using forward planning the sequence in which the set-ups are planned corresponds to the sequence in which the set-ups will be machined. With backward planning the sequence in which the set-ups are planned is opposite to the sequence in which the set-ups will be machined. Apart from some exceptional situations the set-ups for the *IDM* system are planned backwards. Using this method the set-up planning process has maximum control over the machining of the most accurate tolerance relation. The *ApplyMOs* of the most accurate tolerance relation will be placed in the first planned set-up, and will consequently be manufactured in the last set-up. In this way possible damage to faces of the vulnerable *ApplyMOs* or deformation of the workpiece caused by handling or machining of the workpiece can be reduced. The developed planning strategy tries to minimise the number of set-up as well.

The set-up generation process is started by generating the precedence graph, the position - and orientation tolerance graph of the designed part. The generated graphs are merged into the combined-graph (figure 7).
The next step in set-up planning is finding the most accurate tolerance relation between two *ApplyMOs* . The valid machining direction vectors of the *ApplyMO* pair are checked against the candidate machine models. If this *ApplyMO* pair can be manufactured in the current set-up on a suitable manufacturing machine all *ApplyMOs* having a tolerance relation to one of the *ApplyMOs* in the most accurate *ApplyMO* pair are checked whether they can be manufactured in the current set-up.
When a dependent *ApplyMO* cannot be manufactured in the current set-up a non-critical tolerance will be broken (i.e., the corresponding *ApplyMO* is put in another set-up). If it is an critical tolerance relation, for which it is not allowed to break the relation, another manufacturing machine should be chosen. The latter case necessitates redoing the set-up planning of the current set-up for the newly chosen manufacturing machine. As mentioned before feedback loops in process planning, and thus in set-up planning, are necessary.
The following step in set-up planning checks each *ApplyMO* pair that has to be manufactured later than the *ApplyMO* pair with the most accurate tolerance relation (i.e. all the descendants in the precedence graph). For each pair belonging to this group it is checked whether it fits in the current set-up. If this is not the case it is necessary to check if it is allowed to break the tolerance relation. If so, a suitable set-up is generated to which the *ApplyMO* pair can be appended. Note that this set-up has to be used for manufacturing later than the one currently under investigation.
When all *ApplyMO* pairs that have to be manufactured later are dealt with, the set-up planning deals with the single *ApplyMOs* to be manufactured later than the *ApplyMO* pair with the most accurate tolerance relation. Again it is checked whether each *ApplyMO* fits in the current set-up after the most accurate *ApplyMO* pair. If not, the *ApplyMO* is appended to a suitable later set-up.
When all dependent *ApplyMOs* are dealt with, the next most accurate tolerance relation between two *ApplyMO* operations is searched for. The planning cycle starts over with this currently most accurate tolerance relation. If required a new set-up is created for this *ApplyMO* pair.
Finally, after all *ApplyMO*-pairs and their dependent *ApplyMOs* are assigned to a set-up, all single and independent *ApplyMOs* left over are planned. Whenever possible they are assigned to one of the already existing set-ups. Otherwise new set-ups are created for these *ApplyMOs*.

6. Conclusions and future research.

Only part of the total process planning is worked out in this paper. The described set-up planning is a part of process planning and will ultimately fit in a complete approach.
The chosen design representation, a hybrid Solid Modeller, consisting of a Constructive Solid Geometry representation and a Boundary Representation, combined with Implicit Locatings, which model the desired position and orientation including their tolerances, is thought to be a complete design representation for integrating design and process planning. The incorporated tolerances in the design representation in combination with the Boundary Representation allow to make precedence-graphs and tolerance-relation graphs. These graphs have proven to be powerful planning tools. It is expected that the representation will also show great advantages for other planning processes. *Tool(s)volumes*, for example, can be used with fixture planning and collision surveillance. The result of the micro process planning in the design phase in combination with *tool(s)volumes* and the results of set-up planning can be used for operation sequencing and NC code generation.

The chosen method of planning set-ups (backward planning) has proven to be a satisfying solution. But as shown, the backward planning strategy needs to be extended in certain situations with elements of forward planning. *Tool(s)volumes*, precedence graphs and tolerance graphs are clearly indispensable to this method.

Future research directions are the development, implementation and refinement of the three remaining planning processes (i.e. fixture planning, manufacturing operation sequencing and output preparation/generation). Furthermore the inclusion in the *IDM* system of other manufacturing processes than material removal and a tolerance analyser for the design phase.

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