Function-based Modeling of Fabrication Plans for Structural Assemblies

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Abstract

Function-based reasoning (FR) has typically been applied to capture causal understanding of devices. We are applying and extending the FR approach to capture fabrication plans for manufactured artifacts. Our goal is to develop a framework for conceptual planning of composite structures manufacturing; our testbed is fabrication planning for composite structural elements in an unmanned aerial vehicle (UAV) of the Boeing Helicopter Company, as part of the DARPA RaDEO effort.

1. Introduction

Tools supporting manufacturability analysis can greatly accelerate the design process by reducing the time spent on iteration of the design description between the design engineer and the manufacturing engineer. Such tools help the engineer to evaluate different parameters of potential manufacturing processes, identify possible problems, and provide feedback to the designer on how to eliminate problems.

Our research interest is in the application of a *plan-based* approach to manufacturability analysis. Following this approach, the manufacturing plan is generated then used to evaluate different manufacturing factors. Most manufacturability analysis systems developed in recent years are targeted for either metal parts machining (Gupta and Nau 1995; Hayes 1996; Kambhampati et al. 1993) or metal assembly manufacturing (Fazio and Whitney 1988; Hsu and Lee 1993). Considerably less research has been done for the composites domain, but see for example (B. Davidson 1997; Huh and Kim 1991). Manufacturing knowledge plays a very important role in this domain due to the number of design factors (geometry, use temperature...) which restrict or suggest specific fabrication techniques. We intend to fill this gap by developing tools that support manufacturability analysis for the early stages of the composites artifact design; and in particular the re-design of existing metal structural assemblies with polymer composite materials..

Our purpose is to enable the designer to evaluate manufacturability of the product in early stages of the design before a detailed description of an artifact is developed. The input is given on the "conceptual level" – a level of detail suitable for a verbal or a sketched description. The output is a manufacturing plan for a designed artifact, which can be used for evaluation, troubleshooting, and explanation. We have selected the Function-based reasoning methodology (FR) (Sembugamoorthy and Chandrasekaran 1986) for this purpose; we are developing a version of it tailored specifically for process modeling.

In Sections 2 and 3 we specify our problem and analyze it from an AI planning viewpoint. In Section 4,we give a brief background on FR and indicate why the FR methodology is appropriate for our problem. In Sections 5 we describe our specialization of FR for process modeling and in Section 6 we give an illustrative example. Finally, we discuss the contribution of our approach and describe how it may be integrated with related work to produce an application suite for support of Design for Manufacturing in the polymer composites domain.

2. Motivation

In *AI planning* the actions in a particular domain are usually represented as a set of generalized operators. Operators are defined through the set of preconditions that must be satisfied before the operator can be applied and the set of effects that become true after the operator is executed. Most of such planning systems use expressions involving parameters. In the plan, operators are instantiated by binding parameters with values. The planner's task is to find the sequence of operators which will accomplish a given set of goals and in the process to bind the variables specifying the plan. Since the search for an appropriate sequence of operators for this classical AI planning problem is generally PSPACE-complete, most AI planning research aims to find methods and techniques that facilitate the search process.

AI planning techniques can be potentially useful for manufacturing planning with metals. The domain of planning in metal manufacturing can be described in terms which are close to those of classical AI planning. The structure of operators is simple, and a large number of operators is usually required to achieve the goal. The search for the right order of operators can become very complex and AI planning methods can be effectively used to simplify the search.

However, for many practical problems AI planning methodologies have little applicability. One reason is the preoccupation of AI planning with abstract problems and the form of operator representations that omit "unimportant" details (Nau et al. 1995). Gaines and Hayes (Gaines 1996) list some of the operator-related problems:

1) The set of operators included in the planner may not actually cover the full range of domain actions. Moreover, in very large domains it is difficult to think of all possible operators and produce an adequate list of preconditions and effects.
2) Operators may contain redundant information.
3) It may be difficult to maintain operator descriptions in complex domains.

The domain of fabricating structural assemblies made of composite materials is an example of such a complex domain. A single manufacturing step here can be an entire technological process which consists of a number of stages. For example, in composite manufacturing the process called Hand Lay-up consists of the following stages: cut fabric, lay fabric, vacuum bag, and cure. All parameters for all stages have to be defined before using the "Hand Lay-up" operator in the manufacturing plan (in our example for the curing stage it might be temperature, pressure, and time). The problem of assigning correct values to these parameters may be very difficult, considering the multi-stage nature of the operators and their dependence on the material used. However, there is no reason to decompose basic operations into simpler planning operators because the sequence of sub-steps for each operation is set and does not require any additional planning.

On the other hand, the search space in planning for composites is less complex than that in metals. Composite assemblies generally have fewer components in comparison to functionally analogous metal assemblies. Moreover, the fabrication process in composites usually results in a component with most features already in place. This is in contrast to metals where in order to add one feature at least one operation has to be performed. As a result, the number operations required to produce a composite assembly is usually much smaller then that for metal assemblies. Consequently, the search space for the composites domain is considerably smaller. To summarize ... two points were made so far:

1. The search space in fabrication planning with composites is smaller than that of metals, and
2. Operators for composites manufacturing are much more complex.

The bottom line is that there is a mismatch between traditional AI planning techniques, and the domain of fabrication planning for structural assemblies made from composite materials. The nature of the mismatch suggests a more appropriate solution. Because the mismatch between approach and domain is rooted in the granularity differences between traditional planning operators and the artifacts which are to be fabricated, a solution path which emphasizes larger grain operators about which substantial domain knowledge is available. We are pursuing such a knowledge-rich path.

3. Problem requirements and Information Processing Task

The information processing task (IPT)[1] of the problem is as follows:

Inputs:

a) a description of a conceptual design for the structural assembly expressed as a "configuration model"[2] (Zhou et al. 1998), (Zhou et al. 1997) developed on early stages of the design.

b) a set of manufacturing constraints including available fabrication equipment, personnel, time, and cost

Output:

a family of satisfying conceptual fabrication plans.

For purposes of exhibition here, we will assume our fabrication planner will operate on the single output representing design proposal, namely on its "configuration model".

The generated plan will be nonlinear: that is, actions are represented as parallel if no ordering constraints exist. Moreover, the granularity of the plan will depend on the level of precision at which the design is described, i.e. the modeling technique should support arbitrary levels of detail.

We introduce three types of planning operators:

1) Fabrication technologies are used to produce components along with associated features
2) Feature technologies are used to add features to components
3) Joining technologies are used to join components.

For these operators a fixed "base-level" does not exist. Conceptual design is an iterative activity in which more detail is added to the conceptual model at each round. Thus, for the corresponding manufacturing plan, "base-

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[1] The idea of IPT is due to Marr (Marr 1982)

[2] A *configuration model* is a hierarchical representation of an assembly, which reflects not only assembly-component relationship but also the relationship between geometry parameters and design features of the assembly. Within such a hierarchical configuration model, ontological members include structure objects (an assembly or a subassembly), component objects (the base level of atomic parts for the structural assembly), joining objects (fastening one structure or component to another), and feature objects (expressing such features as holes). Ontology of link types expresses the relationships between objects. Link types include part-whole links (assembly-component or assembly-internal joint), join links (expressing connectivity between objects and the joins between them), and feature links (component-feature or subassembly-feature). Each component node contains the description of its type, rough geometry and material class. Each joining node contains information about joining parameters.

level" operations at one iteration should be smoothly expanded in the next iteration.

In addition to satisfying the requirements of the information processing task described above, the method and tool for representing fabrication planning for structural assemblies should meet a number of other prerequisites.

First, the modeling tool should allow the base knowledge of manufacturing processes to be *reused*. In composite fabrication, a relatively small number of fabrication technologies are commonly available. A "standard library" of fabrication base technologies will allow efficient reuse.

Second, the fabrication modeling method should allow *accumulation of fabrication parameters* for the process such as processing time, amount of materials needed, cost, and so forth. The accuracy of estimation for such accumulated values should be approximately correct even when details of individual parts of the plan are not elaborated.

Third, and arguably most important, the modeling method for fabrication planning should support *systematic human examination* of a fabrication plan. We view the development of a fabrication plan for a structural assembly to be a joint human/computer operation. Our software fabrication planner will output a family of proposals for fabrication. A human engineer will then examine the proposals and downselect the one felt to be most appropriate. Because of this tight interaction between software and human engineer, the engineer must be able to systematically explore the alternatives offered in order to make an informed decision.

Fourth, the modeling technique should support both *explanation and troubleshooting* in order to be human understandable.

These four desirable features of a modeling technique for fabrication plans set the terms for representational adequacy, which we require. The information processing task sets the requirements for inferential adequacy. In the rest of this report, we concentrate on the representational adequacy; we attack this aspect of our problem by adapting and extending the function-based reasoning viewpoint to the general domain of representing fabrication plans.

4 Background

There were a number of solutions proposed to facilitate the representation of operators for complex domains similar to composite manufacturing. In the SIPE system (Wilkins 1988), the operators are represented explicitly in the form of an operator refinement hierarchy that lists all possible operators at different levels of abstraction. This facilitates the process of selecting the right operator by organizing and narrowing the search space and directing the search.

In the Operator Construction approach proposed by Gaines (Gaines 1996), the planner keeps a hierarchy of objects that perform actions. An operator hierarchy generator is used to produce a needed operator. In contrast to SIPE, the entire operator hierarchy is never explicitly represented; Operator Construction generates only those portions of the operator hierarchy that are applicable to the current goal. This property makes the Operator Construction approach particularly useful in domains where changes in operator description depend on changes in physical objects that perform these operations. If the physical objects in a domain change, the operator generator then translates those changes into specific operator instructions. This is easier than attempting to infer the changes to produce operator descriptions directly.

Another method is described by P. Clark et.al. (Clark et al. 1996). Following their approach, an operator set is built from components, rather than manually enumerated. Each component encapsulates information about a feature of the domain that may contribute to many plan operators. The basic unit of the representation is a domain feature, not a plan operator. This encapsulation of a particular feature allows modeling the domain with respect to the particular needs, the domain representation can be limited only by those features that are important to the problem.

Despite the many advantages of the described methods, they are unsuitable for our purposes:

- The special engine is required to produce the operator. Instead, we would like to have the representation that can be parameterized in the plan similarly to the simplistic form of the operator.
- The selected operator, used in the plan, is always on the fixed lowest level of abstraction. Whereas we prefer more flexibility in the operator representation used in the plan.
- The causality of the domain is not encoded explicitly. However, the knowledge of causal relations is vital for our goals.

We surmount these problem by starting with the use of a *functional decomposition approach*. The function-based reasoning (FR) approach was first proposed by Sembugamoorthy and Chandrasekaran (Sembugamoorthy and Chandrasekaran 1986) to support causal device understanding. The basic idea of function-based reasoning is that understanding the purposes of a device provide anchors to causal understanding of the device's behavior.

The FR framework has been widely applied in device modeling. Goel has used this approach as a basis for design and redesign problem solving (Goel and Chandrasekaran 1989). Bond et al. (Bond et al. April 1993) applied FR to develop a model of the fuel system for a high performance aircraft. Sticklen and Kamel (Sticklen et al. 1991) have demonstrated that an FR framework can be used to organize quantitative calculations about a device. Price (Price 1996) applied the FR approach to identify sneak paths in electrical circuits.

Typically, FR has been applied to engineered artifacts. In such devices, the possible roles the device plays are tightly governed by the *intended purposes* the device.

These intended purposes are termed *functions* of the device. When the FR approach is applied to naturally occurring devices (biological organisms, ecologies, etc.) the functions of the device take on the more neutral sense of "behavioral role;" instead of standing for engineering intent, functions become a central tool for organizing causal behavior in manageable units.

To date, there has been little effort in the FR community to use the function-based reasoning viewpoint to capture process knowledge. One effort by Sticklen and his group, attempted to apply FR to capture chemical processing to cure composite materials (Adegbite et al. 1991), (Sticklen et al. 1992).

The next few paragraphs contain a brief overview of the FR paradigm.

Conventional FR Modeling Primitives. In the FR methodology, a device is a real or abstract "chunk of the world" with identifiable purposes (or roles), which we term "functions." To represent device functionality, the device is first recursively decomposed into its constituent sub-devices. In engineered artifacts, this decomposition typically parallels major structural systems of the device. The second step in representation of a device functionally is to enumerate the functions of each of the sub-devices. The function is defined by three elements:

a *Provided* clause specifies the preconditions under which the function is operative,

a *ToMake* clause specifies the results after the function successfully completes, and

a *By* clause provides a reference to the description of the "behavior" of device, which is the causal description of how the function is implemented.

Behaviors are represented by directed graph structures in which the start nodes of the graph are tests on state variables, and other nodes are statements of change in state variables of the device. Behaviors resemble fragments of causal nets. However, unlike causal nets, the links in a behavior are annotations which point to an elaboration of why each node transition takes place. These annotations are either pointers to world knowledge or to other parts of the functional description itself, i.e. to lower level functions or behaviors.

In understanding the device functionality from the top level, we are normally led via a chain of

device =>function=>behavior
=> sub-device => function => behavior ...

to lower and lower levels of sub devices until the traversal "bottoms out" on world knowledge.

FR Primitives for Process Modeling. Our application of FR for fabrication process modeling is based on the view that at a high level of abstraction, a process can be viewed as a device. To develop a functional representation for a manufacturing plan we use similar steps to those used in device decomposition:

process => function => behavior
=> sub-process => function => behavior ...

A manufacturing process can be naturally represented as a set of sub-processes, each of which can be decomposed further into sub-processes. This resembles the decomposition of the device into sub-devices. While maintaining such positive characteristics as hierarchical representation of operations, explicitly expressed relationships between objects and actions, the ability to encapsulate different domain features in single function module, ... FR has additional advantages for our domain. First, the ability to represent the causal understanding of the process supports deep level diagnostic and explanatory reasoning about the process. Second, causality is represented in modular chunks, which allows modular reusability for construction of a complete manufacturing process model from library fragments. Thus the inherent modularity of FR meets our requirement that the process model support different levels of description. Third, the global behavior of the process can be understood as a composition of the relevant causal net fragments, which provides a mechanism to estimate different output characteristics based on process parameters. Finally, the representation of the manufacturing process is rooted in the same representational framework. That is, the same primitives are used to describe the manufacturing process, sub-processes, and operations at different levels of abstraction.

5. FR Modeling of a Manufacturing Plan

To model a manufacturing process we start with the FR representational terms and specialize them according to our goals.

The decomposition of a manufacturing process to produce an assembly mirrors the designed structural decomposition of the assembly. More specifically, the process decomposition is topologically isomorphic to our configuration model for a structural assembly.

The functional decomposition of the process is based on an implicit causal relationship between manufacturing an assembly and manufacturing its components. The function of a manufacturing process for a structural assembly rather than simply *ToMake* is *ToProduceTheAssembly* and can be further interpreted as *To Produce All Sub-Assemblies And Components One Level Below And Join Them.* Using this simple specialization of FR terms to the case of fabrication processes, we can identify the FR terms for decomposition of the assembly fabrication process. The function achieved by the process that produces an assembly can be seen as a synthesis of processes that produce sub-components of an assembly (namely, sub-assembly or component) and processes for joinings. The function *To Produce Subassembly* can be achieved by further decomposition of the subassembly. The function *ToProduceComponent*[3] (or *ToProduceJoining*) is considered a separate plan operator

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[3] Remember that a component is the atomic unit corresponding to a single part in the assembly.

and is achieved by corresponding technological process (or in pure FR terms, world knowledge).

It is convenient to keep functional models of fabrication processes (plan operators) in a "model fragment library" and hence to be able to instantiate them into the plan when necessary. This is similar to the concept of functional modeling using standard parts (Pegah et al. 1994). Appropriate technologies for components and joinings are selected in advance, so when constructing the entire manufacturing process model for all components and joinings we can use predefined modules from this library. These modules will be instantiated automatically when used in the plan.

In "standard" function-based representations of devices, causality is typically directly represented in the "behaviors." For manufacturing processes the causal relationship between sub-processes is reflected in temporal ordering constraints on the sub-processes and resource allocation.

The following section describes the application of FR to model one fragment of a manufacturing process for the horizontal stabilizer of the Boeing unmanned aerial vehicle.

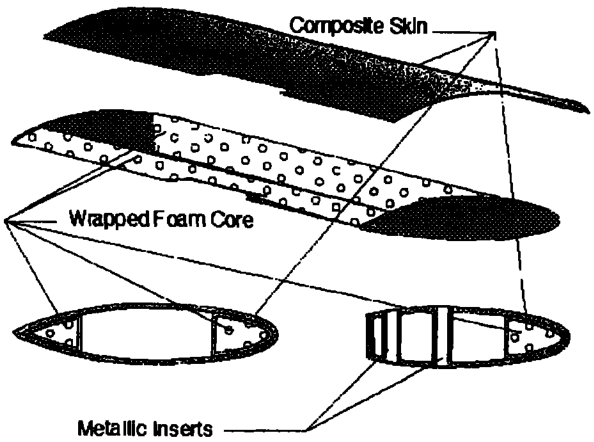

Figure 1: Horizontal Stabilizer

6. Manufacturing Process Plan Example

We use a composite design of a horizontal stabilizer from a Boeing Helicopters unmanned aerial vehicle as an example. In sketch form, the composites design for the horizontal stabilizer is shown in Figure 1.

Figure 2 shows a view of the configuration model for the horizontal stabilizer of Figure 1. As shown, the horizontal stabilizer consists of seven components (gray terminal nodes), 6 joins (white nodes), and 3 add-on features (bold font on gray nodes) – a cutout and two sets of holes. Each node of the hierarchy can be expanded in order to provide access to the detailed information.

The fabrication process plan for the horizontal stabilizer can be decomposed into sub-processes, which reflect the structural decomposition of the horizontal fin into sub-components. The process of manufacturing of the trailing edge spar assembly is one of the sub-processes in this FR-motivated decomposition. The highlighted part of Figure 2 represents the Trailing Edge Spar Assembly.

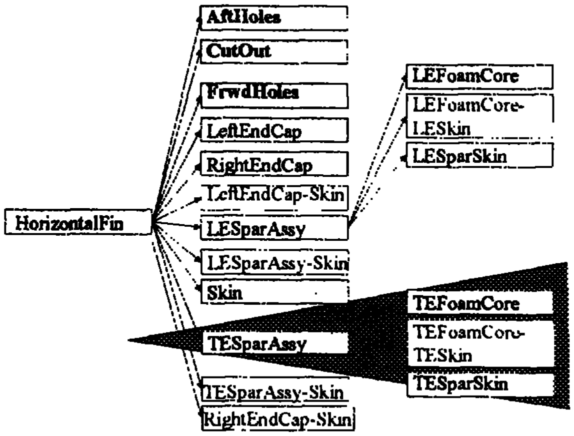

Figure 2: Configuration model fragment

The hierarchy on Figure 3 shows a representation of the functional components for producing *TESparAssy* with their intended functions (functions are specified under process names). From the configuration model we can conclude that in order to produce *TESparAssy* we need to perform three operations: make the foam core, make the skin, and then join them together. The corresponding FR components for the process to accomplish this are as follows: machining the Foam Core, hand-lay-up of the fabric for TESkin, and film-adhesive-joining which achieves the function *ToProduce TESparAssy*. The top-level function is achieved by the elaborated behavior shown in Figure 4.

The causal relations between sub-processes represented in Figure 4 reflect fabrication constraints on the order of manufacturing shown in the configuration model fragment of Figure 2. We obtain this by specifying the precondition to the function *Join TEFoamCore-TeSkin* as a result of functions *Make_TEFoamCore* and *Make_TESkin*. These functions set constraints on the order of manufacturing. By examining their behavioral extensions we determine that the foam core and the skin components can be done concurrently. However, joining of skin and foam core can be performed only after both components are ready.

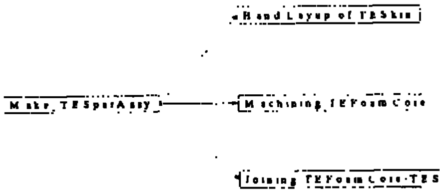

Figure 3: FR decomposition of TESparAssy fabrication process

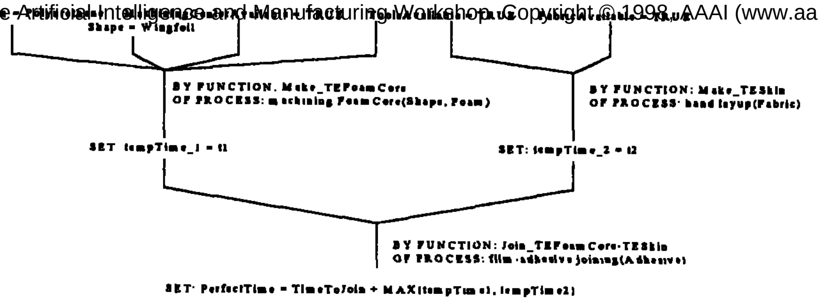

Figure 4: Behavior of function ToProduce TESparAssy

manufacturing steps. For example, the model of the process "hand layup" (Figure 5) is used in the plan to specify manufacturing steps that utilize corresponding technology. When the module is plugged into the plan, all parameters are set and appropriate behavior is chosen. In our case the following parameters are used: material – graphite epoxy resin, performance requirements – high, resin content – 33%. The behavior actuated with respect to these parameters is highlighted in Figure 6.

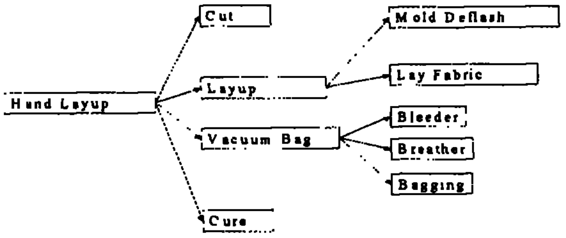

Figure 5: Functional decomposition of process Hand Layup

7. Conclusions

We have described our work in progress towards extending and applying the function-based reasoning methodology to develop fabrication plans for structural assemblies, emphasizing issues of representational adequacy. This issue is very important in the composites domain sinceit differs from the metal domain as follows:

1. The search space is less complex Thus applying traditional planning-based search techniques is not necessary
2. The fabrication operators in our domain are much more complex (large grain). Hence most of the processing time will be spent on adjusting operators' parameters.

These domain-dependent characteristics of our target area lead us in general to believe a more knowledge intensive approach was called for in our fabrication domain.

Moreover, the application of the FR paradigm for modeling manufacturing processes enables us to systematically describe how the various fragments of a process plan for fabrication fit together, and how temporal constraints on the ordering of operations may be explicitly represented. Moreover, as we will show in a forthcoming report, an FR model for a fabrication plan can also be used for identification of existing and potential problems in a fabrication plan.

Our project consists of two major sub-projects: an NSF Rapid Prototypes project to develop software support for structural assembly redesign, and a DARPA RaDEO project to support fabrication planning of the redesigned artifact for manufacturability analysis. The two projects are tightly integrated and in case of success we expect them to be useful throughout the design process as well as during manufacturing planning.

Acknowledgements. Research reported here has profited from discussions within the Intelligent Systems Laboratory (ISL) and the Composite Materials and Structures Center (CSMC) at Michigan State University, and with individuals from our sister projects in the DARPA RaDEO program. In particular, Timothy Lenz and Jim McDowell helped clarify composites specific knowledge. Our ISL colleagues Rob Hawkins, Yue Lin, and Kongyi Zhou have helped us sharpen our application of FR to the fabrication planning domain. Judith Spering and Adam Petruszka, Boeing Helicopters, aided our understanding of the Boeing testbed domain. Our RaDEO colleagues at the University of Utah, Rich Risenfield and Elain Cohen helped sharpen our understanding of metal structures fabrication. And our colleagues at the Auto Air Company (Lansing MI), John Scanlon and Gary Wigell, helped us immensely in our understanding of fabrication of composites structures. Of course, any flaws in this report are ours alone.

General support for ISL activities is supplied by the Composite Materials and Structures Center of Michigan State University and the Research Excellence Fund of the State of Michigan. Research reported here is supported in part by the DARPA RaDEO projects (ONR N00014-96-1-0678), by the NSF Rapid Prototyping Initiative (NSF MIP-942-0351), and the Technology Reinvestment Program (eec-9412783 61324).

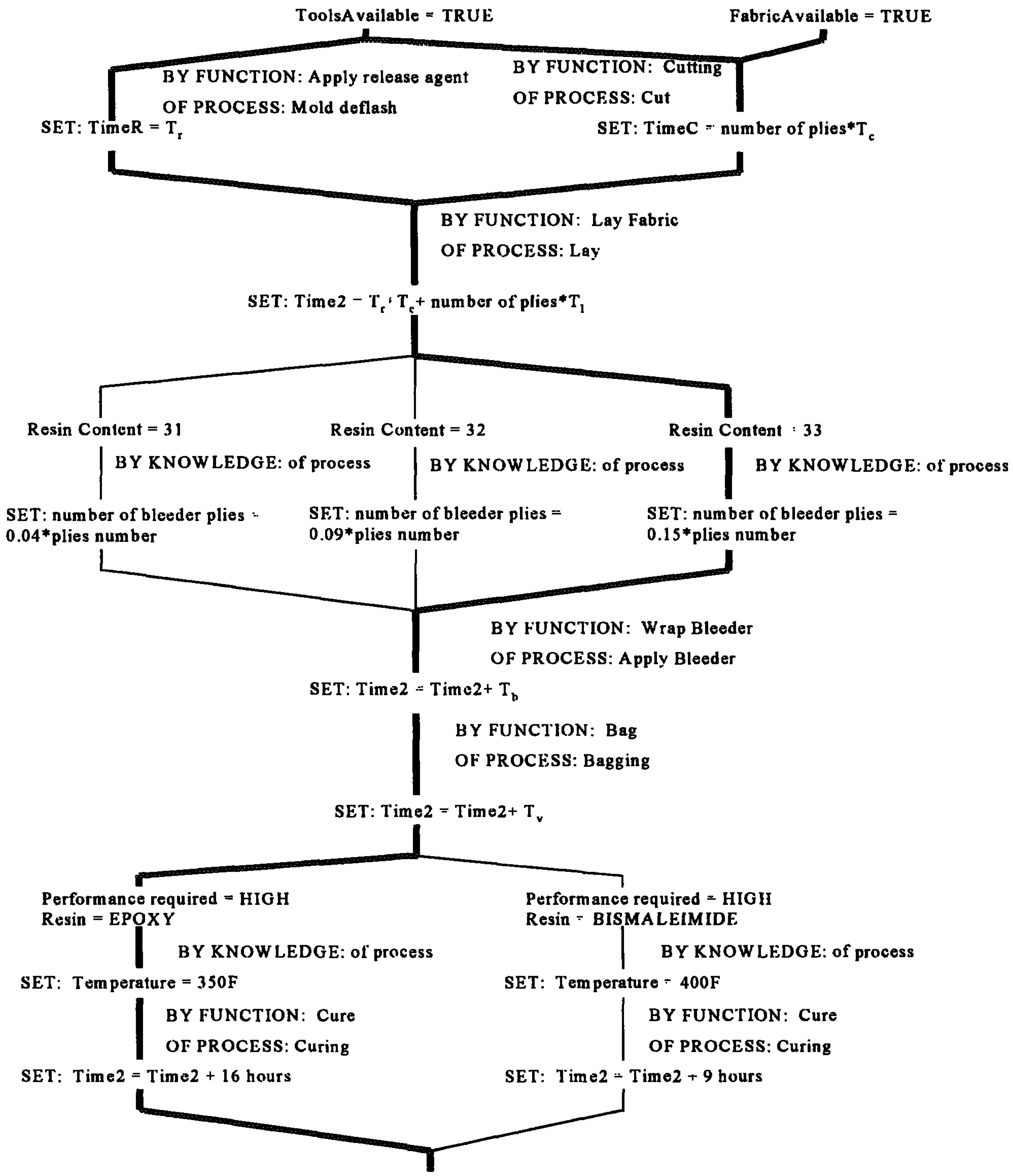

Figure 6: Partial macro expansion of *Hand Layup* function

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