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# Socharis: The instantiation of a strategy for conceptual manufacturing planning

OLEG LUKIBANOV,[1] ILIANA MARTINEZ,[1] TIMOTHY J. LENZ,[2] JAMES K. McDOWELL,[3] CLARK RADCLIFFE,[4] AND JON STICKLEN,[4]

[1]Department of Computer Science and Engineering, Michigan State University East Lansing, MI 48824, USA
[2]Department of Chemical Engineering, Michigan State University, East Lansing, MI 48824, USA
[3]Mad Dog Composites, Inc.
[4]Department of Mechanical Engineering, Michigan State University, East Lansing, MI 48824, USA

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**Abstract**

Considering manufacturing expertise during the early stages of design can be of great benefit. Such information can greatly improve not only the quality of a design, but it can also ensure the generation of an easily manufactured design. This, in turn, can lower the final cost of the designed product. By evaluating how easily an evolving conceptual design can be made, potential hazards can be avoided before any detailed design efforts commence. The conceptual manufacturing planning requisite to such an evaluation is the focus of this paper. A domain-independent strategy for conceptual manufacturing planning is presented. A task-structure analysis of this strategy shows its domain independence. A specific implementation of this strategy for polymer composites manufacturing planning (Socharis) is discussed. The high-level implementation details of Socharis are presented as instantiations of the conceptual manufacturing planning strategy. Finally, the validity of the planning strategy and the utility of Socharis are assessed.

**Keywords:** Conceptual Design; Design For Manufacture; Intelligent Systems; Manufacturing Planning; Polymer Composites

## 1. INTRODUCTION

Designing a complex product involves the collaborative efforts of many specialists: designers, manufacturing engineers, marketing teams, and others. Although the overall goal of the design process is to develop a marketable product, the subgoals of each team vary. For example, the designers develop a product according to technical specifications, whereas the manufacturers make sure that the product can be made easily, and the marketing team minimizes the cost of the product and identifies target markets.

Traditionally, new products are developed sequentially. Design engineers dominate the early stages of the design process. The manufacturing team develops fabrication plans for the prototypes developed by the design team. Finally, marketing and sales personnel introduce the product to the consumer. In this scenario, problems in the later stages mandate repetition of the entire process. Consequent changes made to correct these problems generally invalidate detailed development efforts in the earlier stages. The need to scrap portions of the design and start over results in a long development cycle and increased manufacturing cost.

Concurrent engineering methods have been developed to overcome the drawbacks of the serial approach by requiring that everyone work simultaneously on the detailed design specification of the product. Concurrent engineering can be viewed as an integration of three activities: product engineering, process engineering, and production engineering. Together, each of these activities contributes to the final design.

Design for Manufacturing (DFM) is one of the core principles of concurrent engineering. It embodies the use of manufacturing expertise during product design. Throughout the course of a DFM-centered product development, both design and manufacturing concerns play equally important roles. Whereas a serial development process uses the manufacturing knowledge solely to approve or reject the final

Reprint requests to: Jon Sticklen, Intelligent Systems Laboratory, 3115 Engineering Building, Computer Science Department, Michigan State University, East Lansing, MI 48824-1226, USA. Phone: 517/353-3711; Fax: 517-432-1061; E-mail: sticklen@cse.msu.edu

product design, a DFM-driven approach uses that same knowledge to guide and support the development of the product in every stage. Manufacturing expertise plays a twofold role in DFM:

- *It can serve as a preemptory filter for design decisions*. Manufacturing expertise can be used to validate the design solutions and to identify potential manufacturing problems at all stages of product development, most notably at the early stages of design. For example, the thickness of a protective coating for a part is specified based on the environmental conditions to which the part will be exposed. However, if a manufacturing analysis reveals that the resulting product cost exceeds expectations, then the thickness of the protective coat can be reduced as a trade-off between the part's cost and functionality.
- *It can suggest alternative design emphases*. Manufacturing expertise can be used to suggest an appropriate fabrication technology that subsequently guides the design in a new direction. Although such a change is ostensibly made to accommodate the manufacturing decision, it can give rise to better overall designs (e.g., reduced manufacturing costs, a lower part count). For instance, stringent functional requirements or limited machinery availability may dictate the use of a specific fabrication technology. This limits the design space and can direct the development towards parts with, say, simpler geometries.

Various computer tools that support DFM have been developed in recent years (e.g., SOLIDCAM, MSC/PATRAN, and MADEsmart (Barrett et al., 1997)). Most of these tools have used parametric or feature-based design representations. Such representations are typically used in the later stages of design. However, little attention has been given to DFM at the early stages of design. This situation contrasts with a need evinced in a 1997 National Institute of Standards and Technology (NIST) study (Phillips & Katragadda, 1997), which found that up to 80% of the cost of the final product is decided at the conceptual design stage. Therefore, it is highly desirable to exploit manufacturing expertise at the early design stage to augment the design process by providing manufacturing advice for the product being conceptualized.

Unfortunately, the nature of the information available at the conceptual stage poses difficulties and limits what methods can be used for DFM. Mathematical modeling, scheduling, operation research, and other quantitative methods are handicapped by the qualitative and incomplete nature of the accessible data. However, knowledge-intensive methods (e.g., knowledge-based systems, hierarchical task networks) can make use of such qualitative data if a formalized body of expertise exists.

The need for a principled approach to conceptual design for manufacturing, especially manufacturing planning, serves as the primary motivation of this article. A strategy for conceptual manufacturing planning that emphasizes knowledge-intensive methods is presented. Socharis (Martinez et al., 1999) has been developed as an implementation of this strategy. Although this particular implementation emphasizes a specialized application domain (i.e., polymer composites), the assertion is made that the strategy is equally germane to any domain. The intent of this article is to show that principled conceptual manufacturing planning can be done.

Issues related to conceptual DFM are presented in Section 2. Section 3 presents our strategy for implementing conceptual manufacturing planning. Section 4 describes Socharis, an implementation of this strategy for polymer composite manufacturing planning. An example from Socharis is presented in Section 5, and Section 6 discusses how well Socharis handles manufacturing planning for a variety of situations. Finally, Section 7 draws conclusions about the conceptual manufacturing planning strategy from the performance of Socharis.

## 2. CONCEPTUAL LEVEL CONSIDERATIONS OF MANUFACTURING

Before the definition of a *conceptual manufacturing plan* can be discussed, some idea of what a *conceptual design* entails must be presented. The following discussion considers the nature of the information available at the conceptual design stage and its consequences. The discussion further elucidates conceptual manufacturing planning by comparing it with traditional manufacturing planning approaches.

### 2.1. Conceptual design and manufacturing

Design intent is more apparent at the conceptual level, and consideration of such intent deflects any fixation on design details. Both the function and general structure of the design are more important than detailed geometry at this early design stage. Shah and Mäntylä (1995) capture the essence of this when they refer to the conceptual level as the "intensional realm of design." The motivation for performing design here is because it is where the maximum advantage for the work exists: investing the effort pays off tremendously.

Another advantage of the conceptual level is the generation and management of design alternatives. As designs are intrinsically sparse at this level, relatively little effort is required to generate them. Therefore, many design alternatives can be explored with minimal effort. This is an effective way to navigate through an available design space.

A more concrete definition for conceptual design can be obtained by considering the five stages in the design process identified by Chang et al. (1991): 1) design conceptualization, 2) design synthesis, 3) design analysis, 4) design evaluation, and 5) design representation. During the first two stages, the functional requirements of the part should foment the design idea. These two stages comprise the conceptual level of design referred to in this discussion. We consider a conceptual design only in terms of functional characteristics, rudimentary geometrical information, and a part–

subpart hierarchy. This level of description is sufficient for an engineer to consider initial design feasibility.

The data available at the conceptual design stage effectively dictates the computational methods used to manipulate it. This data is intrinsically incomplete and qualitative. Often, there is no detailed geometrical information save for generic shapes and bounding box dimensions. Design attributes are expressed in qualitative terms (e.g., high, medium, and low) rather than in precise numerical equivalents. Information about the manufacturing environment is sparse and often does not mention the available resources or logistic requirements.

Consequently, a conceptual manufacturing plan can be evaluated with, and expressed in terms of, qualitative and incomplete information. It must contain enough detail to evaluate the ease with which the product can be manufactured. It should also contain general characteristics of the indicated fabrication techniques.

## 2.2. Conceptual *versus* traditional manufacturing planning

There are three areas in which conceptual manufacturing planning differs from traditional manufacturing planning: goals, domain knowledge, and plan representation. Each of these three areas implicitly stipulates what types of problem solving methods can be used to generate manufacturing plans.

### *2.2.1. Goals*

The goal of traditional manufacturing planning is to detail the manufacturing sequence down to the floor-shop operation. This can be done if both an adequate manufacturing choice has been made and resource information is available. Conversely, the goal of conceptual manufacturing planning is to supply the engineer with a variety of generic manufacturing plans feasible to manufacture the product as it is being conceptualized. Additionally, these plans serve to identify possible problems and recognize ineffective designs. The generated plans then can be used for evaluating the ease with which the artifact can be manufactured, estimating its cost or limiting the design space.

### *2.2.2. Domain knowledge*

Traditional manufacturing planning generally occurs in the final stages of the design process, when a decision about the manufacturing method has already been made. Therefore, it focuses on a particular manufacturing technology. Hence, the domain knowledge is limited to comprehensive knowledge for only a few manufacturing methods. This results in a narrow focus, as the efforts of the planning stage are concentrated on the enhancement of a particular plan rather than the exploration of different (and possibly more promising) manufacturing alternatives. An important feature of conceptual planning is its capability to provide a global view on the space of possible manufacturing choices before a detailed design is specified. Because of the potentially large size of the search space, conceptual manufacturing planning often requires the use of a ranking metric that allows evaluation of conceptual manufacturing plans against preferences.

### *2.2.3. Plan representation*

Detailed manufacturing planning results in a precise plan of actions where each action is assigned to a manufacturing agent. The resulting plan is then used to manufacture the product. To support a comprehensive analysis of an artifact's fabrication options, conceptual manufacturing planning must cover a variety of manufacturing processes. This entails a trade-off between the precision of the conceptual plan and its general applicability at the early stages of design. Because of the lack the of detailed resource information during conceptual manufacturing planning, the generated conceptual manufacturing plans (CMP) are more general than those generated as a result of traditional planning. Furthermore, the actions in the CMP represent operations on the product without necessarily specifying the agents that accomplish them.

# 3. A STRATEGY FOR CONCEPTUAL MANUFACTURING PLANNING

As has been stated previously, knowledge-intensive strategies can be used at the conceptual design stage to generate manufacturing plans if a formalized body of expertise exists. Proceeding upon the assumption that such expertise is available, the following discussion presents a strategy for conceptual manufacturing planning.

The conceptual manufacturing planning strategy outlines an approach to generate a manufacturing plan that is used to estimate how easily a product can be made. A detailed description of the product does not exist at the conceptual stage of the design process, and therefore it is impossible to create an itemized manufacturing plan. Instead, an assessment of the manufacturing possibilities must guide any necessary augmentation or change to the initial design. However, the generated conceptual manufacturing plan can be used as a baseline for the later development of a detailed manufacturing plan.

The assertion behind this strategy for conceptual manufacturing planning is that it is domain independent. No claim is made that it does not require computationally complex and/or knowledge-intensive methods to execute it; in fact, such methods are expected. Both a task description and a task-structure analysis of this strategy are presented in the following discussion to provide bases for the claim of domain independence. The applicability of the strategy, especially across multiple domains, is also considered.

## 3.1. Task description

The most direct way to define conceptual manufacturing planning is by examining its Information Processing Task (Marr, 1982). This involves an identification of the information in-

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put to and output from the planning process. The input is the description of the product as it is conceptualized. Information contained in the description includes: partial geometries, part–subpart relations, preliminary joining specifications, material specifications, add-on features, and functional requirements. As output, conceptual manufacturing planning produces a family of applicable plans that include partial assembly and joining orders, and manufacturing alternatives for every design component. Generic fabrication technology descriptions and qualitative parameterizations of them are also included in the component manufacturing alternatives.

### 3.2. Task-structure analysis

It is important to understand the general task structure of the required problem solving for conceptual manufacturing planning. This will enable the creation of a system with the appropriate architecture. In addition, a task analysis may identify similar tasks in other domains where the same problem-solving strategy and methods could be applied.

The task-structure decomposition for conceptual manufacturing planning evolved from repeated observations of expert problem solving. It consists of four major subtasks: Model Analysis, Process Selection, Process Refinement, and Evaluation. When executed consecutively, these four tasks result in a conceptual manufacturing plan. The generated plan contains information that can be used to evaluate, revise, and augment the design. This can make the artifact easier to manufacture, decrease manufacturing costs, or prompt an adjustment of the design to fit a given manufacturing profile.

**Model Analysis** involves restating the product description in manufacturing terminology and other auxiliary operations that prepare the design data for the conceptual manufacturing planning problem-solving modules. **Process Selection** involves identifying the appropriate manufacturing methods for the product or its components. During **Process Refinement**, the selected manufacturing methods are instantiated and some of the manufacturing parameters are defined based on the available part/product information. **Evaluation** ranks the instantiated plans according to metrics provided by the user. The following discussion presents additional details of these task descriptions.

#### *3.2.1. Model Analysis*

This task prepares the data for processing in the manufacturing problem-solving modules. The translation of the model from design to manufacturing terminology occurs first. Such a translation is necessary as designers and manufacturers often use different vocabularies to say the same thing. Even more problematically, they may use the same term to mean different things. For instance, to a designer "the shape" of a part is the concept that corresponds not only to a geometric form, but also to specific load requirements for the part. Therefore, a designer's description of a part may include such shapes as column (to withstand compression loads), torque box (to withstand rotary loads), or beam (to withstand bending loads). Conversely, manufacturers consider a shape solely as a primitive for manufacturing, regardless of the loading.

Besides translation, it might be necessary to perform other information transformations. For example, the partial assembly order can be derived directly from the design description. This partial assembly order is a skeletal manufacturing plan that contains sparse information about joining order precedence, manufacturing, and feature addition operations. The generated conceptual manufacturing plan only reflects the constraints imposed by the available structural information. Consequently, the manufacturing plan is analogous in topology to the design's configuration model.

#### *3.2.2. Process Selection*

After the structure of the manufacturing plan has been set, it is necessary to select manufacturing method(s) that can be used to fabricate each portion of the product. The list of potential methods must cover all manufacturing possibilities in the domain of interest. This enables a comprehensive exploration of the design space. The list of recommended manufacturing methods can be critiqued and pruned to reflect the designer's preferences, cost concerns, and other factors.

#### *3.2.3. Process Refinement*

The third stage refines (i.e., parameterizes and instantiates) fabrication methods that survive the second stage. It is important to note that multiple instantiations are possible: a part may be manufactured in various ways with the same fabrication technology if different sets of process parameters exist.

The set of parameters to be defined must be selected carefully. First, it should be possible to define these parameters based on the limited description of the design, that is, incomplete and qualitative. Second, because the goal of conceptual manufacturing planning is to select appropriate manufacturing methods without generating a detailed shop plan, it is appropriate to define only those parameters whose values affect the evaluation of the design.

#### *3.2.4. Evaluation*

Each of the tasks described above can result in multiple outputs. Model analysis can have multiple resolutions of an ambiguous design term. Process selection can identify multiple feasible processes. Process refinement can generate multiple sets of manufacturing parameters. This multiplicity is due to the conceptual nature of the design and the emphasis on the generation of relevant alternatives. Navigation in this potentially exponential design space is difficult. Therefore, it is necessary to evaluate the generated plans according to some predefined set of metrics (e.g., functional properties and geometric repeatability) and their importance to the designer. The use of these metrics will allow the designer to choose those manufacturing plans best suited for the current situation.

### 3.3. Applicability of the Strategy

Although the strategy outlined above was presented without any explicit domain dependence, detailed domain knowledge is required for it to be realized. This domain knowledge must include sufficient information to describe both the conceptual design and manufacturing plans, as well as generate them. The knowledge must be structured so that it can function with incomplete and/or qualitative information. Additionally, this knowledge must be contained within problem-solving units capable of interacting with other problem solvers within the strategic architecture. Depending upon the nature of the domain knowledge, the way in which each of the problem-solving units accomplishes its subtask may vary.

These requirements are not trivial. However, any domain in which established manufacturing practice exists already meets these requirements. Such domains can include both specific materials (e.g., steel, polymer composites, and ceramics) and market sectors (e.g., automotive or rapid prototyping). However, the more closely held the domain knowledge is, the more difficult it is to apply this strategy. Therefore, this strategy is most easily applicable to domains in which a great deal of knowledge is freely available.

The following section builds on the preceding presentation of the conceptual manufacturing planning strategy and describes a particular instantiation of it. The domain of interest for this system was polymer composites. This domain was chosen because of its richness, the availability of domain experts, and our familiarity with it.

## 4. CONCEPTUAL POLYMER COMPOSITES MANUFACTURING PLANNING IN SOCHARIS

A composite material is a heterogeneous combination of two or more materials that maximizes specific performance properties traceable to one of the constituent materials or to the aggregate composite material. Composites allow designers the flexibility to customize a material to the requirements of a specific application. However, this increased design flexibility is often accompanied by an increased design complexity. Unfortunately, designers using composite materials only work within narrow subareas instead of the entire domain. Consequently, the full design flexibility of composite materials is not typically realized.

Design for manufacture has been historically more prevalent for polymer composites than metals. In part, this is because many design factors (e.g., geometry, functional requirements, production rates, and material system) either constrain or suggest specific composite fabrication technologies. As the selection of a manufacturing process can greatly affect both the functional qualities and cost of the final product, manufacturing concerns often dominate purely design concerns. Even for solely manufacturing issues, the variety of available composites fabrication technologies can complicate any conceptual-level comparison of alternatives for a part.

A software suite has been developed in the Intelligent Systems Laboratory at Michigan State University to accomplish integrated design and fabrication planning at the conceptual level (Lenz et al., 1998; Martinez et al., 1999; Zhou et al., 1999). It supports the conceptual design/redesign process for the transformation of metal structural assemblies to polymer composites. This software suite assists engineers in exploring the space of design and manufacturing possibilities and evaluating evolving solutions without detailed design or analysis.

The suite produces a family of conceptual composite redesigns from the original metal part. Each member of this family is a valid redesign option, meeting the original design requirements. These redesigns, called Conceptual Composite Assemblies, are passed to a manufacturing planner for further evaluation. By reviewing alternative manufacturing plans suggested for the functionally equivalent conceptual designs, the designer can rule out those that are less effective and concentrate on the more effective plans. The resulting solutions not only satisfy functional and aesthetic requirements, but also can be made easily.

This discussion presents Socharis, the manufacturing planning portion of the software suite. It generates a family of applicable conceptual manufacturing plans from a conceptual description of a composite assembly. The conceptual manufacturing planning strategy served as the framework upon which Socharis was built. Details of the problem-solving architecture and the communication protocol used to represent knowledge are presented in the following discussion.

### 4.1. Problem-Solving Architecture of Socharis

The architecture embodies the strategy for conceptual manufacturing planning in three major steps: 1) developing a skeletal manufacturing plan, 2) deciding and detailing a technological process for each planning step, and 3) ranking the generated technological processes. These correspond to the identified tasks of Model Analysis, Process Selection/Refinement, and Evaluation, respectively. Each of these steps is divided into specialized problem-solving steps.

The Generic Task methodology (Chandrasekaran, 1983; Bylander & Mittal, 1986; Brown, 1987; Chandrasekaran & Johnson, 1993) was used to implement the various modules of Socharis. This methodology provides high-level building blocks for knowledge-based systems and enables the encoding of domain knowledge for use in problem solving. However, Socharis consists of multiple problem-solving modules whose activation cannot be determined *a priori*. The original GT methodology does not support cooperative problem solving by a number of GT-based individual agents. Therefore, it was necessary to program control mechanisms outside of the current GT-based shells for implementing separate modules.

The following discussion relates how each portion of the high-level problem-solving architecture was implemented in Socharis. Each of the three stages of the architecture is addressed individually.

### 4.1.1. *Skeletal plan generation*

This stage creates a skeletal manufacturing plan and prepares design parameters that will be processed by the downstream technology selectors/refiners. This step is divided into three substeps: creation of the skeletal manufacturing plan, data translation, and selection of the feature addition methods. Figure 1 shows the relations among these sub-tasks.

*Skeletal plan creation.* Construction of a skeletal manufacturing plan requires an analysis of the existing conceptual configuration model of the artifact. The generated skeletal plan is topologically analogous to the configuration model of the design. At this point, the skeletal plan has only a rudimentary structure, as any required add-on features have not yet been included in the manufacturing plan. These additional details are extracted from the configuration model in a separate series of steps (detailed below).

*Data translation.* At this stage, the descriptive information about the mechanical structure is translated from the terminology used by designers into that used by manufacturers. The translation involves a mapping of the design ontology to the manufacturing ontology. However, the application of a primitive dictionary is not always sufficient; auxiliary data must often be considered to make a competent translation. For example, mapping the shape **Panel** to an acceptable choice from the manufacturing ontology of shapes (shell, closed shell, casting, and beam) requires additional considerations such as the aspect ratio, relative wall thickness, and the stipulated combinations of add-on features.

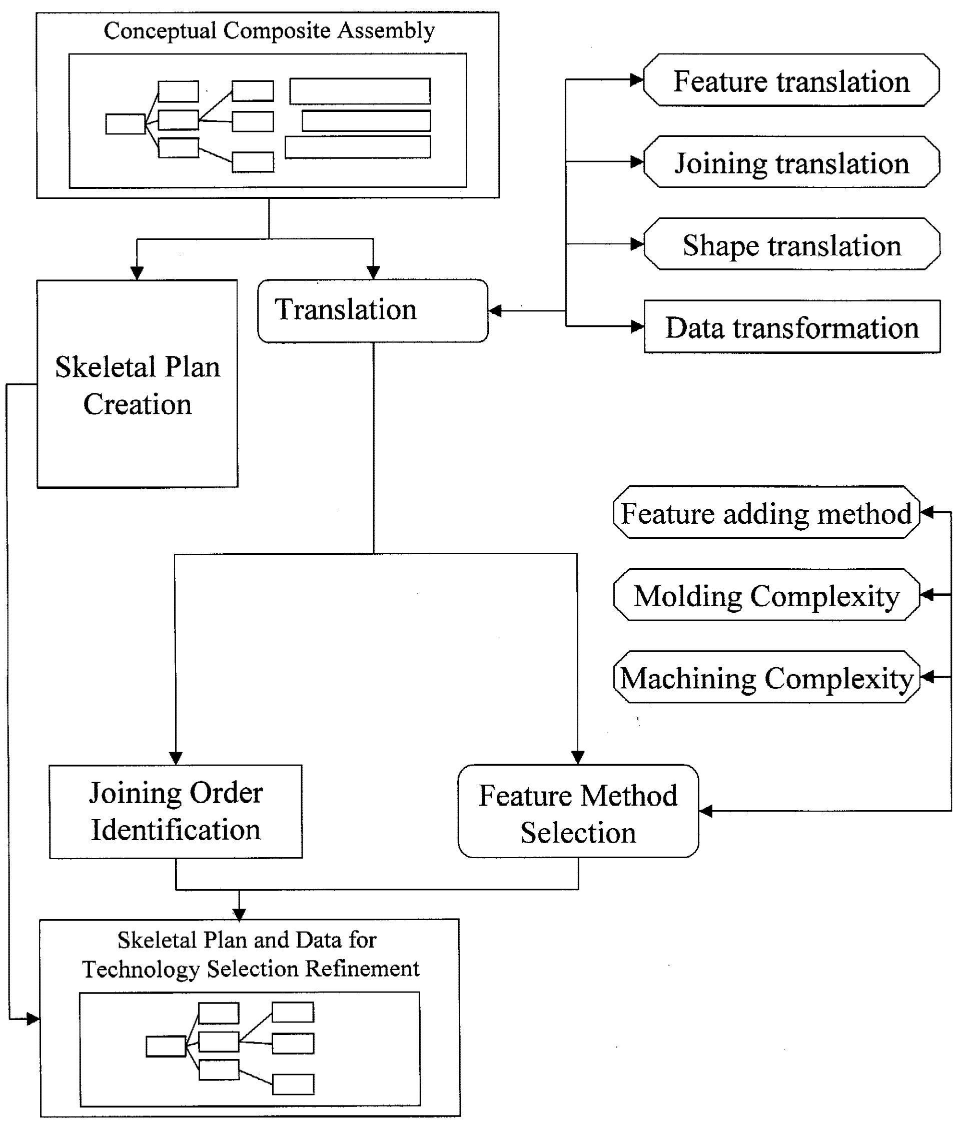


**Fig. 1.** Stage one (skeletal plan generation) problem solving in Socharis. In this and the following figures, rectangles represent algorithmic modules, octagons represent knowledge intensive modules, and rounded rectangles represent integrated modules.

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*Feature addition method selection.* There are two methods for adding a feature to a component of a composite part: machining or molding. In machining, the feature is added to the component after the component has been fabricated, whereas in molding the feature is incorporated as the component is produced. The method of creating each individual feature is decided based on that feature's tolerance allowances and the production quantities of the component. For example, a prototype component (i.e., only a few parts are produced) containing highly precise features would typically have machined features. Implicit within these considerations is the manufacturing cost and required time to produce each of the features. This step attempts to minimize both of these whenever possible.

### *4.1.2. Deciding and detailing technologies*

After a skeletal plan has been generated, Socharis assigns one or more fabrication technologies to each component within the manufacturing plan. After each applicable fabrication technology is selected, manufacturing parameters specific to each technology are set. Figure 2 shows the details of this stage of the problem-solving architecture.

*Technology selection.* The first use of the translated data occurs in this stage as the appropriate manufacturing technologies are selected. Two independent problem solvers select applicable technologies based on geometric features of the component (e.g., shape, aspect ratio, and wall thickness) and material features (e.g., type of resin, fiber architecture). The results of both problem solvers are lists of manufacturing technologies that theoretically could produce a given component. The intersection of these lists, therefore, represents the technologies that satisfy all criteria given in the input data. The technologies contained in this intersection are then passed to the refinement step for further processing.

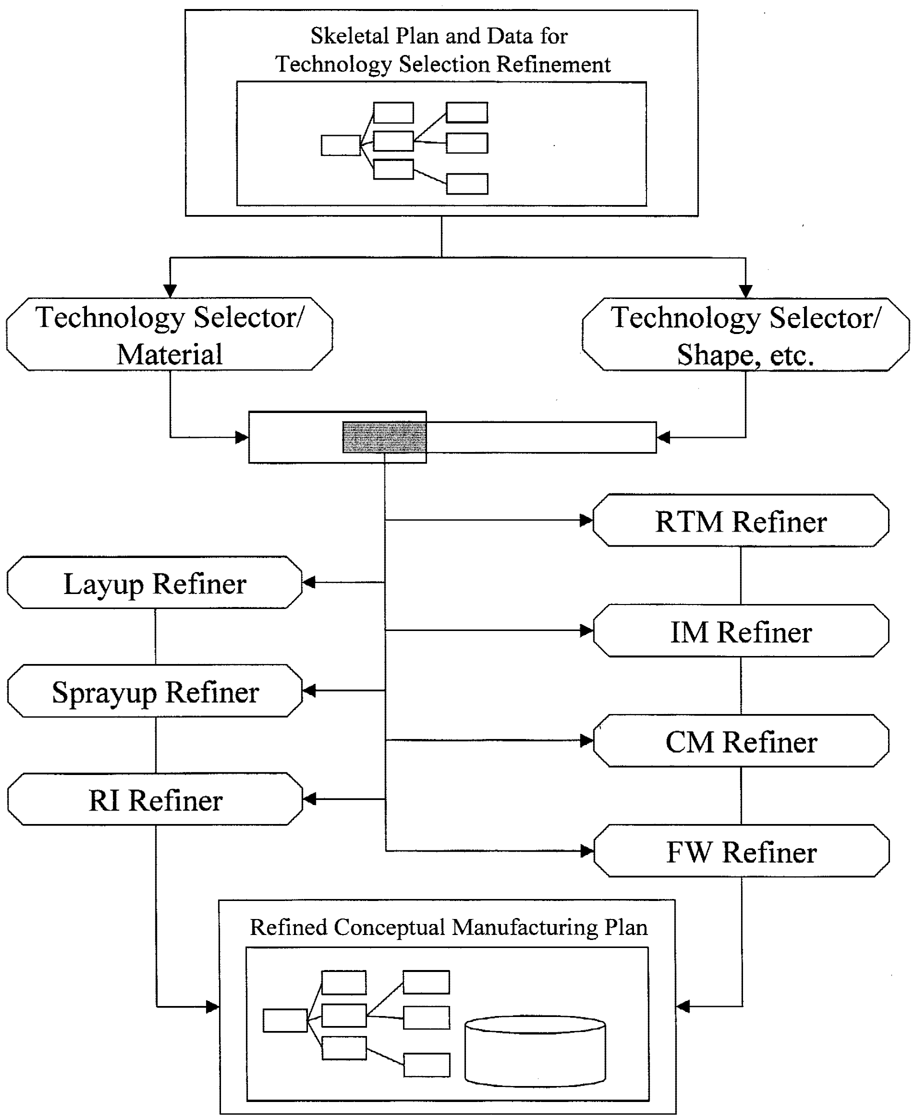


**Fig. 2.** Stage two (fabrication technology selection and refinement) problem solving in Socharis.

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*Technology refinement.* After the technologies are selected, the parameters for each technology are defined. These parameters include curing requirements (e.g., time, pressure, curing type, post curing), tooling requirements (e.g., tooling complexity, tooling material), and so on. The specific subsets of parameters vary among the different generic technologies. Component data (e.g., geometry, material, and add-on features) and global parameters (e.g., production and global tolerance allowances) are used to define these parameter values. Each generic technology may contain many different sets of parameter values. Additionally, each component may be produced with multiple technologies. Therefore, some way to compare the generated manufacturing options is required.

### *4.1.3. Evaluation*

On average, Socharis produces 5 to 12 fabrication alternatives per component. Given $N$ components in the assembly, there are between $N^5$ and $N^{12}$ different possible manufacturing plans. Additional considerations of the semi-deterministic assembly order and the fact that assemblies are multicomponent, exponentially increase the number of possible manufacturing plans. To enable navigation of this expansive space of possible manufacturing plans, a means of evaluating each option is necessary. Merit tables are used to estimate and rank the fabrication technologies for each node in the manufacturing plan. Figure 3 shows the details of this approach.

Merit tables are traditionally used in engineering practice for ranking different design solutions. Every row in a merit table is associated with a critical manufacturing metric (e.g., cycle time, tooling turnaround time, and operator skill level). Each metric is linked to a weighting factor that reflects its importance to an engineer. Alternative technologies are ranked according to these merits by calculating the weighted sum of the estimated metrics.

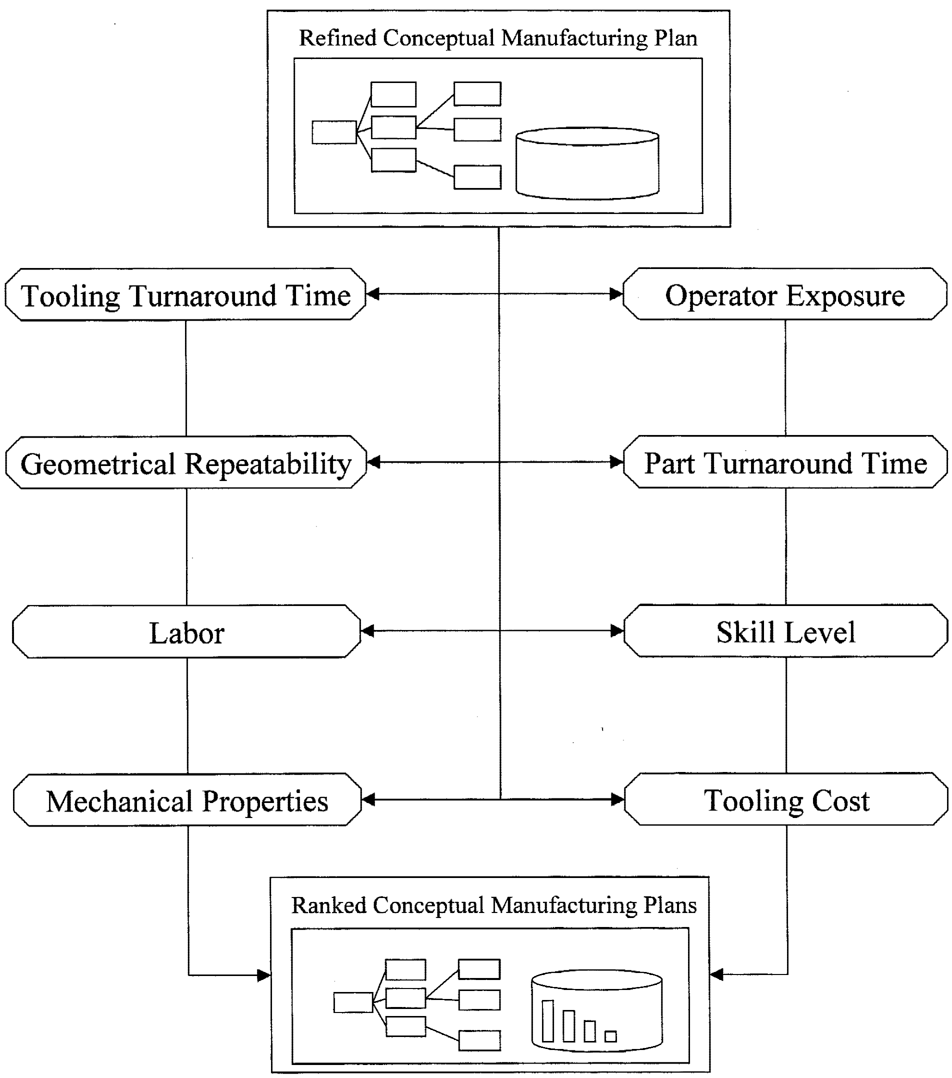


**Fig. 3.** Stage three (evaluation) problem solving in Socharis.

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The specific metrics used in Socharis were selected to enable the evaluation of time (cycle time, tooling turnaround time), quality of the product (mechanical properties of the product, geometrical repeatability) and human factors (operator skill level, operator exposure, labor). These metrics are estimated according to the nature of the technological process, the process parameters established during the technology refinement step, and specific part features. This estimation assigns a qualitative value from 1 to 10 for each metric. The alternative processes are then ranked according to the value of the weighted sum of the estimated metrics.

The user can limit the design space under examination by requesting that Socharis only display the best few options for each component to be manufactured. This is possible because of the merit table evaluations. This significantly reduces the number of refined fabrication options among which the user must choose.

### 4.2. Structure and use of domain ontology

As detailed in the previous section, the problem-solving process that leads to generation of a conceptual manufacturing plan consists of several cooperating problem-solving agents. A composite materials domain ontology (Lenz et al., 1998; Martinez et al., 1999; Zhou et al., 1999) is used to facilitate this cooperation. This domain ontology provides a vocabulary for representing knowledge about polymer composite materials. An ontology editor was created for the software suite primarily because other available ontology methodologies (e.g., Ontolingua (Gruber, 1992), STEP) presented difficulties with maintenance of the ontology. A specific ontology for polymer composites (both design and manufacturing) was developed by gathering information from literature (e.g., *Engineered Materials Handbook*, 1987) and domain experts.

The domain ontology is a four level hierarchy: Class Category → Class→ Attributes → Parameters. Experience in constructing multiple knowledge-based systems in the domain of design, redesign, and manufacturing with composite materials has shown that this four-level hierarchy covers all necessary terminology and relations. Occasionally, it is even possible to describe a concept using only three of the four available levels.

Each concept in the ontology also contains a succinct description of any assumptions made. Take, for example, a term definition for Shape → Shell → {AspectRatio, Wall Thickness,...} → {{low, medium, high},...}. An explicit definition of Shell (e.g., thin-walled planar or curvalinear structure) and quantitative correspondence for the qualitative values of the AspectRatio attribute minimize any potential ambiguity inherent in the term definition. Such comments are mandatory parts of the representation and add meaning to the syntax of the term.

The purpose of this ontology is threefold (Gruber, 1992). First, it helps to organize the domain terminology and to clarify possible misreadings of a term. Second, it helps in creating a database backbone for the multitude of problem solvers in the domain of interest. Third, the ontology serves as a basis for interagent communication. That is, agents that participate in the problem-solving process communicate using this ontology and interpret domain-specific information in the same way.

## 5. AN EXAMPLE FROM SOCHARIS

To illustrate the behavior of the Socharis system, a working example will be presented focused around the commander's seat in a Bradley fighting vehicle. The U.S. Army Tank-Automotive and Armaments Command (TACOM) of Warren, Michigan, provided this example.

Socharis can accept two kinds of inputs: 1) a design-based configuration model or 2) a manufacturing-based configuration model. The design-based configuration model is generated by Socharis' sister system, Raven (Zhou et al., 1999). Raven takes the description of a metal assembly and generates design alternatives that use polymer composite materials. The conceptual composite assembly generated by Raven is expressed in terms of a design-based configuration model detailing the components, assembly–subassembly relationships, partial geometries of the components, and materials.

The commander's seat was originally produced as an aluminum and steel assembly and, as input to Raven, was assumed to be a structure composed of a platform and a support. Table 1 presents the details of one of the designs generated by the Raven system that would serve as the input to Socharis. Raven determined that the platform could be redesigned as a flat panel in a vinyl ester carbon composite. The support component was redesigned as a shell structure also using vinyl ester carbon composite but with a braided fiber architecture.

If this design-based configuration model is the starting point for the conceptual manufacturing planning activity then it must be translated into a manufacturing-based configuration model. If the user does not have a result from Raven but has a polymer composite assembly for which he or she would like to explore manufacturing concepts, Socharis has the facility to construct a manufacturing-based configuration model from scratch.

Table 2 presents the details of the platform and support, now with information useful to their manufacture as polymer composite components/assemblies. The details now focus on parameters that will determine how the components will be manufactured and what features might have to be molded or machined. The details in Table 2 can also be entered directly by the user if a Raven design model is unavailable.

The user provides values for the weighting factors for each of the evaluation metrics and information about the production volume and functional requirements of the assembly. Socharis uses this information in reasoning about process

**Table 1.** *A design ontology description of the components in the Bradley commander's seat*

| Name | | Platform | Name | | Support |
|---|---|---|---|---|---|
| Type | | Flat panel | Type | | Shell |
| Functions | Load severity | Medium low | Functions | Chemical environ | Weak acid |
| | Temperature | 60 F | | Bending moment | Medium |
| | Smooth skin | Two side | | Flame retardance | No |
| | Elongation | Not required | | Tension | Medium |
| | Flame retardance | No | | Smooth skin | Two side |
| | Stress environment | No | | Stress environment | Unknown |
| | UV exposure | No | | Light weight | Required |
| | Load complexity | 3D | | Load severity | Medium |
| | Impact Tolerant | No | | Impact tolerant | Unknown |
| | Compression | Medium | | Elongation | Not required |
| Geometries | Thick envelop | Low | | Load complexity | 3D |
| | Width | 13 in | | Humid environment | Unknown |
| | Thickness | 0.125 in | | Torsion | Medium |
| | Depth | 15 in | | Temperature | 60 F |
| | Attachment | Latch/Bracket | | Compression | Medium |
| | Curvature Complexity | 2D | | UV exposure | No |
| | Section Regularity | 2D | Geometries | Thick envelop | Unknown |
| Material | Additive | Styrene | | Accessibility | Unknown |
| | Matrix material | Vinyl ester | | Section aspect | Low |
| | Fiber architecture | Quasi-isotropic | | Shape | Shell |
| | Fiber type | Carbon | | Width | 6 in |
| Add-ons | | 4 holes | | Height | 12 in |
| | | | | Length | 10.25 in |
| | | | Material | Additive | Styrene |
| | | | | Matrix material | Vinyl ester |
| | | | | Fiber architecture | Braided |
| | | | | Fiber type | Carbon |

alternatives, determining process details, and the final evaluation of the fabrication options.

Table 3 displays several manufacturing options for the Bradley seat platform that were generated. Socharis selects relevant manufacturing processes and generates details for using these options. This provides a multiplicity of results both among manufacturing processes and options within a specific process. In the case of the seat platform, Socharis determined that it could be manufactured using compression molding, resin transfer molding, or six variations of layup.

These activities of process selection, process refinement, and process evaluation are performed without user intervention. At the conclusion of the problem-solving process, the user is presented with a graphical display of the conceptual manufacturing plan. Socharis provides access to a merit table for each of the manufacturing options and allows the user to alter the value of the weights of a selected component manufacturing choice. This enables an exploration of the available manufacturing plans.

In Table 4, a merit table is presented for the various approaches to manufacturing the support for the Bradley seat.

**Table 2.** *A manufacturing ontology description of the components in the Bradley commander's seat*

| Name | | Platform | Name | | Support |
|---|---|---|---|---|---|
| Type | | Shell | Type | | Shell |
| Parameters | Aspect ratio | Low | Parameters | Aspect ratio | Low |
| | Wall thickness | Medium | | Wall thickness | Medium |
| | Geometrical complexity | Low | | Geometrical complexity | Low |
| | Size | Small | | Size | Small |
| Add-on | | Hole/none | Add-on | | Hole/none |

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**Table 3.** *Manufacturing options for the Bradley seat platform generated by Socharis*

| | |
|---|---|
| **Compression Molding1** | |
| **'labor'** | 'medium' |
| **'tooling'** | 'Aluminum' |
| **'Tool complexity'** | 'low' |
| **'pressure—ksi'** | '0.5–1.5' |
| **'temperature'** | '150–200 F' |
| **Resin Transfer Molding1** | |
| **'Tool complexity'** | 'low' |
| **'labor'** | 'low' |
| **'Curing temperature'** | '25–100 F' |
| **'Curing time'** | 'minutes' |
| **'FiberFormingMethod'** | 'Cut-and-Place' |
| **'Heating method'** | 'heated platens' |
| **'Postcuring Required'** | 'no' |
| **'tooling'** | 'Aluminum' |
| **Layup6** | |
| **'temperature'** | '150–200 F' |
| **'pressure'** | 'high' |
| **'post-curing'** | 'no' |
| **'labor'** | 'low' |
| **'Tool complexity'** | 'low' |
| **'resin prepreg/wet'** | 'prepreg' |
| **'curing type'** | 'autoclave' |
| **'tooling'** | 'CRP' |
| **Layup5** | |
| **'temperature'** | '150–200 F' |
| **'pressure'** | 'moderate' |
| **'post-curing'** | 'unknown' |
| **'labor'** | 'low' |
| **'Tool complexity'** | 'low |
| **'resin prepreg/wet'** | 'prepreg' |
| **'curing type'** | 'microwave' |
| **'tooling'** | 'CRP' |

Here, the user was especially concerned with mechanical properties and tooling costs; thus, filament winding was generated as the preferred manufacturing option.

Faced with the iterative nature of design exploration in the early phases of conceptual design, Socharis provides considerable flexibility for changing parameters of the assembly or of individual components and regenerating a new conceptual manufacturing plan. At the close of the design activity, when the designer is satisfied with the set of manufacturing alternatives, they can generate a hard copy output of the conceptual manufacturing plan using Socharis' export facility.

## 6. TESTING SOCHARIS

The knowledge base in Socharis was implemented with an inclination towards aerospace applications, as that was the specialty of the domain experts from whom the knowledge was acquired. Socharis has been tested on numerous examples, both within the aerospace arena and without. The following discussion addresses the performance of Socharis for a variety of additional examples.

One of these examples, the tail airfoil for a Boeing unmanned aerial vehicle (UAV), was described in detail in Martinez et al. (1999). The results generated by Socharis were compared with those independently generated by a panel of experts. The conceptual manufacturing plans generated by Socharis not only included all of the technological plans suggested by the engineers, but also included several additional valid technological alternatives not considered by the experts. Upon questioning, the experts indicated that they did not consider those fabrication variants as they did not have access to the proper equipment.

Other aerospace experiments were conducted by introducing real-life designs from the practice of a local composites shop to Socharis. The specific examples included an aircraft engine bell mouth, a nose cone, and several fairing assemblies. A bell mouth is the front part of the aircraft engine cover and is a part that is manufactured using hand layup with autoclave curing. Socharis generated a conceptual manufacturing plan for the bell mouth that indicated several possible fabrication technologies. Included among these technologies was hand layup-autoclave curing. A nose cone is a part of the engine casing assembly that is manufactured using hand layup. A model of the nose cone was run through Socharis with similar results. Fairing assem-

**Table 4.** *A merit table for the various approaches to manufacturing the support for the Bradley seat*

| Weight | Merit | FW | Lp6 | Lp2 | Lp5 | Lp1 | Lp4 | Lp3 | RTM | CM |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Geometrical repeatability | 8 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 10 |
| 1 | Tooling turnaround time | 3 | 8 | 8 | 8 | 8 | 8 | 8 | 3 | 3 |
| 10 | Mechanical properties | 9 | 8 | 8 | 8 | 8 | 8 | 8 | 6 | 8 |
| 1 | Operator exposure | 7 | 3 | 3 | 3 | 3 | 3 | 3 | 5 | 7 |
| 1 | Labor | 6 | 3 | 3 | 3 | 3 | 3 | 3 | 5 | 8 |
| 1 | Skill level | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 6 | 10 |
| 10 | Tooling cost | 7 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 2 |
| 1 | Cycle time | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 8 | 9 |
| | TOTAL | 191 | 185 | 185 | 185 | 185 | 185 | 185 | 173 | 147 |

(FW: filament winding; Lp: Layup; RTM: Resin Transfer Molding; CM: Compression molding.

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blies are produced by the composites shop using compression molding. Other fabrication technologies used to build these parts for aircraft, automobiles, and boats include hand layup and resin transfer molding. Socharis suggested all three of these technologies as valid choices for manufacturing fairing assemblies.

The last set of examples to verify Socharis's capabilities in the aerospace domain was taken from recent publications and includes a Tiltrotor wing torque box (Clements, 1999), a missile launcher (Alliant Composites, 1999), and a z-stiffener for the F-22 (Joint Strike Fighter, 1998). For these models, Socharis produced lists of technological choices that consistently reproduced real-life manufacturing selections.

The results of this study show the relevance of the knowledge base and problem-solving strategy in Socharis to the aerospace domain. The performance of Socharis was also tested on examples from a variety of different domains (marine infrastructure, automotive, and sporting goods). They included an automotive quarter panel, a golf club, and the Dodge Viper windshield surround, among others. In every example, Socharis generated a list of conceptual manufacturing plans that included the technology actually used to manufacture the product.

The validation experiments described above all show that the knowledge base and problem-solving strategy in Socharis were relevant to the manufacturing of polymer composites in general. This is very encouraging.

## 7. CONCLUSIONS

A recent NIST study of process planning for conceptual design (Feng & Nederbragt, 1999) noted that research into tools for the support of conceptual design is still nascent. The majority of the tools that provide manufacturing expertise during the conceptual design stage have limited functionality and target specific subareas of the conceptual design process. Both Esawi and Ashby (1997) and Farris and Knight (1992) describe systems that support the selection of generic manufacturing processes. These systems, although effective at their tasks, do not make any generalization of the problem-solving process. Such a generalization is a necessary step towards the next generation of conceptual design support tools.

Socharis was implemented as a test of a strategy for conceptual manufacturing planning. The high-level implementation details of Socharis are instantiations of the conceptual manufacturing planning strategy. Although this strategy provided a framework upon which to base Socharis, additional knowledge acquisition and engineering was required to complete Socharis. This was expected, given the knowledge-intensive nature of the presented strategy.

Socharis has passed every test given it to date. One interesting point about the behavior of Socharis is that, although its knowledge base had an aerospace bias, the practical experiments showed its relevance to composites manufacturing in general. This not only highlights the diligence and excellence of the consulted experts, but also indicates the utility of Socharis and its conceptual manufacturing planning strategy.

Despite the successes of Socharis, its main shortcoming was that the implementation of the overall problem-solving architecture did not support the development of a sufficiently complex integrated architecture. This forced the developers to implement (i.e., hardcode) an overall control strategy. Therefore, any modifications to the control architecture will require substantial effort and intimate knowledge of the details of legacy software.

Socharis consists of 30 different separate expert systems. However, as noted above, the complex control structure of the integration of these modules required hand coding. Because of this, this implementation of Socharis is not very reusable. This problem has been solved through the development of a shell that allows the redesign of the control architecture of Socharis (or any integrated Generic Task problem-solving system) by enabling:

- immediate access to the system's problem-solving architecture;
- explicit definition of information and control flow between parts of the system;
- and the possibility of on-the-fly changes in the system's architecture, architecture of its parts, and knowledge content.

This article repeatedly emphasizes the importance of manufacturing considerations during the early design stages. The lack of a principled methodology for the design and manufacturing planning activity at the conceptual stage was suggested as a reason for the lack of software support. The availability of such methods and software systems would enable designers to do their jobs more efficiently by generating designs that are more feasible to manufacture and more cost effective. In a world when most manufacturing planning tools are oriented towards detailed planning, it stands to reason that conceptual level planning tools could help. The strategy presented herein is an attempt to provide such a principled methodology for conceptual level manufacturing planning.

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