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A METHODOLOGY FOR THE CONCURRENT DESIGN OF PRODUCTS AND THEIR ASSEMBLY SEQUENCE

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ABSTRACT

This thesis reports on the development of a Two-Tier methodology that provides support for assembly sequence construction, validation and evaluation in parallel with the design. This facilitates the production of products that are optimised for assemblability. The proposed approach diverges significantly from many of the sequence generation methods developed to date, which assume that assembly planning starts at the conclusion of the design process. It is believed that the latter approach misses an important opportunity to concurrently implement design and sequence improvements that would result in products inherently suited to assembly.

The industrial assembly planning process was found to be completely different from the automatic sequence generation approach. The Two-Tier methodology has its foundations in this manual process, which uses a breadth-first, depth-second search. A constraint-based method is used to interactively validate the sequence. In direct contrast to traditional sequence generators, the hard and soft constraints are invoked throughout the process. A novel approach to sequence evaluation allows the user to quantitatively determine the suitability of the sequence at any time during the construction process.

However, designers are rarely assembly experts and it is unreasonable to expect practical sequences to be generated without assistance. Thus, a set of generic assembly planning rules was identified from industrial surveys by the author. These were collaboratively implemented into an Expert Assembler, which currently consists of two mini advisors. Support is available to identify the most suitable base component and the most appropriate component to add next.

The Two-Tier methodology has been implemented into a computer-based system called **SPADE** (Sequence Planning And Design Environment). A four-layer model holds the product data that underpins this implementation. The methodology and **SPADE** have been successfully tested using representative case studies and the results are reported as part of this thesis.

ACKNOWLEDGEMENTS

The main acknowledgement has to be extended to my supervisor Graham Jared, without whom this research would never have been completed. He has encouraged and supported me throughout this work. I should also recognise his speed reading capabilities, which were put to the test as my submission deadline loomed. My unofficial supervisor, Ken Swift, also helped a great deal with this research and I would like to thank him for his views and ideas in the area of assembly

Special thanks should also go to my colleagues, Susan Tate and Gordon Dalgleish who provided endless hours of stimulating discussion, practical help and chocolate biscuits.

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1. INTRODUCTION

Assembly is a critically important function within industry, but it consistently fails to attract the attention and investment that it both deserves and requires. Throughout the manufacturing sector, there is little evidence of substantial progress in this area. Indeed, most assembly work is still undertaken using methods that have changed little in recent years. This is in contrast to the enormous advances in the application of new approaches in the manufacture of engineering components. Those charged with the direction of businesses neglect to identify the importance of assembly improvements. It is no excuse that company accounting systems often cannot explicitly demonstrate cost savings made from assembly. This thesis focuses upon this essential area of production and argues that assembly should be taken into account at all stages of the Product Introduction Process (PIP). To facilitate this, a method is presented for the consideration of assembly during the all-important design stages.

Before delivering goods to market, a number of functions must be completed. Two fundamental stages in the PIP are the product design and its production processes. The latter can be sub divided into the component manufacture and the overall assembly. These processes add value to the product, and thus have a significant impact on the profitability of a company. However, it is incorrect to believe that to reduce costs one must only improve production processes. Whilst progress in this area can decrease overall costs, a step change is only possible if the product design is also optimised. This is because much of the overall cost is built into the product during the design stage. Industry must appreciate this fact and develop strategies to improve designs in terms of manufacturability and assemblability to fully realise major cost reductions.

Figure 1.1 illustrates the split of Gross Domestic Product (GDP) by business sector in the UK. It can be seen that manufacturing contributes 22% to the overall GDP, and as such is a significant contributor to the economy. However, the overall share of the manufacturing sector is decreasing due to foreign imports undercutting our own products. Today's discerning consumer demands high quality products at low prices and therefore is increasingly turning to these imported goods. This can be demonstrated by a look at the lucrative new cars market in the UK. Rover, a domestic company, has been losing market share at an alarming rate to the benefit of overseas manufacturers such as Renault who have seen their market share rise by 31% in the last three years[1]. For British, and indeed all, manufacturers to successfully compete in the global market greater focus must be placed upon improving quality but reducing costs, working smarter not harder. It is apparent that tools and techniques are required to achieve some of these necessary improvements. The Two-Tier methodology proposed in this thesis aims to help with these cost reduction exercises by facilitating the consideration of product assemblability during the design stages. To fully define a process such as this, three distinct development steps must be considered; Product Design, Assembly Planning and the Product Assembly. These will be explored in detail in the following sections of this chapter.

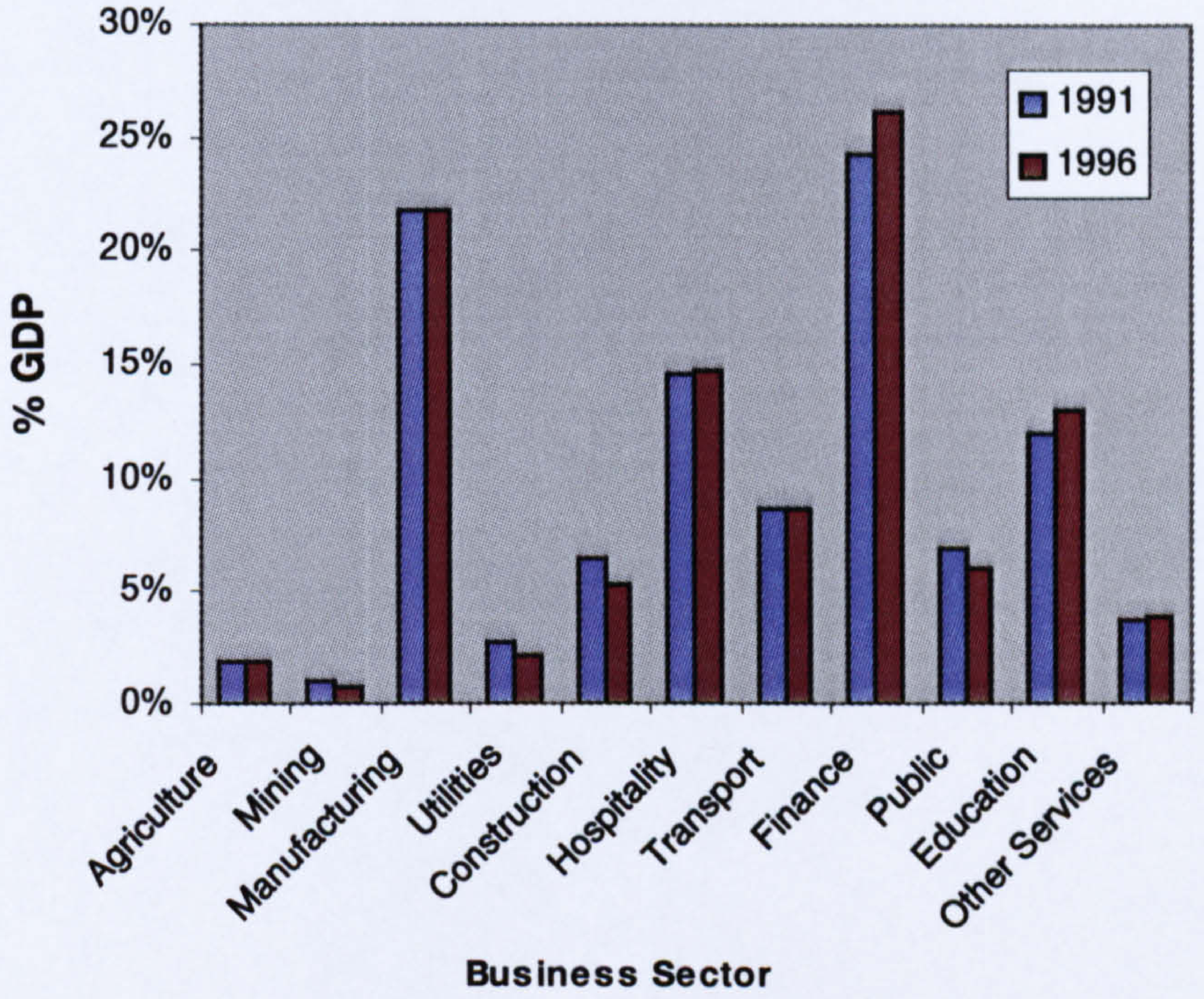

Figure 1.1: ***UK % GDP by Business Sector***

1.1 Product Design

Design is an iterative process involving both creativity and synthesis to solve a problem that results in an identifiable product or system. It has been defined as "the process of establishing requirements based on human needs, transforming them into performance specification and functions, which are then mapped and converted, (subject to constraints) into design solutions (using creativity, scientific principles and technical knowledge) that can be economically manufactured and produced"[2]. However, designers must consider more than functional requirements. It is imperative that it is economically viable to both manufacture and assemble the final product.

1.1.1 Improvements in Product Design

It was once believed that providing Computer-Aided Design (CAD) software would reduce design times and improve overall product design. Whilst CAD has aided many improvements in the production of suitable designs, it could be said that it allows the geometry of poor designs to be captured more quickly. Most current commercially available packages still tend to concentrate upon component oriented design. Individual parts are modelled and only then are these models assembled to create the final product model. To fully explore the assemblability and manufacturability issues of any design a more assembly-oriented approach to design and CAD, in particular, is required. This is termed 'top-down design' and its application allows the consideration of assembly issues whilst the design is actually progressing.

It is generally accepted that optimisation of product assembly during the early stages of design promotes the study of the product as a whole and has been proven to deliver overall cost, quality and time to market improvements. However, to achieve this, industry must move from the traditional "over the wall approach" to design and manufacturing and introduce more collaborative working practices between different business functions. The concurrent engineering philosophy has been proposed as a means to facilitate such co-operation and the simultaneous execution of many product introduction activities. Even though much of industry is aware of the potential benefits of this proactive approach, many designers and manufacturing engineers still fail to discuss assembly issues until after the design is essentially fixed. It is then often too late to make significant changes to the product design because investment has already been added to the current design configuration. This lack of contact is probably due to a number of dependent factors. Historically, communication channels between design and manufacturing are poor and based around formal forums that generally occur once decisions have been taken. In addition, designers would state that products are designed for function. Assemblability and manufacturability should only be considered once the design fulfils the required specification. It is true that a product that does not perform its required function is worthless, it must be able to be manufactured and assembled with minimum cost and effort. The complex and fundamental relationship between the product structure and its assembly processes is simply not understood, neither is it appreciated how assembly improvements can significantly reduce product costs. However, this is extremely difficult to implement in practice as there are few suitable tools and techniques to help engineers consider the many design options and their impact upon assembly.

One group of methodologies has been proposed as the opportunity to help engineers to overcome the barriers to good assembly design. These are known as the Design For Assembly (DFA) methodologies[3,4,5] and consist of a series of structured analyses which calculate the ease of assembly of a set of parts. These have been applied successfully to reduce the number of parts and significantly improve the manufacturability and assemblability of a product. However, DFA methodologies are essentially reactive tools, generally applied late in the design process, which unfortunately acts as an obstacle to their acceptance. Understandably, designers do not like to discover that the product they have spent much time working on is poorly designed from an assembly perspective. At this late stage in the design process, major changes are often impossible due to the investment tied up in the existing configuration. Traditional DFA methodologies can offer little assistance with the identification of assemblability issues early in the product introduction process.

Other advantages can be gained from the application of the DFA analysis because it includes more than just the consideration of handling and fitting problems. An intrinsic, but not always explicit, part of the DFA process is the requirement to define a sequence of assembly. Because the analysis is generally completed towards the end of the design stages, it forces the designer to generate an assembly plan. A designer is rarely expected to document the assembly sequence but this execution of the exercise can only be beneficial. Assemblability issues are then considered earlier and further issues could be identified and resolved before production. However designers are not assembly planning experts and can often make significant errors in the generation of a proposed assembly plan, which can create many additional problems. It is critically important to use an accurate assembly sequence for the DFA analysis. The sequence forms the basis of much of the analysis and an unsuitable sequence invariably results in an inaccurate DFA analysis.

1.2 Assembly Planning

Once a design has been finalised, it is passed to the manufacturing engineers for translation into shop floor tasks and plans. Historically, the assembly plan is first considered at this stage once the design is fixed. However, the increasing implementation of the concurrent engineering philosophy should be beginning to move the task of sequence definition into the design process. However this change in working practices is not underpinned by any tools and techniques to support the engineers and consequently is rarely implemented in practice.

The term 'Assembly Planning' is commonly used to refer to "the process of creating a detailed manufacturing plan to create the whole (product) from separate parts"[6]. 'Assembly Sequence Planning' is generally defined as the subset of assembly planning which only considers the ordering of part placement and the constraints required for definition. It can be argued that any assembly sequence plan that does not take any account of external influences fails to adequately represent reality and is consequently of little use to engineers. This thesis uses the two terms interchangeably to denote the process of defining a plan which details the order of component insertions and associated operations required to create a product from constituent parts.

Other sequence-related words used in this thesis are defined as:

- **Feasible** – it is possible to build the assembly using this sequence but only the hard constraints have been used to check the liaisons.
- **Practical** – the feasible sequence has also been validated using the soft constraints. Thus, the assembly can actually be built using this sequence.

1.2.1 Improvement Of Assembly Planning

Until recently, assembly planning was a manual process that relied completely upon the experience and ability of the individual manufacturing engineer to produce a good plan. The last decade has seen a significant increase in the attention this area has attracted from the research community. Much work has been devoted to the development of methodologies and software that use a complete geometric description of a product to create a correct and complete assembly plan. Constraints are often applied to the sequence generation process to ensure that the plan is both feasible and practical. Two types of constraints are generally used, which are often termed hard and soft constraints. Hard Constraints deal with the geometric feasibility of the assembly. Soft Constraints constitute suggestions for 'best practice' and so, whilst particular options may be feasible, they may not be recommended. By definition, a valid assembly sequence will not violate any hard constraints and will satisfy as many of the soft constraints as the user feels is acceptable after consideration of any potential conflicts.

The high level of complexity involved in this task has meant that no single planner has been developed which can perform a fully automatic assembly sequence definition on any industrial product. The proposed systems include varying degrees of automation but most still rely upon tedious levels of user input. This fact has contributed to little evidence of industrial application of the methods and systems developed to date. In most of the proposed systems, the assembly sequence generation commences after the design has been completed. This eliminates the possibility of exploiting any knowledge gained from the sequence construction to further improve the design. If the sequence generation and the design process were more aligned; it would lead to the production of designs that are better suited to the assembly processes involved. This thesis describes a way of exploiting this opportunity to produce designs that are optimised in terms of overall assemblability.

1.3 Product Assembly

Once a design has been finalised, parts are manufactured and then brought together to be assembled into the complete product. Assembly can thus be defined as "the process of putting together a number of parts to make a machine or other product"[7]. The methods and stages of the assembly process are generally detailed before production in an assembly sequence. However there are a number of widely available types of assembly systems for the building of products. Robotic assembly was once seen as the answer to every assembly problem because repeatability is assured. Unfortunately, there are many negatives to the introduction of robots that have significantly limited their introduction. Robots are expensive to install and thus, to be commercially viable, must be utilised as much as possible. The complexity of many product ranges mean that many different assembly tasks are required and industry is often not able to provide the necessary work time to economically employ robotic assembly techniques. It is a sad fact that on many shop floors an unused robot sits gathering dust, the result of an expensive error of judgement, whilst engineers are busily employed manually assembling the current products. However, the high cost of labour in some Asian economies has forced industry into the use of robotics to assemble many products.

Novel design approaches have ensured that their products are suitable for this form of assembly. Another type of assembly system is automatic assembly. This is essentially an assembly machine that follows a predefined program. This approach is often more flexible than robotics as careful design of change parts can allow a number of different products to be assembled. The final assembly system, manual assembly, offers the most adaptable process and comprises an operator who carries out the predefined assembly tasks using simple tools and fixtures. This can consist of anything, from one operator at a single bench assembling a product from start to finish, to a line of operators completing repetitive tasks as the product reaches their station.

1.3.1 Improvement Of Product Assembly

In recent years, there has been much focus on understanding and improving manufacturing processes seemingly at the expense of assembly. This may be because in many industries, the impact of product assembly upon overall costs is grossly underestimated. Current figures suggest that in a high volume business, 50 to 70% of the product cost is accounted for by raw materials and bought-in items and direct labour is in the order of 30% of the overall cost. Only half of these direct labour costs are specifically attributable to assembly processes[8], so it could be assumed that effort would be better spent improving other areas. However, this does not account for the fact that assembly can be shown to contribute significantly to the 'hidden' product costs such as rework and scrap, which are often neglected when it comes to the analysis of product costing. Many of these hidden costs are built into a product early in the design process. Thus, it would seem that the focus could be better placed upon designing products that are easy to assemble and not on the assembly processes themselves.

A recently completed survey of the US requirements to improve assembly in industry[9] aimed to identify the assembly processes and support that would most impact overall product costs. The results of this investigation are presented in Figure 1.1.

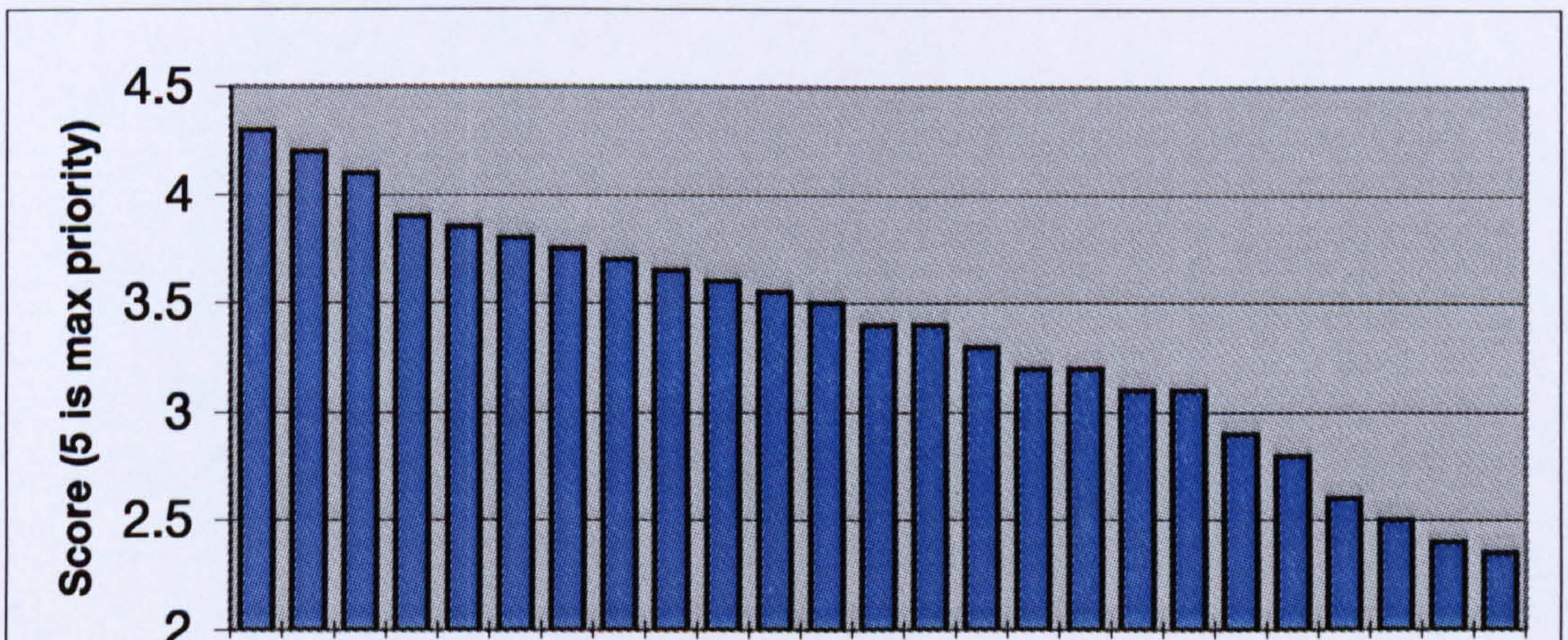

Figure 1.2: ***Scores For Assembly Process Improvement Priorities from Industrial Survey***

It can be seen that that US industry believes that the application of DFA is the single most important method that could improve their assembly processes. It is believed that the next level of improvement could be gained by applying a number of support activities. Of these, it can be seen that assembly planning is a major concern. This could be said to confirm the need for the Two-Tier methodology proposed in this thesis, which details how the assembly sequence planning and DFA can be integrated into the design process. The survey shows there is a perceived need for tools that do not focus upon improving the actual assembly processes but rather concentrate upon the design of products which are easy to assemble.

1.4 Problem Formulation

The previous discussion has highlighted a number of serious issues with the design and assembly of products in the manufacturing sector. There are solutions to these problems, but significant modifications to current working practices are involved. In addition, few robust methods have been developed which could assist industry to implement these necessary changes. The improvements required to increase the competitiveness of many manufacturing businesses are as follows:

- Designers should design assemblies not parts.
- Assembly improvements should be considered in the design phase
- Designs should be analysed for assemblability issues prior to production.
- Good quality assembly plans should be generated as early as possible.

The recent areas of research focus have provided few tools and techniques that can help industry to overcome these issues. The various DFA methodologies have had some success, but are generally applied too late in the design process to help with the issues raised. The evolution and integration of CAD systems into the design process has hindered the consideration of assembly issues due to their part centred approach. Industry has failed to appreciate the necessity of a good assembly plan. Academia has spent much time trying to develop methods for automatically generating such a plan from a complete product description, but with little success. It is these wide ranging issues that this thesis will try to address by asking the question:

> ***How can an assembly sequence be developed in conjunction with a design in a way that can exploit the benefits to be gained from their concurrent consideration?***

In order to attempt to answer this challenging question, a number of issues must be tackled.

1. What is the current best practice in industrial design processes?
2. What is the current best practice in industrial assembly planning process?
3. Are these defined processes suitable for use in determining a process for concurrent generation of the assembly sequence and design and what should this process be?
4. Are constraints the best way to validate the design and sequence and what is the generic list of planning constraints that can be used to represent reality?
5. Can the assembly rules from the DFA analyses be integrated into this process to help identify and quantify general assemblability issues?

6. How can the assembly sequence be appropriately evaluated to ensure the optimum sequence is defined?

The scope of this work is intentionally broad. It is believed that the defined methodology is as valid for automobile assembly as it is for specialist electronic equipment. By necessity, only a number of applications of the process can be documented but it is hoped that throughout, the reader will appreciate the generic nature of this work and extrapolate the findings into alternative applications.

1.5 Outline Of Thesis

This thesis proposes a methodology for generating the assembly sequence concurrently within the design process. Appropriate support is provided for the definition of the assembly structure and construction of the sequence. Feasible and practical sequences are ensured by judicious use of validation and evaluation modules that analyse the developing design and sequence in terms of assemblability. Assistance is given in the construction of the sequence, which aims to guide the designer towards the optimum configuration. The chapters of this thesis can be classified as shown in Figure 1.3.

Chapters 1,2 and 3
Introduction and Background

Chapters 4,5,6,7,8 and 9
Definition of the Methodology

Chapters 10 and 11
Methodology Applications

Chapter 12
Conclusions

Figure 1.3: ***Layout of the Thesis***

Chapters 1, 2 and 3 of this thesis define the state of the art in assembly sequence generation and design. Chapter 1, the introductory section, provides a framework for the research. The next chapter details all the associated research in the context of four very different, but interrelated, areas. Chapter 3 reports on a series of visits to a number of diverse British manufacturing companies to try to define a best practice for assembly sequence generation and connects the work in the thesis to industrial practice. The main portion of the thesis concentrates upon the definition of the Two-Tier methodology for the concurrent consideration of the assembly sequence generation and the design. The general sequence generation and design process is defined in Chapter 4. Looking in more detail, the role of the assembly structure definition is covered in Chapter 5. Chapter 6 details the requirements of the sequence construction process. Designer assistance is considered with a discussion on the use and implementation of expert system help for the generation of assembly sequences in Chapter 7. The validation processes and suitable evaluation metrics are discussed in Chapters 8 and 9. The methodology is implemented into a **S**equence **P**lanning **A**nd **D**esign **E**nvironment, **SPADE,** and tested with three industrial case studies in the penultimate section that comprises Chapters 10 and 11. Finally Chapter 12 presents the conclusions that discuss the use and applicability of the defined methodology and identifies opportunities for further investigations.

2. BACKGROUND

Research into methods to facilitate concurrent generation of the design and the assembly sequence has been identified as an emerging area, which requires much work to improve the understanding of the complex interrelationships[10]. The research aims to take an important step towards providing tools which can help to create an industrial sector that can produce cheaper products in a shorter timeframe. Much of the work in the area of Computer Aided Assembly Planning (CAAP) has concentrated upon solving the problem of finding an appropriate assembly sequence once the design is complete. This approach may improve the current situation, in which a manufacturing engineer takes a complete design and produces the assembly plan, by ensuring the construction of a complete and correct sequence that is optimised for the circumstances involved. It does not, however, support the trend towards concurrent engineering and enable the sequence generation to be completed simultaneously with the design process. It is disappointing that current research directions have failed to develop any methodologies for the analysis of the assemblability of a product whilst the design is still in development. Many processes have been proposed for the generation of an assembly sequence from a complete product representation, but little consideration has been given to the complex interactions between the design and its sequence. This chapter reviews literature pertinent to the development of a process for the concurrent generation of sequence and design but finds few ideas and methods that are of immediate use. Simultaneous sequence generation and design processes draw ideas from a number of active research areas, pulling together the different philosophies and methods. To understand fully the contribution of the work reported in this thesis, it is necessary to appreciate four of these research areas in detail. These are as follows:

- *Development Of Tools to Aid Assembly Planning*
  Work towards the determination of an environment that can help Industrial Assembly Planners take a completed description of the design and produce a practical and feasible assembly sequence. Work in this area is generally termed Computer Aided Assembly Planning (CAAP).

- *Advancement Towards A Methodology To Evaluate Designs For Assemblability*
  Development of novel ways to analyse a completed design in terms of assemblability and occasionally, manufacturability. These methodologies are generically known as Design For Assembly (DFA) analyses.

- *Identification Of An Integrated Process Of All Tasks Needed To Develop A New Product*
  The definition of design process models, which have recently evolved into the more business-oriented Product Introduction Process (PIP). These models define the links between the core design process and the other functions that are required to develop a new product successfully.
- *Progress Towards A Process For The Concurrent Generation of The Assembly Sequence and The Design*
  Research aimed at the realisation of an environment that can provide assistance to construct the assembly sequences and create designs simultaneously.

2.1 Computer Aided Assembly Planning, (CAAP)

CAAP research has developed from the world of robotics and concentrates upon solving the problem of finding the most suitable assembly sequence for a complete product. It is a well funded area of research which has provided a wealth of published literature, most of which only addresses a small sub-problem within the overall issue[10,11]. The area is a complex one, integrating many aspects of engineering and computing research. The overall research issues will now be outlined in the order that they are considered when building a sequence.

Firstly, the assembly representation must be defined and the method of acquiring the data. This is often input directly into the planner or alternatively can be inferred directly from a geometric model. Once this issue has been resolved, the attributes relevant to the particular planner's data requirements must be extracted or inferred from this representation. This can take the form of part connectivity graphs, precedence relationships or a combination of these and many other data types. The search for the optimum assembly sequence can now commence. Again, there are as many variations of this as there are assembly planning systems implemented. In general, CAAP systems have three separate modules that combine to complete this task; sequence construction, the validation of the generated sequences and then the application of evaluation to find the optimum plan. The construction techniques are primarily concerned with sorting through the many part combinations for a feasible solution. These search techniques vary considerably and employ many different methods to narrow the extensive search space. This pruning is often achieved by the application of suitable constraints, which are also used to validate the set of generated sequences for feasibility and practicality. Once a set of potential sequences is available, they can be evaluated to find the optimum sequence for the defined circumstances. However, many systems stop at the validation step and expect the user to identify the best sequence from the set.

The review presented here is not attempting to be exhaustive, it serves to introduce the main themes of recent work and pull together the similarities and indeed differences, of the many approaches proposed. It will also demonstrate the evolution of these systems through time, from early attempts to automate the process fully, to the realisation that a more user interactive method yields a quicker and more practical result. The discussion will focus upon entire systems reported, not the proposed solution of smaller sub-problems. Separate consideration of these 'single-issue' methods will be discussed, where relevant, throughout the main body of this thesis.

2.1.1 Automatic Sequence Generation - The First Approaches

In the mid 1980's a seminal thesis[12] was published, which detailed a method for generating an assembly sequence algorithmically using a predefined set of rules. Information was gained from a parts list and an assembly drawing to generate a network where nodes represented parts and the lines between the nodes defined a liaison[a]. The user was then asked a series of questions. Precedence rules were developed which depended on the answers to these questions. A search generated an inverted tree or liaison diagram, Figure 2.1, often also called "Diamond Graph", that documented all sequences for the given assembly. The state of the assembly at any rank is represented by a rectangle filled with smaller rectangles, which indicate the individual liaisons. A white cell indicates that the liaison has not been closed and a black cell shows a completed liaison. The lines connecting the boxes represent the state transitions. The liaison graph proceeds from fully disassembled to fully assembled. The number of different paths possible through the state transitions represent all possible assembly sequences. If *l* is the number of liaisons, (L), this method involves asking the user $2l^2$ questions of the form:

1. Is it true that L_i cannot be done after L_j and L_k have been done?
2. Is it true that L_i cannot be done if L_j and L_k are still undone?

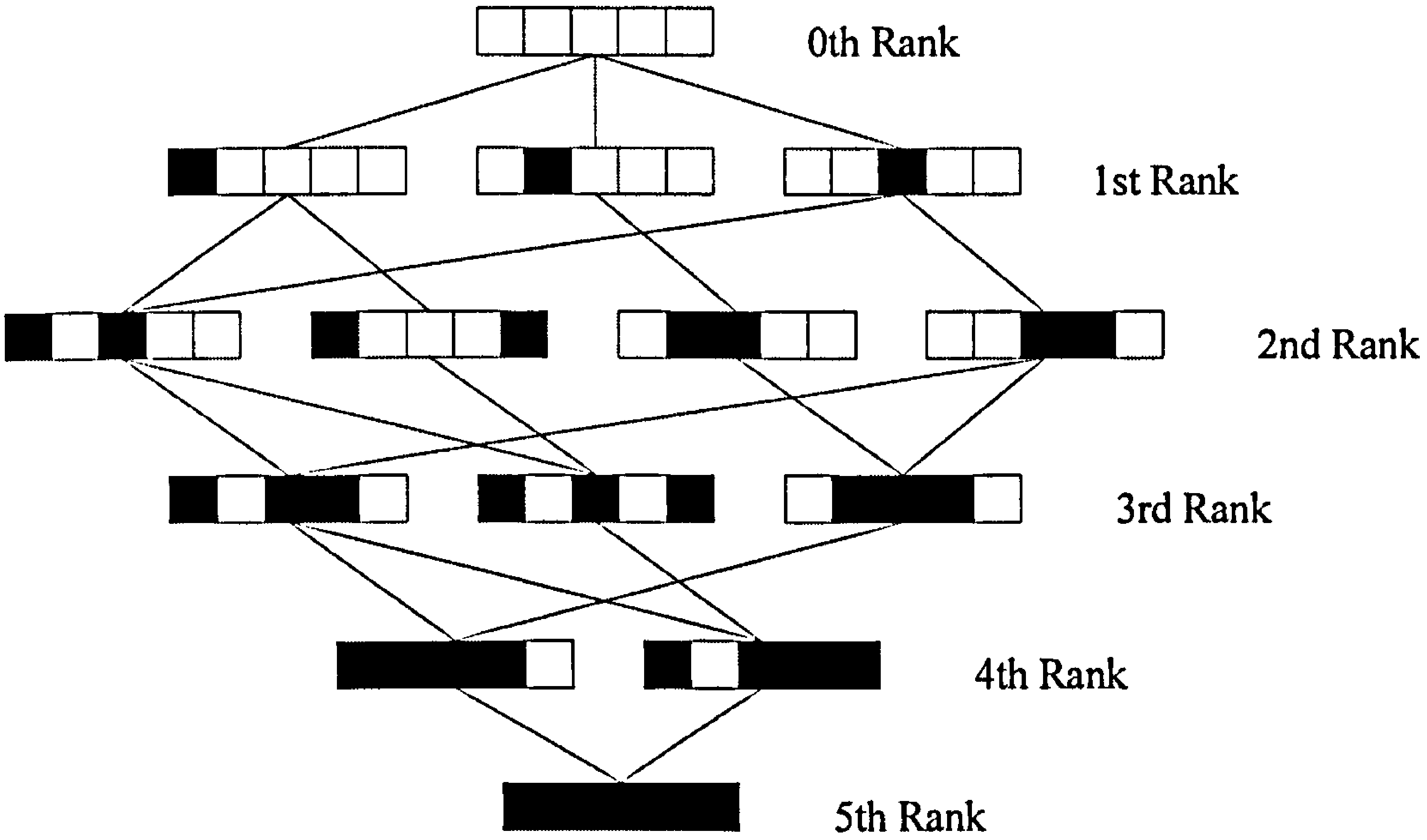

Figure 2.1: ***Liaison Diagram or Diamond Graph***

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[a] Both Bourjault, and De Fazio and Whitney define a liaison as "a close bond or connection", which generally, involves a physical contact. The author will continue to use this definition throughout.

For even a relatively simple assembly, the answering of these questions may require the user to employ advanced geometric reasoning techniques. The number and complexity of the questions necessitates a large amount of effort on the part of the user. Because of this difficulty, the method of sequence generation was refined to simplify the user questioning[13,14]. This reduced the number of questions to *2l.* These questions must be answered for each liaison and took the form:

1. What liaisons must be done before doing L_i?
2. What liaisons must be left to be done after doing L_i?

It could be argued that this set of questions is significantly more difficult to answer than the original set. However, it is pointed out that the latter closely resembles those that a production engineer asks when commencing the manual sequence generation of an unfamiliar product. It is thus said to be no more difficult.

Once the complete set of questions is answered and the precedence relationships determined, the initial liaison graph must be generated. This is achieved by finding all possible first liaisons, "1st Rank" and then searching for all the potential "2nd Rank" liaisons, and so on until all the relationships have been searched and included in the graph. Once the liaison graph is complete, the number of defined sequences should be pruned to a manageable size for analysis. At this point in the analysis the method applies the constraints detailed below:

- Avoidance of a large number of subassemblies.
- Assembly to be completed within a designated region before assembly within any other region begins.
- Ordering the assembly sequence of a subset of parts.
- A part group assembled in sequence but concerning the order within the group.
- Assembly is to pass through one or more specific subassembly states.

The use of such constraints can remove unwanted states and state transitions from the liaison graph, which generally leaves a few good sequences from which the user must choose. The application of constraining rules at this late stage in the sequence generation process does not effectively narrow the search space for the generation of the initial liaison graph. This means that a large number of state transitions are identified, only to be discarded immediately when the constraints are invoked. Whilst this was an important piece of research, many opportunities for refinement and improvement were available which will be seen to be exploited later.

Around the same time as the development of the liaison diagram method, another assembly planning approach was proposed. This involved the generation of a form of hypergraph, called the AND/OR graph[15]. Figure 2.2 shows a typical AND/OR graph, where white and black squares represent unassembled and assembled parts respectively, from a complete product to a totally unconnected set of parts. The nodes each define a database describing a state of the product being assembled. The hyperarcs leaving a particular node correspond to a particular method of disassembly for any partial assembly. Each hyperarc points to the resulting two partial assemblies remaining from that disassembly operation. This representation also offers a complete view of all possible assembly sequences for a particular product, but again is often difficult to interpret for complex assemblies. The AND/OR graph is generated using a decomposition disassembly approach[16]. The disassembly of a product is broken down into the disassembly of two subassemblies. This method of breaking the partial assembly into all possible decompositions is continued until all parts are disassembled. The approach assumes that any path through the AND/OR graph represents the exact reverse of the assembly sequence.

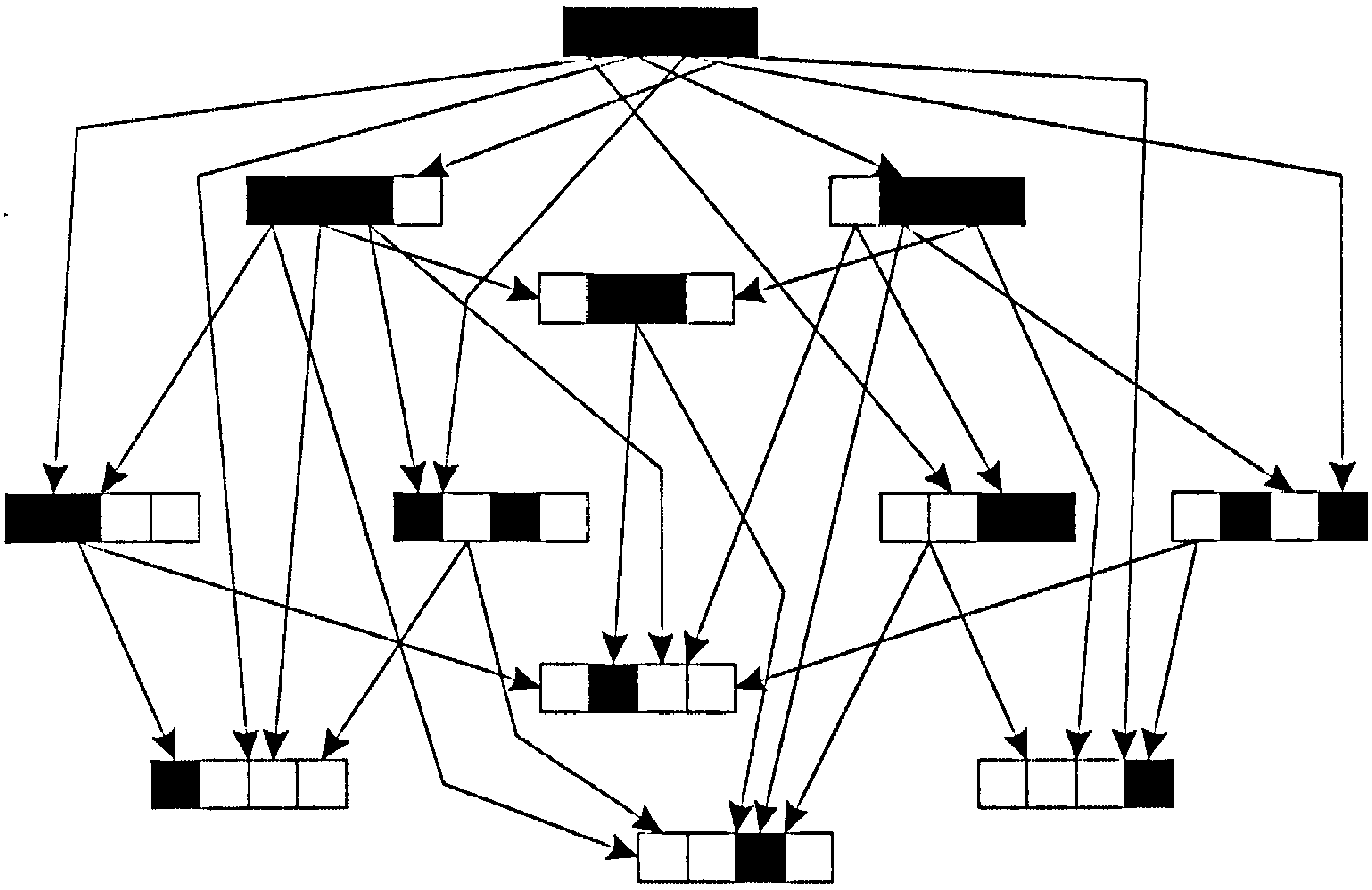

Figure 2.2: *AND/OR Graph*

A decomposition is said to be feasible if it satisfies two separate assertions:

- TASK FEASIBILITY- The task of joining the two subassemblies is possible if it satisfies both internal and external conditions. An example of an internal condition is one which depends solely on the assembly; the existence of a collision free path and the accessibility of fasteners. External conditions also depend upon factors outside that actual assembly and include tool accessibility and handling equipment availability.
- SUBASSEMBLY STABILITY – When a part is added, all other parts maintain position and do not spontaneously break contact.

Once all the decompositions are enumerated for feasibility, the construction of the AND/OR graph is completed. Each of these decompositions or cutsets correspond to a hyperarc in the graph. The relational model of the assembly is used to iterate through the list of feasible decompositions and produce the AND/OR graph of all possible assembly sequences. In effect, this method checks each assembly operation for suitability before the expensive computation generates the list of all sequences. This is a much more efficient approach than the liaison diagram, which is generated purely on precedence relationships and the search space is not pruned until after the generation of the set of sequences. Despite their apparent differences, these two representations have been shown to be correct and complete, interrelated and able to be derived from each other[17].

These two approaches, whilst being very different, laid the foundations for the growing field of CAAP. The only assembly operations considered consisted of rudimentary part placements. Reorientations or the use of workholders was not included. Most research since these important pieces of work has concentrated upon improving the search strategy and narrowing the search space to improve the sequences generated and the speed of computation. In addition, some later approaches allow the inclusion of a more detailed level of operation to increase the practicality and usefulness of the resultant plan.

2.1.2 Discussion Of The Differing Approaches To CAAP

Since this early work, there has been an increase in the interest in this topic and thus a large quantity of literature has been published, a representative selection will be summarised in this section. The focus of this discussion will be the search strategy to define the set of feasible assembly sequences and a comparison of the methods used to cut down the search space and thus avoid unnecessary computation. Individual system developments and refinements will also be covered where possible.

An early attempt at an automatic sequence generation was defined in the XAP/1 CAAP system[18], which could only generate linear plans. It is based upon insertion operations, represented by a subassembly tree, Figure 2.3. These tasks are defined at a lower level than the liaison diagrams or AND/OR graph methods. Each node relates to a part or subassembly to be inserted. The horizontal links define the order of insertion and the other lines connect to children of the nodes. Insertion trajectories and precedence relationships must be manually input into the planner to define the set of assertions that are needed to generate a plan. Constraints are defined as the mandatory relationships between these assertion sets. The generation process subdivides the assertion set until a single plan is found. This could be repeated until all combinations of assertions are translated into plans. However, XAP/1 does not claim to identify all possible plans, rather it searches for the optimal linear plan for the assembly using a variation of the A*[b] search. This is achieved by defining an optimal ratings function, f (P). If this was calculated for a complete plan it would be the sum of all the applied heuristic evaluation criteria. Because the enumeration of this function is to be used to narrow the search space, f (P) ratings estimates are evaluated to determine if plans are worthy of further refinement. The novelty of the approach is the discarding of unpromising sequences during the generation process. This is an intermediate situation between liaison diagrams where pruning does not occur until the end of the sequence computation and the AND/OR graphs where each cutset is validated before adding to the graph. Because XAP/1 operates at a lower level of detail and explicitly represents insertion trajectories, many of the validations are simpler to enumerate. However, this makes it difficult to represent directly any other types of assembly operations such as reorientations or transfers.

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[b] A heuristic search based upon the best first search which guarantees an optimal solution

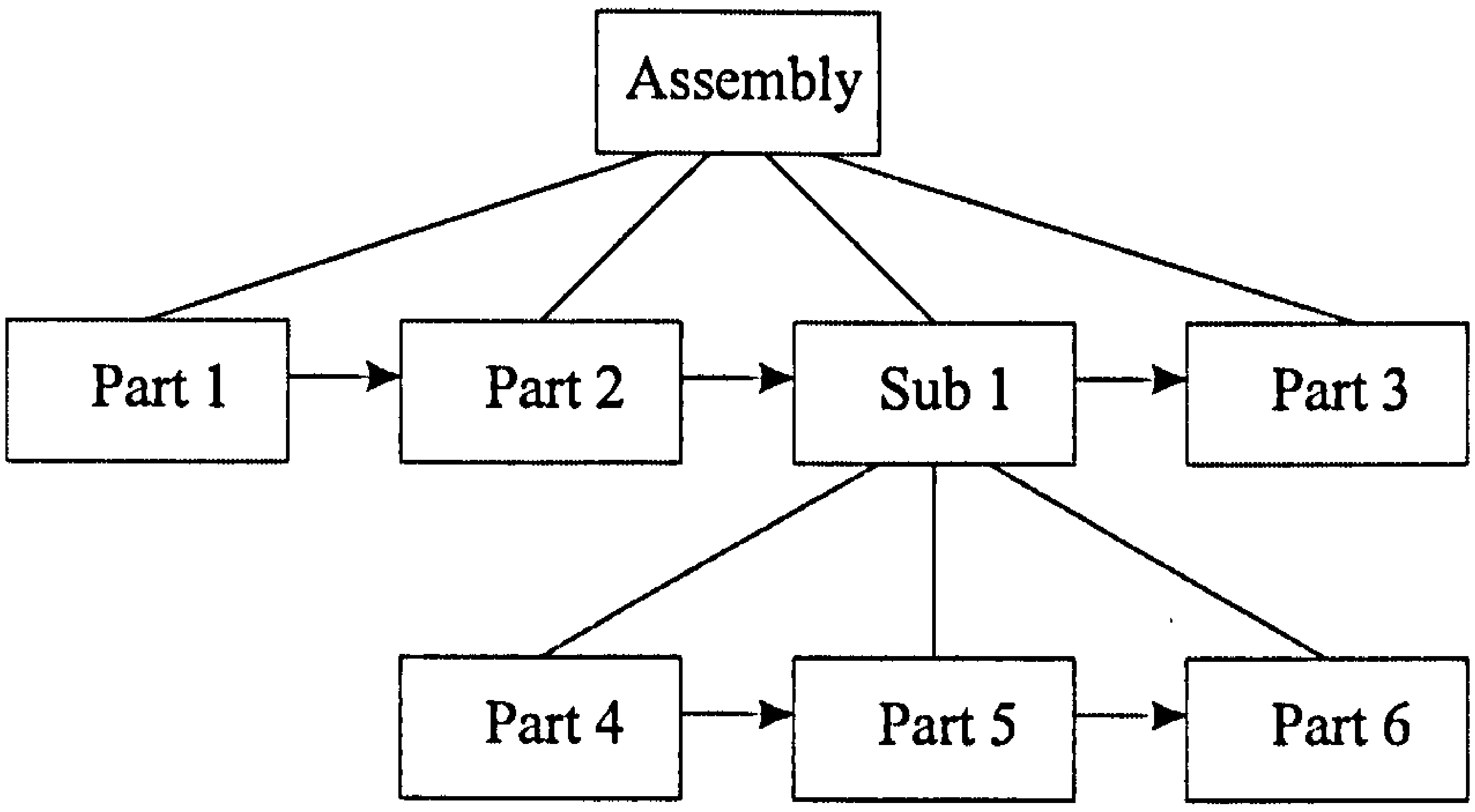

Figure 2.3: ***Subassembly Tree as Used in XAP/1***

XAP/1 represented a significant step in automatic sequence generation but was limited by its inability to produce plans with subassemblies. Thus, the method has been extended to allow the planning of subassemblies[19]. The assertion sets are generalised and are now based upon a deepest common ancestor relation[20]. By not identifying directly the subassembly that a particular part belongs to, the search can continue, as before, extra assertion sets are not necessary for the subassemblies. This has considerably complicated the search, but has enabled the planner to be applied to industrial assembly examples.

Because of the amount of geometric data needed to be entered by the user to enable the generation of the assembly sequence, it was inevitable that steps would be taken to link this process to a CAD modeller. An early attempt at this was 3D MAPS[21]. The geometric model describes parts and spatial relationship and a symbolic frame based representation is used to hold the non-geometric data. Mating faces, connectivity relationships, insertion directions and collision information are generated using appropriate algorithms. This data is stored in Part Connectivity Graphs (PCG), Mating Direction Graphs (MDG) and Spatial Constraint Graphs (SCG). The graphs and the assembly solid model are input into the two stage planning process. This sequence generation method decomposes these graphs into an Assembly Precedence Diagram (APD), see Figure 2.4. As the name suggests, this representation indicates which parts must be inserted before which others. A set of heuristics and the non-geometric attributes are used to create the final set of feasible plans, as defined in the APD. This approach is somewhat different to the non-CAD-linked methods described previously. Automatic derivation of the precedence relationships and mating conditions adds an additional, non-trivial level of complexity to the system. It is reported that it is this computation which takes the majority of the analysis time. However, more geometric criteria are inferred from the model than are input by the user in the previously described systems, but the additional criteria to narrow the search space are not applied.

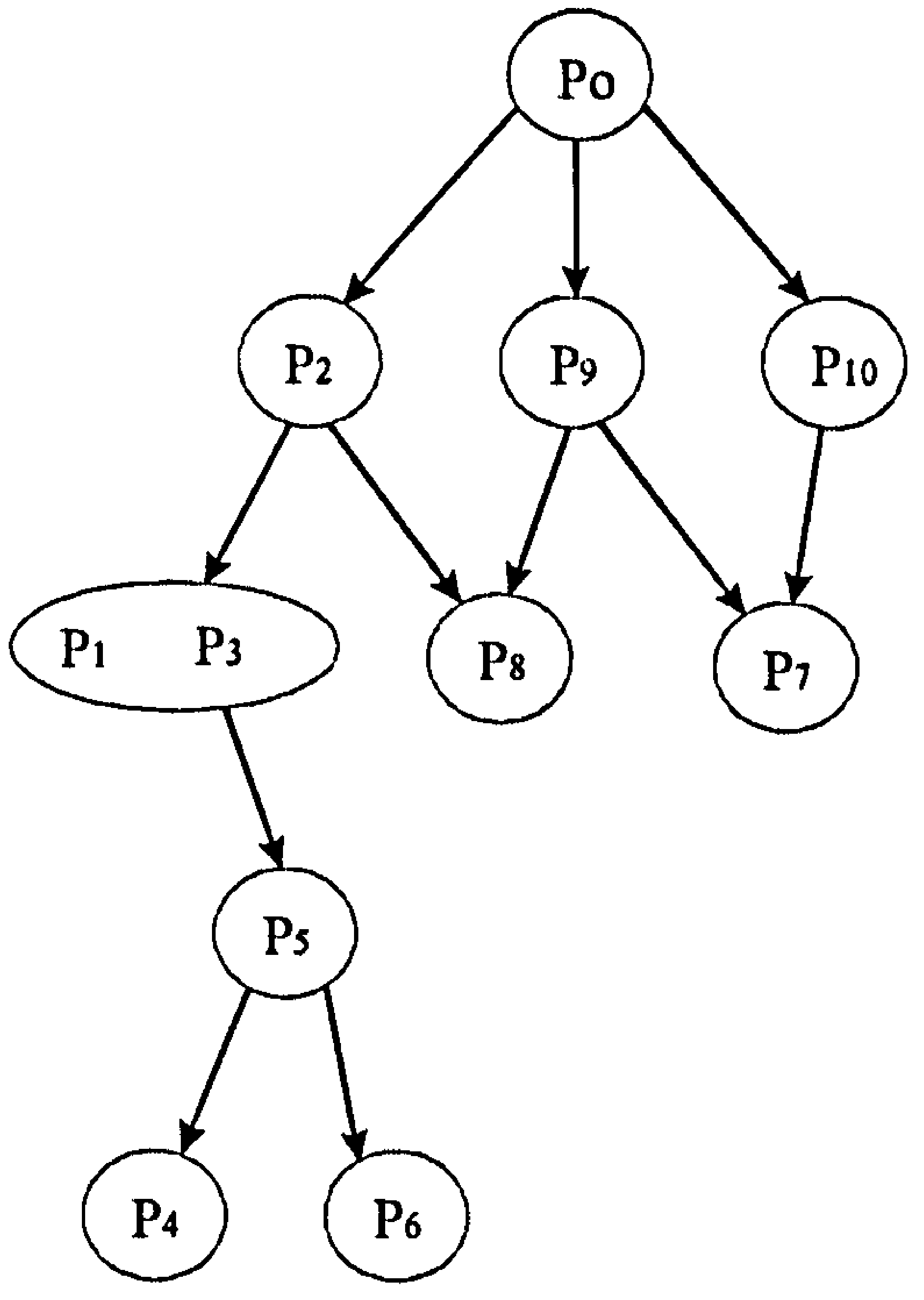

Figure 2.4: ***Assembly Precedence Diagram***

Another CAAPS system with links to robotic systems is FLAPS[22], which uses the geometric description of the product. Interestingly, technical assembly knowledge and details of the working area are considered in the definition of the optimum plan. Figure 2.5 shows a schematic of the system, which, in contrast to the previously described systems, includes modules for gripper and tool selection and assembly plant simulation. This makes this system far more comprehensive and potentially capable of creating actual plans. The sequence generation process utilises the CAD model and operates a disassembly approach. A compromise has been reached between automation and user input because of the computational expense of finding part collisions along every axis. Thus, the user is required to input trajectories for each component. There are four stages to the sequence generation. Firstly, the part contacts are defined along the 6 major axes to build a table of contacts. This is used to recognise possible subassemblies for inclusion in the final sequence. Once the user has defined a base part, the sequence generation algorithm iteratively obtains the elements and their extraction direction from the table of contacts and removes the element when planned in the sequence. This method finds all the geometrically feasible sequences and does not narrow the search space with constraints until these are defined.

This system is interesting because other attributes of the sequence are considered as well as assembly geometry. The inclusion of external factors such as tool selection means that appropriate relevant criteria are used to find the most suitable sequence generated by the system

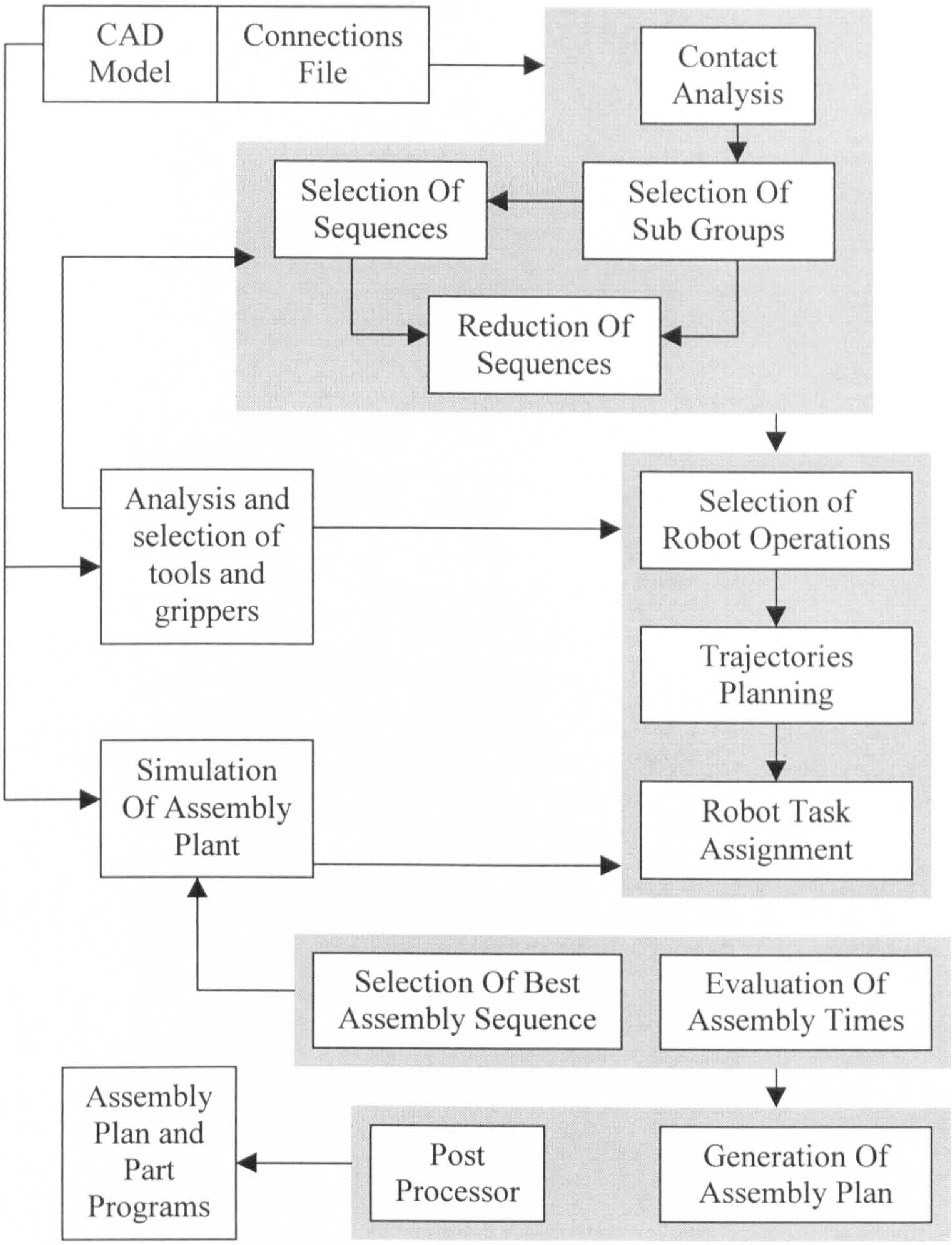

Figure 2.5: ***Schematic of the FLAPS CAAPS system***

Similar ideas to those presented in FLAPS were included in a CAD-based automatic sequence generation system called CIAPS[23,24], see Figure 2.6. This again comprised a method for automatically generating and evaluating an assembly sequence from a suitable solid model, however, no user interaction was required to find the set of all geometrically feasible sequences.

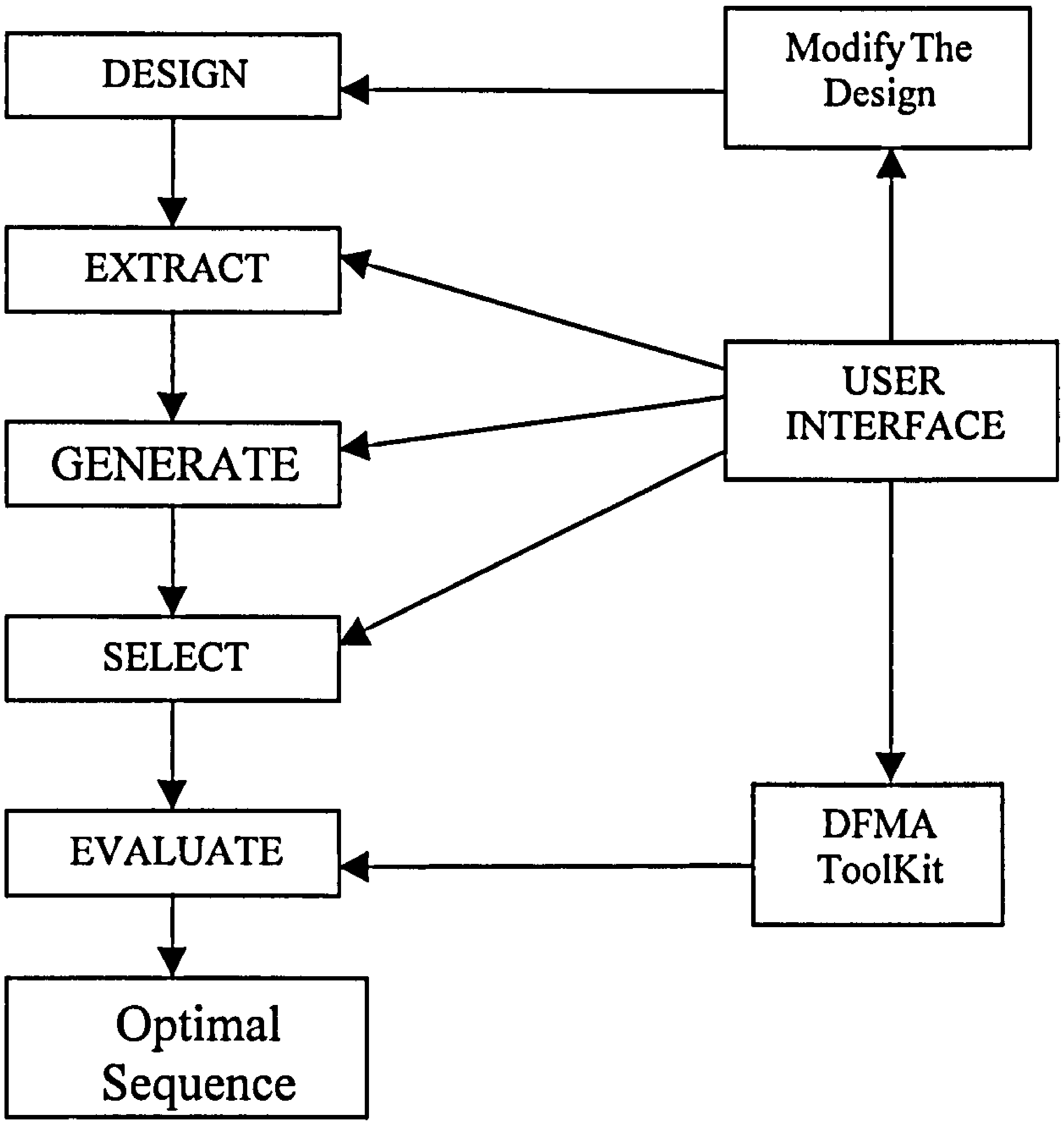

Figure 2.6: *Architecture Of CIAPS*

The sequence generation process is divided into three stages. The initial stage extracts the direction of potential part collisions and precedence knowledge from the solid model data in terms of contact and translational functions. Secondly, two procedures use this data to generate all the feasible sequences. The contact function is checked to list all the feasible assembly pairs. Then the algorithm attempts to add other components to these pairs to create higher order subassemblies. This is achieved by analysing the contact and precedence relationships. Once these subassemblies are defined, the process is repeated to find the contacts between these subassemblies and thus create the assembly sequence. Finally, the constraints are applied and the resultant sequence states must be manually edited to facilitate the selection of several candidate assembly plans. Like many other systems, CIAPS only applies geometric constraints initially to narrow the search space. For complex assemblies this can lead to many feasible sequences being generated. An extensive list of quantitative and qualitative criteria is used to remove impractical sequences, but many of these are computationally expensive. Thus, it is interesting to note that a user edit facility is included to allow the user to eliminate unsuitable sequences. The DFA Toolkit software is used to evaluate the remaining small number of sequences to identify the best sequence.

The three identified stages of sequence construction, validation and evaluation are easily apparent in this method, although some geometric validation is included in the initial creation of the feasible sequence set. The use of the DFA analysis for this purpose is somewhat of a contradiction in philosophy. By definition, DFA should be applied at the design stage to ensure that any design passed to production is optimised in terms of assemblability. In CIAPS, it is used in the production stage to check for the best assembly sequence. An opportunity has been missed in this approach. The DFA analysis can highlight areas of sub-optimal design; another iteration could ensure these are addressed before production.

The ARCHIMEDES[25,26] is a comprehensive assembly planning system which generates appropriately coded sequences for a dedicated robotics work cell. The ARCHIMEDES has been developed over a period and there are several versions of the system reported in the literature. The Architecture of ARCHIMEDES 2 is shown in Figure 2.7. The system requires inputs of part solid models, mating information, subassembly recommendations and possible insertion directions. The State Space Planner calls the 'Geometric Engine' to find the geometrically valid component movements. This identifies all the part to part contacts and insertion trajectories and stores the data in the Non-directional blocking graph, (NDBG). This data is used to find all feasible subassembly partitions[27]. The State Space Planner uses a standard A* search algorithm to find the set of feasible assembly sequences from a search space based around the AND/OR graph of subassembly states and operations. It applies an extensive list of additional constraints, such as tooling considerations[28,29] to identify an optimum plan based upon cost factors. The Illustrator module simulates the assembly plans to enable visualisation of the final sequence and the Translator compiles the plan into V+ robotics code.

The underlying data structure, NDBG[6,30], was first implemented in a prototype system called GRASP[6]. It represents contact relationships in assemblies by taking a component and defining the adjacent parts that would block an infinitesimal translation. ARCHIMEDES has been based upon this first attempt at a CAD-linked automated sequence planning system. The original aims, like many other systems, was to provide a "Black Box" system that took solid models as input and returned a practical and feasible assembly sequence as its output. It is apparent that through time and the realisation of the difficulty of this task, the aspirations towards totally automated assembly sequence generation changed to allow increasing amounts of user interaction. Later revisions of the ARCHIMEDES software aim to find a balance between user input and the judicious use of automation.

A comprehensive survey of assembly planning constraints was completed[31,32], which was used to refine the current implementation[33] from a computationally complex automatic plan generation system to a more intuitive and interactive piece of software, ARCHIMEDES 4.0, see Figure 2.8.

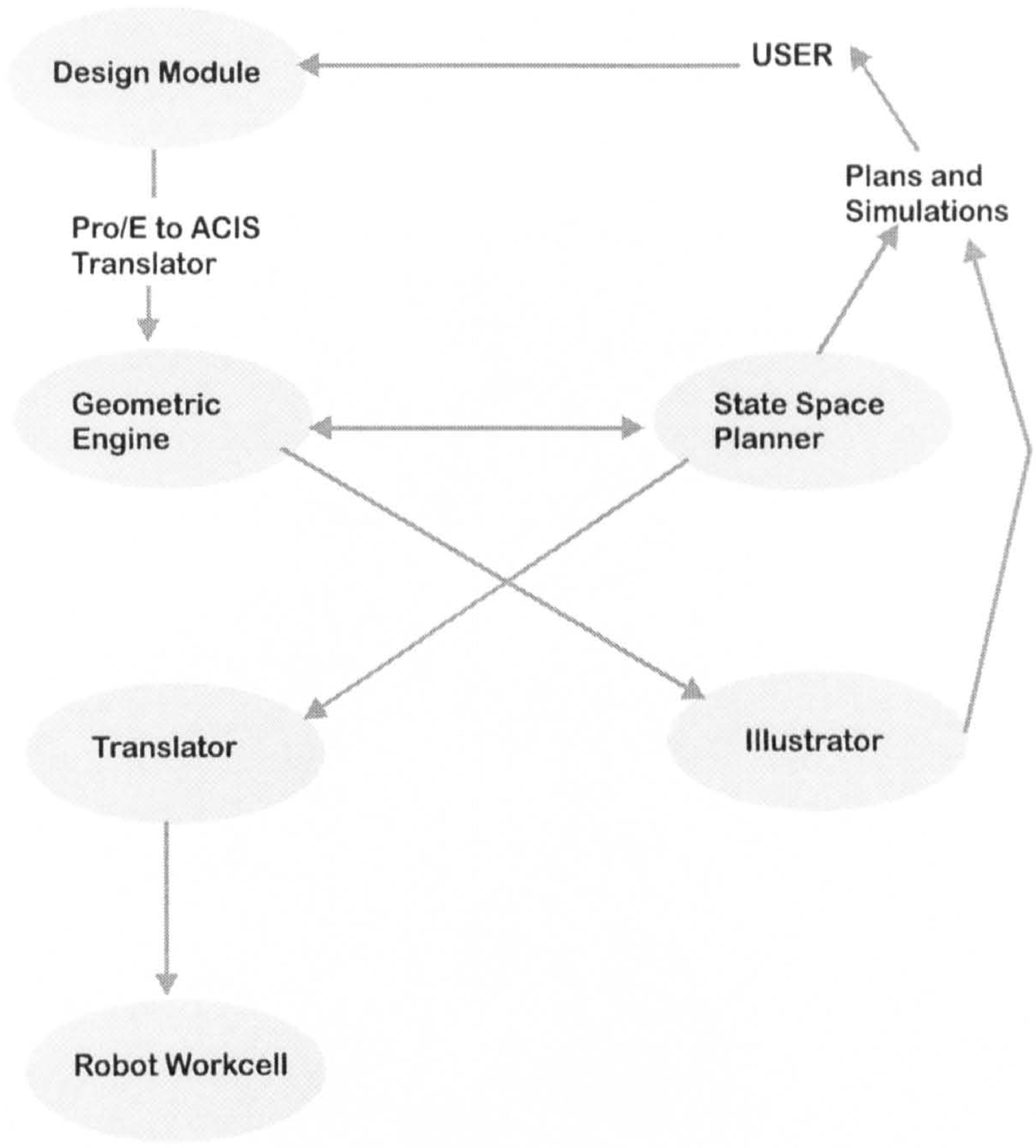

Figure 2.7: ***Architecture of the ARCHIMEDES 2 Assembly Planning System***

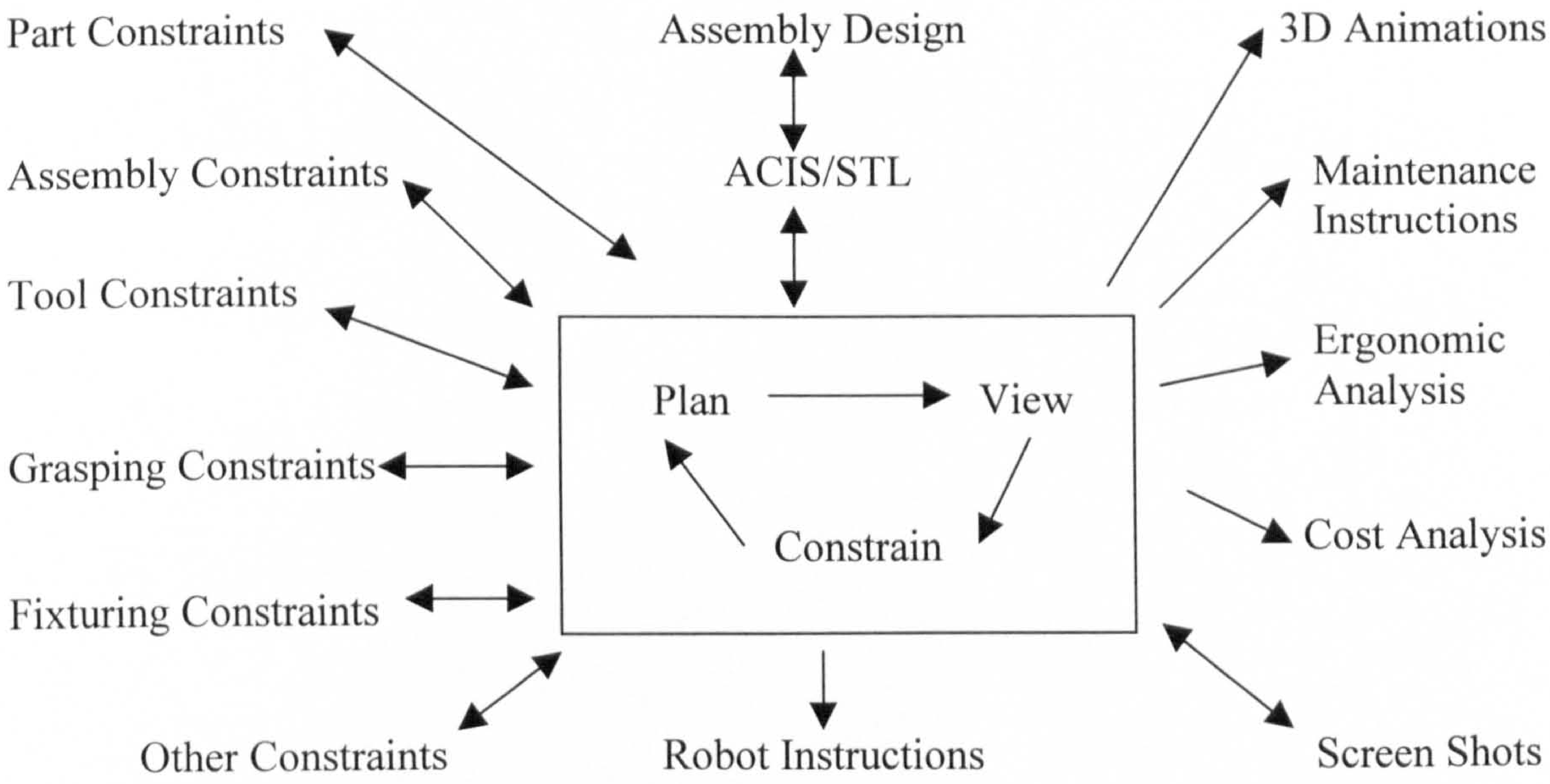

Figure 2.8: ***ARCHIMEDES 4.0 Assembly Analysis and Planning Software System***

The integration of this constraint based approach with simulated annealing[c] (SA) heuristics has increased the speed, accuracy and industrial relevance of the method to bring a commercial application a step nearer. This planner has an extensive range of functionality and is able to consider more than just part placement operations. However, the system structure and underlying algorithms, with the exception of the NDBG, are essentially unchanged from earlier examples of planning software. The geometric and technological constraints are applied separately and thus, do not narrow the search space early in the planning process. It is perhaps significant in the field of assembly planning, that such an important project as ARCHIMEDES has increased the scope of its work and now includes the consideration of lifecycle design factors and cost analysis in the planning process[34,35,36].

The importance of the link between design and planning had been recognised before the evolution of ARCHIMEDES, in another assembly planning system called CAAPS[37,38], Figure 2.9 shows the architecture of this software. A neural network module augments the design development process, which organises the features of each component design in terms of geometry and topology for later assembly sequence generation. From this data, candidate insertion directions are computed to reduce the search space later in the process. All the part liaisons are identified and categorised and collisions are detected in the direction of the candidate insertion trajectories. The precedence relationships are then determined from this data.

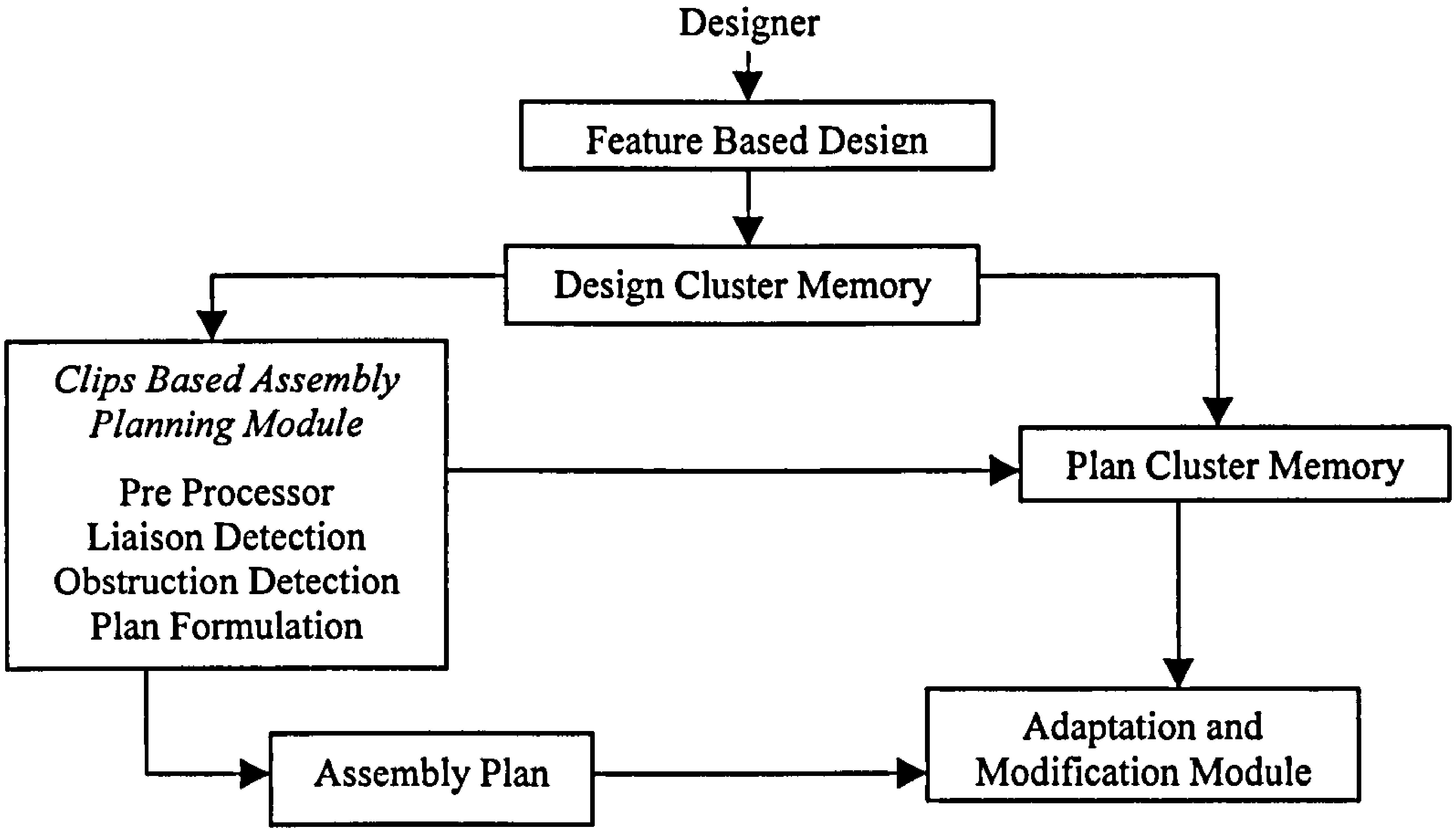

Figure 2.9: *CAAPS System Architecture*

After the computation of this information, the plan generation commences. It is based upon a disassembly technique that utilises a rule-based approach to generate the optimal sequence. The search process, using a predefined base component, finds the best candidate for removal from the partial assembly at each stage according to the

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[c] A systematic search technique considering random moves that favours the uphill direction. It is not guaranteed to find the global minimum but usually gets very close.

embedded heuristics. Although task level optimisation is achieved, the most suitable assembly sequence may not be identified. However, this approach has shown that it is possible to employ heuristics in the validation of the tasks associated with a liaison to find a good sequence. This fact is of potential benefit when considering an interactive sequence generation process. Much data is collected from the designer during the development process but no attempt is made to analyse this to improve the quality of the assemblability of the finished product. This is an area of extension which most sequence planning systems fail to recognise.

Many different assembly plans exhibit similar characteristics and indeed can have identical segments of parts at the task level. Because of this, a case based reasoning approach has been successfully applied to the sequence generation problem by a number of research groups, APE[39,40] being one such system, see Figure 2.10.

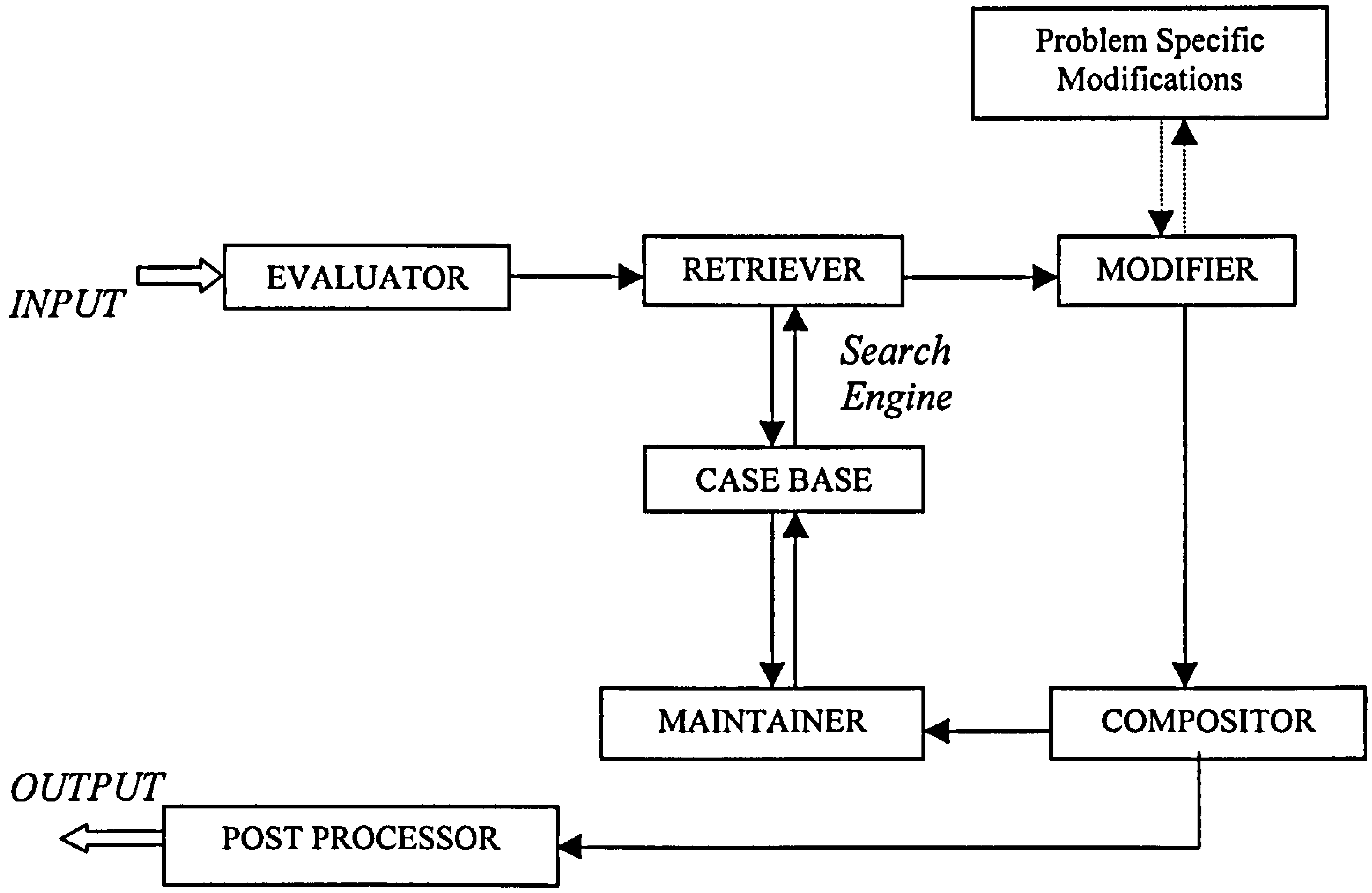

Figure 2.10: *Planning Schematic of APE*

From a suitable CAD model, graphs of connections, mating directions and obstacles are generated. This is done so that once the planning process starts there is no need to interrogate the actual CAD model, reducing overall computing time. The plan is represented by an Assembly Precedence Graph[21], (APG). The EVALUATOR module extracts the planning goals that the RETRIEVER uses to find matches from the CASE BASE. The MODIFIER adapts this information to make it applicable to the current situation and the COMPOSITOR combines the data to create a set of feasible sequences. Once this set of plans has been generated, the POST PROCESSOR imposes the necessary constraints to define the set of practical sequences. In addition, the MAINTAINER decides if any generated plans should be stored for later use in the CASE BASE. The use of case-based reasoning to generate assembly plans does not seem to offer any advantages when applied to an interactive approach. The method still attempts to create the plan automatically with as little user input as is possible. The geometric constraints are invoked before the search for feasible sequences. This method prunes the space, but does not consider technological constraints until the set of plans are generated. This is the same approach as many systems discussed previously and is of little use when building a sequence concurrently with a design.

Yet another CAAP system, KAPSS[41], is shown diagrammatically in Figure 2.11 . This system commences the sequence generation process with the automatic identification of feasible subassemblies from a solid model. The liaisons are identified from both a topological and geometric perspective. This allows the determination of the feasible subassemblies and then a hierarchical Petri net (PN)[d] graph can be easily obtained to represent the geometrically feasible assembly sequences. The search and control strategies are the *concurrent and asynchronous event dispatching method* and the *continuous transition scanning method.* Each circle node of the PN identifies a part or possible subassembly, the bar nodes define the assembly operations and the directed links represent the relationships between the two nodes. A series of quantitative and qualitative selection criteria, including Methods-Time-Measurement, (MTM) and DFA analysis, are then applied which enable the identification of the best assembly sequence for the particular situation. The initial search for sequences again just considers the geometric possibilities. It is only after these sequences are defined that the graph is pruned using the soft or technological constraints that enable the definition of the optimal sequence. This requires that a large amount of computational time be used to determine sequences that will later be discarded. It can be seen from Figure 2.11 that it is anticipated that some feedback will be passed to the designer to improve the assemblability of the design although this process has yet to be defined fully.

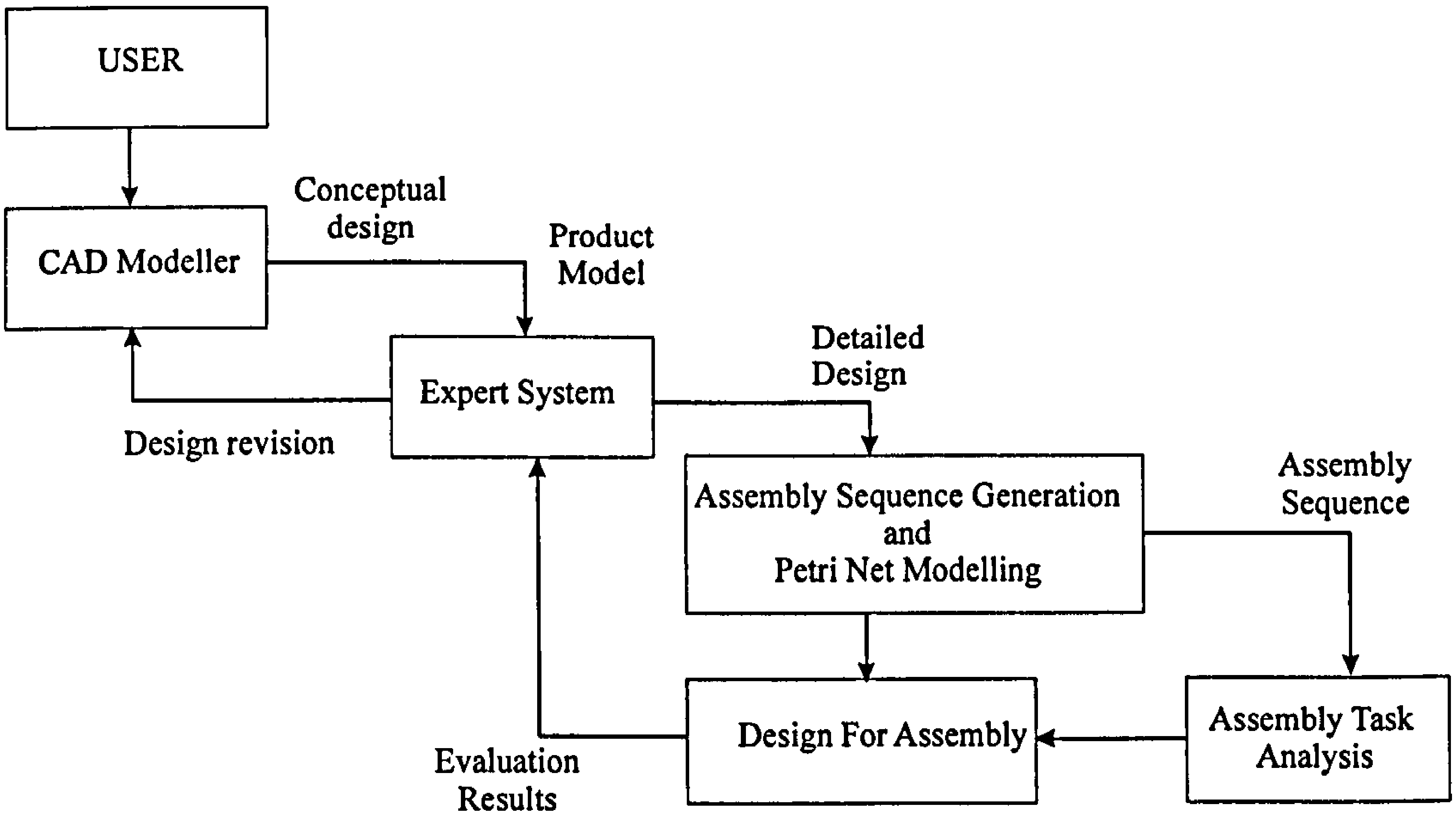

Figure 2.11: *KAPSS Integrated Knowledge Based Assembly Planning System*

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[d] A formal and graphical language which is appropriate for modelling systems with concurrency. It is a generalisation of automata theory which can express the concept of parallel events.

A rather more pragmatic and user-friendly approach to assembly planning has been proposed[42,43] and is currently on trial in Australian industry. Figure 2.12 shows the architecture of this system.

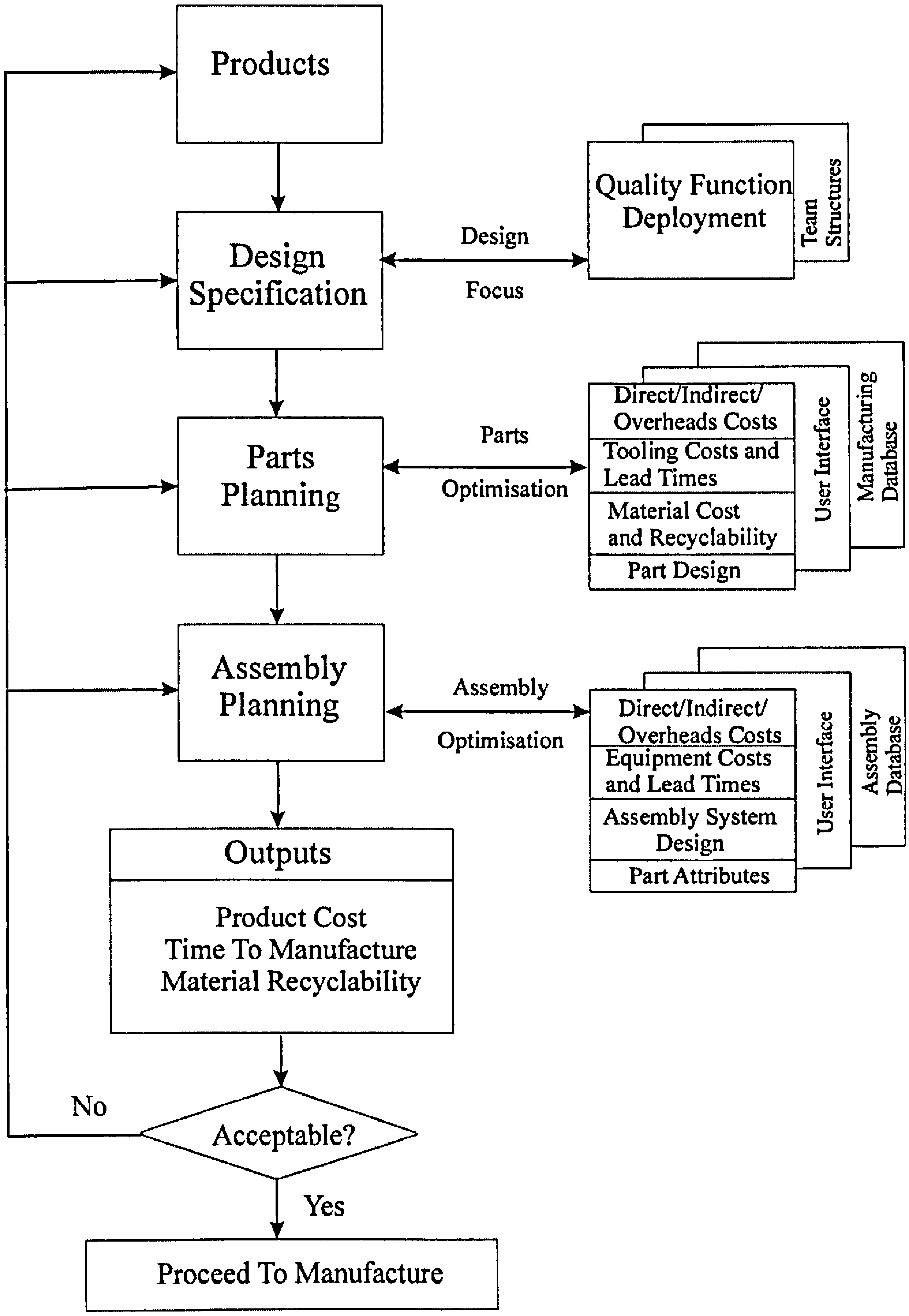


Figure 2.12: ***Integrated Part and Assembly Planning System from CSIRO***

A collaborative methodology is defined, which requires the user to identify icons and key assembly attributes for each component. These icons are then used to represent the part throughout the software. The user builds the assembly sequence interactively using these icons and a selection of predefined assembly tasks. Various on screen facilities allow the user to view and edit the sequence. A window is available to assess handling capabilities, and assembly time is calculated using standard times from Methods-Time-Measurement, (MTM). The functionality of the system has also recently been extended to include part process planning[44]. The approach described represents a significant departure from the traditional sequence generation system. By providing appropriate tools that allow the user to employ experience to build the sequence, the need for automation is eliminated. The industrial response about this approach has been positive, mainly because of the interactive approach, but also because it has not significantly changed the established manual planning process. The identified benefits include the generation of a structured assembly process and the setting of assembly standards. The method requires no computationally expensive domain searches, but utilises the existing experience of the human assembly planner to build the sequence. The user heuristically determines the relevant constraints by adding parts to the sequence. MTM standards are used to evaluate the sequence generated. However, the accuracy and practicality of the sequence is solely the responsibility of the user. No validation of the sequence is available to ensure the output is correct and complete. Whilst the human assembly planner may have gained much experience in building assembly plans, some form of double check would be useful to ensure that no problems are encountered during production.

2.1.3 Discussion on CAAP Literature Survey

It is clear from the above discussion that there has been much assembly sequence generation research completed over the past decade. Many different approaches have been proposed, but no definitive solution appears to have been found. The methods which try to automatically find all possible sequences are, in general, extremely computationally expensive and thus can only effectively deal with simple assemblies. Systems that claim success for higher numbers of components, in the main, rely heavily upon time consuming user input. This means that whilst the sequence generation systems work for the small assemblies tested, industrial transfer of these techniques is impractical.

It is ironic that in the early 1980's when CAPP systems were first given significant attention, computers were not powerful enough to search the many permutations of anything but a very small assembly. Today, the increasing power of personal computers has enabled the analysis of larger assemblies. Now that the concurrent engineering philosophy is becoming widely accepted by the industrial community, it is becoming apparent that these systems may be addressing the wrong problem. To remain competitive in today's market, industry must find ways of reducing costs and lead times. One way to ensure products are fundamentally cheaper is to design them such that they are easier to assemble in the first instance. This can be achieved by considering the assembly sequence and the product design simultaneously. The systems discussed in this section can help to improve the assembly time by providing a facility for finding the optimum sequence configuration, assuming that the design is fixed. This is a reasonable assumption in a traditional manufacturing facility where concurrent engineering is not yet implemented. However, where this philosophy has been embraced, the assembly sequence and the design should be considered together as an iterative process to ensure an overall optimum configuration.

Although it has been proposed here that CAAP systems have been directed towards answering the wrong question, there is still much that can be learnt from prior research activity. A suitable method for representing the assembly is still required and the literature offers many efficient data structures to consider. Whilst efficient search techniques may not be necessary for concurrent sequence generation and design, it is important to represent and validate each liaison. This is similar to the AND/OR graph approach which only considers feasible assembly actions. The interactive construction approach of the CSIRO system, which attaches data to an icon to allow user friendly sequence construction, is worthy of note and may offer some insight into a suitable methodology. It is apparent from many of the CAAP systems described that heuristics have a role in sequence generation and this might be useful if the sequence is generated concurrently with the design. Some planning approaches make appropriate use of evaluation criteria to identify the optimal sequence and a more detailed investigation of these may highlight some relevant metrics. Thus, it can be seen that some transfer of methods and ideas is possible between the prior sequence generation research and this work. However, because the approach that is reported in this thesis is fundamentally different from any other proposed system, only fragments of research can be seen to be applicable.

2.2 Design For Assembly(DFA)

Generating an optimal assembly sequence using any of the systems described in the previous section can indeed help to improve assembly times. However, most systems assume that the design is fixed and thus the opportunity to identify suitable design changes that would ultimately improve the assembly sequence is overlooked. The Design For Assembly (DFA) methodology offers systematic processes which can assist in the identification of candidate design areas for improvement. The application of DFA has been a proven success and is widely used in many industries. It helps to reduce product part count, improve assemblability and thus decrease overall product cost. Within the various applications, three main DFA techniques have been developed:

1. Boothroyd Dewhurst DFA[3]
2. Lucas DFA Methodology[5]
3. Hitachi AEM[4]

The Lucas DFA methodology is the only one that explicitly requires the identification of an appropriate assembly sequence, although it is an integral part of all the DFA processes. Thus, this methodology is considered in detail in this thesis. However applying any of the methodologies with an incorrect sequence has significant implications for the accuracy of the results. The analysis is based upon a detailed examination of the tasks involved in completing the steps in a sequence. If these are wrong, the accuracy of the analysis is in serious doubt. Despite the importance of the assembly plan, the Lucas methodology does not include any syntactic or semantic checks on the sequence used, it is assumed that it is both appropriate and correct. This issue is discussed later in this section.

The DFA methodologies have had many documented successes, but still it is not widely used throughout industry. Computer-based versions have been developed but these still require much detailed part information and are quite laborious to complete.

Historically, DFA is applied towards the end of the design process, when all the data is available for a complete analysis. Any assemblability issues identified at this stage are often difficult to eliminate due to prior investment commitments. Earlier implementation of the DFA methodologies has been proposed and methods are reviewed at the end of this section.

2.2.1 *Lucas DFA Procedure*[5]

The Lucas DFA Methodology has its roots in the same collaborative research between the University of Massachusetts, USA and the University of Salford, UK in the 1980's as the Boothroyd Dewhurst DFA analysis and consequently shares some common features. Figure 2.13 contains a diagram of the Lucas DFA process. There are a number of distinct stages to the analysis. Firstly, a Functional Analysis is completed which forces the designer to justify the existence of all parts. This results in a simplification of the product structure. After the completion of an optional Manufacturing Analysis, the second stage uses the assembly sequence to analyse the fitting and handling characteristics of each component.

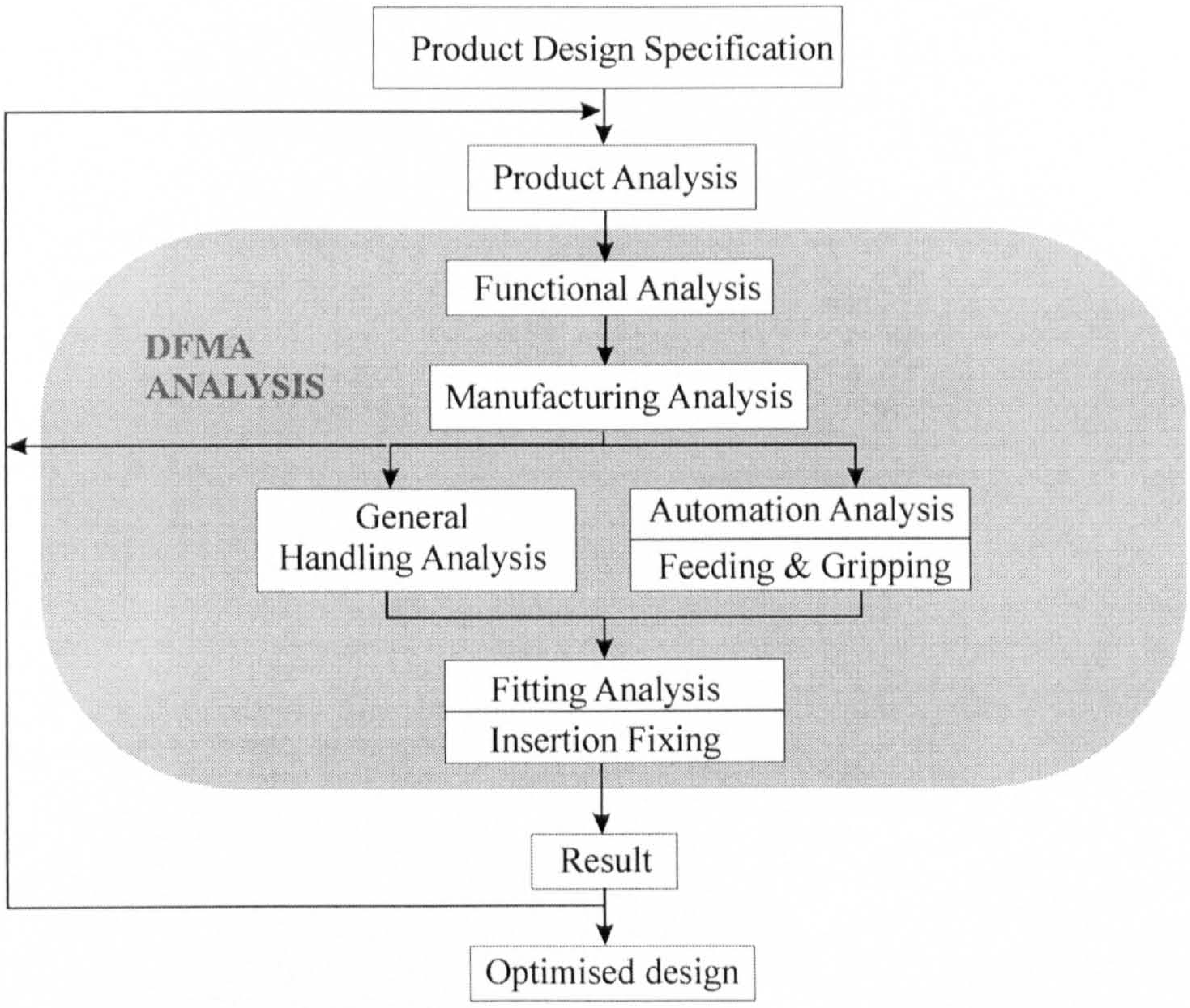


Figure 2.13: ***Lucas DFA Methodology***

Functional Analysis

One of the simplest ways to improve assemblability and reduce costs is to eliminate unnecessary parts. This is not as simple a process as it first appears because a designer does not create a part unless it is for a good reason. The removal of extraneous parts may require novel ways to find appropriate part combinations or to redesign the existing configuration. The Functional Analysis is the process within DFA that assists with the identification of those parts that are candidates for removal or combination. It involves asking a series of questions to define the parts as type A or B. By definition, a type A part is functionally necessary and a type B part should be eliminated or combined where possible. Figure 2.14 details the method defined to assist with this part categorisation. An obviously essential part is defined as a type A and the flowchart of questions shown in Figure 2.14 are then applied to all the remainder of the components.

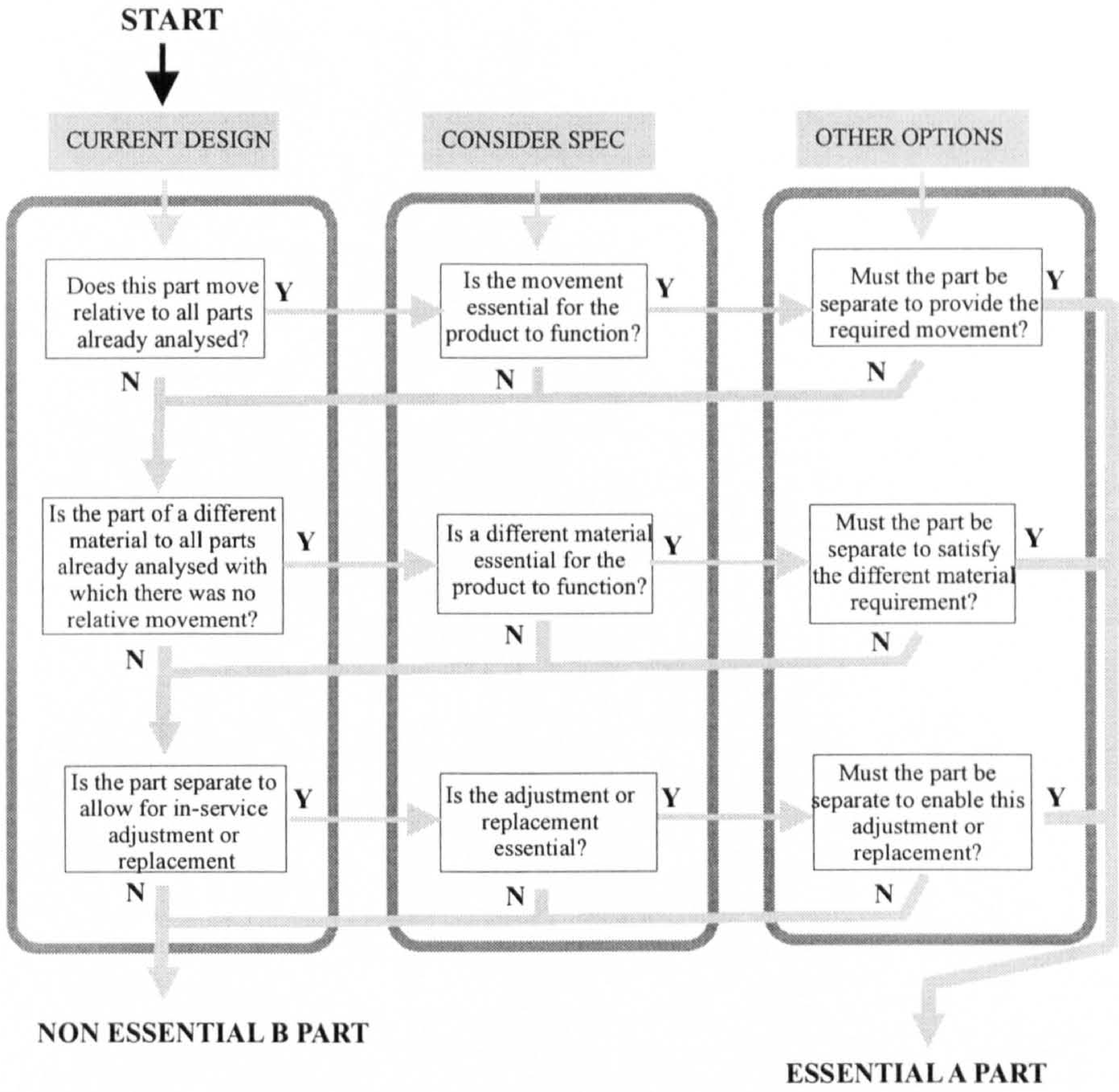


Figure 2.14: ***Lucas DFA Functional Analysis***

Manufacturing Analysis

Figure 2.13 shows that after the Functional Analysis has been completed, the Manufacturing Analysis can commence. This is not strictly true, as this part of the analysis is only advisory and can be completed at any time. The inclusion of this consideration is to allow the exploration of the inevitable trade-off between assembly and manufacture. The Functional Analysis tries to persuade the user to combine parts to reduce assembly costs but there is often an increase in the manufacturing costs of the parts. There comes a time when it is more expensive to make the fewer, but more complex, parts, than it was to manufacture and assemble them in the first instance. Without the inclusion of this analysis the user would have no feel for this escalating cost and thus the result could be an increase rather than a decrease in the overall product costs.

Handling Analysis

The Handling Analysis can now be completed. This part of the DFA methodology assesses the difficulty of handling and orienting the components for presentation to the assembly. Both manual and mechanical forms of handling can be analysed. A Handling Index for the assembly is calculated by assessing each component in turn against a series of handling tables. An equation, known as the Handling Ratio, is defined as below:

$$\text{Handling Ratio} = \frac{\text{Handling Index}}{\text{No Of A Parts}}$$

For a good assembly the Handling Ratio should not exceed a threshold of 2.5.

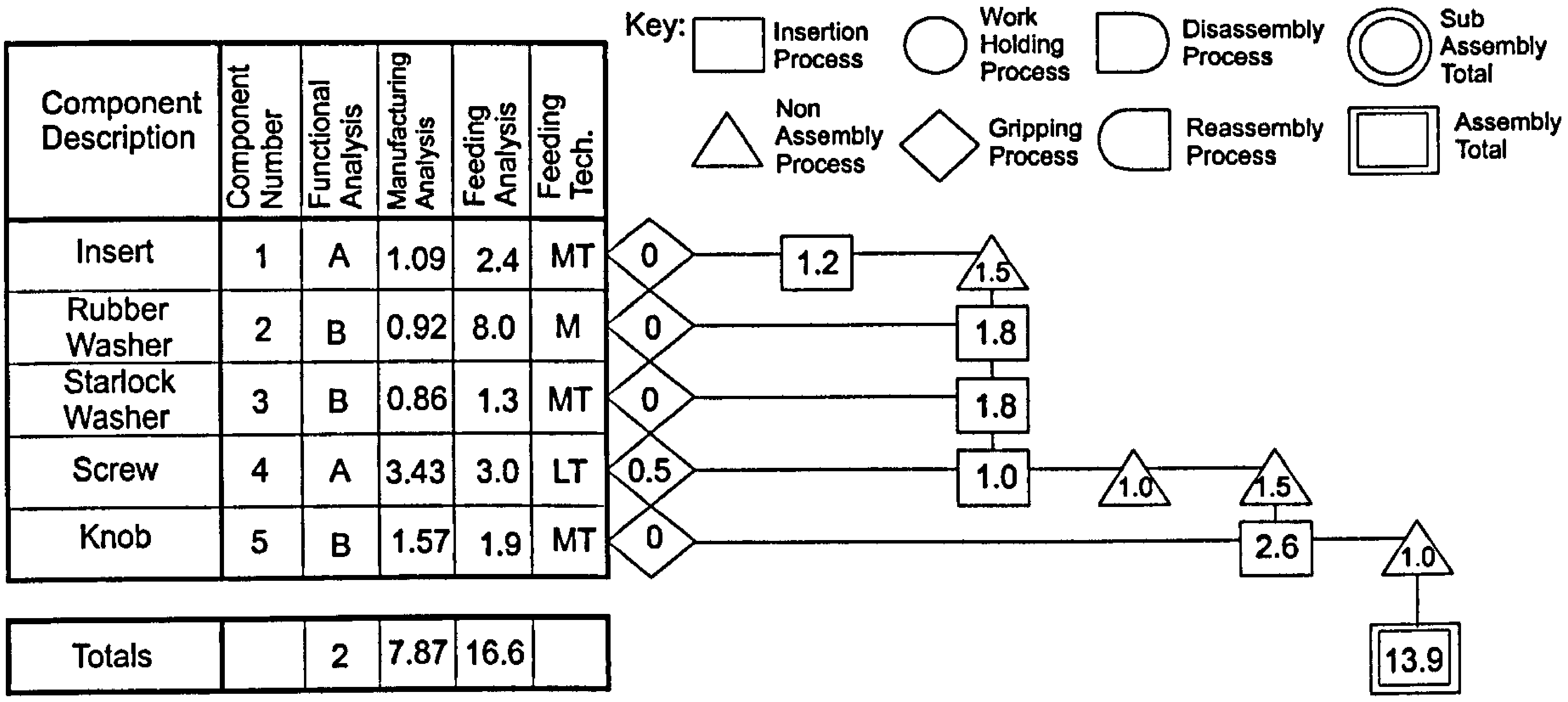
Fitting Analysis

The final analysis in the Lucas DFA method is the Fitting Analysis. This evaluates the actual assembly of each component, including a separate consideration of the possibilities for gripping each component. As the Fitting Analysis is completed, the assembly sequence is defined including non-assembly processes. Each operation is scored according to relevant charts and unnecessary tasks are penalised accordingly. The summation of each component's score is called the Fitting Index. The standard metric which allow design comparisons is called the Fitting Ratio and is given below:

$$\text{Fitting Ratio} = \frac{\text{Fitting Index}}{\text{No Of A Parts}}$$

For a good assembly the value of the Fitting Ratio should not exceed a threshold of 2.5.

A standard worksheet provided for the completion of the DFA analysis is shown in Figure 2.15. The components should be entered in order of assembly, which presupposes that the assembly sequence is known. The results of the completed analyses are added into the relevant columns.



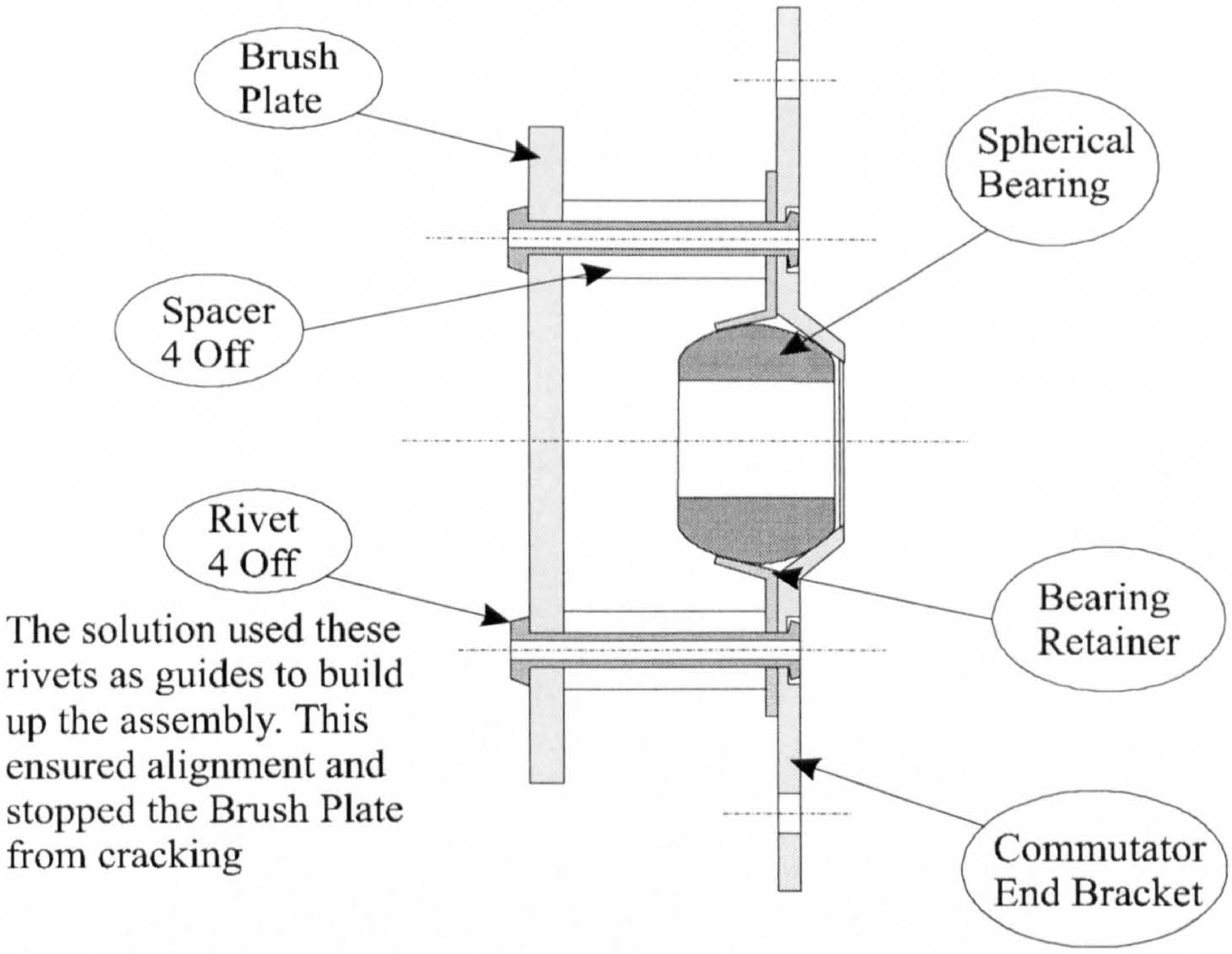
Component Description	Component Number	Functional Analysis	Manufacturing Analysis	Feeding Analysis	Feeding Tech.
Insert	1	A	1.09	2.4	MT
Rubber Washer	2	B	0.92	8.0	M
Starlock Washer	3	B	0.86	1.3	MT
Screw	4	A	3.43	3.0	LT
Knob	5	B	1.57	1.9	MT
Totals		2	7.87	16.6	

Figure 2.15: ***DFA Analysis Worksheet, Completed for a Headlamp Trim Screw***

2.2.2 Importance Of Assembly Sequence in DFA

As seen in the previous section, a number of different DFA methodologies have been developed. The Lucas DFA methodology[5]explicitly requires the generation of an assembly sequence and provides a worksheet to document the work. However, it does not consider the accuracy and suitability of this assembly sequence. TeamSET[47], the computer-based version of the Lucas DFA Methodology, provides limited support for building the sequence but, even here, there are no semantic or syntactic correctness checks or sequence validation procedures. A recent industrial study[45] has found that, in general, companies who applied DFA tools used an existing assembly sequence for analysis. This increases the possibility of inaccuracies in the sequence and consequently, the DFA analysis results are unlikely to be correct.

The significance of accurate generation of the assembly sequence in DFA analyses is apparent in most applications. This can be illustrated with an example, Figure 2.16 showing part of a screen wiper motor assembly. The original assembly sequence used the end bracket as the base component. All other parts were stacked above this and the rivets inserted and fastened simultaneously. This caused the thermosetting polymer brush plate to crack periodically during the riveting process. The problem was caused by the joining process being unsuitable for the brittle brush plate material but was only identified during assembly. An improvised solution was implemented using pegs in a jig to support some hollow rivets. All other components were assembled from the brush plate used as the base. This supported the fragile component such that, when the rivets were formed to fasten the assembly together, few breakages occurred. Although, this is a poor design in terms of assembly, it is not certain that a conventional DFA analysis would have detected this issue. This is because no consideration is given to validating assembly sequences for use in DFA analyses.



The solution used these rivets as guides to build up the assembly. This ensured alignment and stopped the Brush Plate from cracking

Figure 2.16: ***Partial Assembly Of Screen Wiper Motor, Showing Revised Design***

This example, whilst trivial, serves to illustrate the fact that although a DFA analysis may have been completed, it is possible that all assemblability issues have not been detected. If some form of validation was available which ensured that the sequence used in the analysis was feasible and practical, any results would better reflect the true assemblability quality of the design. Production of the product could then commence with the expectation that no further problems would become apparent.

Sequence validation is equally important when the DFA analysis is being completed early in the design process. It is difficult to generate the assembly sequence before the product is completely defined. Accuracy checks would assist the user in knowing whether the sequence is correct. If the user was unaware of errors in the generated sequence, poor design decisions could be made which may result in even more issues further into the product introduction process.

2.2.3 Automation of The DFA Process

Despite the proven success of the various DFA methodologies, there is evidence to suggest that products are designed with around 50% more parts and assembly content than is necessary[3]. This is probably due to the many barriers that hinder the comprehensive introduction of the DFA analysis. The first implementations took the form of paper-based methodologies that required much laborious form filling. This was seen as unnecessarily time and resource consuming and offering many opportunities for errors. Computer-based implementations of the manual methods are now widely available, which can assist with the complexity of the analyses. Benefits are provided in terms of speed and accuracy, but the user is still required to interpret the detail designs in order to complete the analysis.

The DFA Toolkit[46] provides a quicker and less error prone method of completing a DFA analysis using the Boothroyd Dewhurst approach. The Lucas methodology also has a computer-based implementation named TeamSET™ [47]. This offers a little more than a pure translation of the paper-based approach as it includes Quality Function Deployment (QFD) and Failure Mode and Effect Analysis (FMEA). Direct transfers of the paper-based approaches are helpful, but still require much user input and expertise. In general, most of the data required for a DFA analysis is readily available in the computer systems of many companies. CAD models of the product range are routinely produced which means that all the design geometry is accessible for input to some form of automatic DFA analysis software. First indications that this is possible have been reported[48]. It was found that 72% of the necessary data for DFA interrogations could be extracted from enhanced solid models. In this way, less emphasis is placed upon user interaction and more data can be inferred from a geometric model. Frameworks for such an approach to automatic DFA analysis linked to a CAD system have been proposed[49,50] and have been partially implemented. However, due to the difficulties involved in automating the DFA methodology, no generic commercial applications have yet reached the marketplace.

2.2.4 Integration Of DFA Into The Design Process

The problems of late application of DFA could be avoided if the analysis was to be completed earlier in the product introduction process, concurrently within the design process. However, this approach presents a number of issues. As discussed in a prior section, an assembly sequence is required which is very difficult to generate at this stage using current techniques. In addition, the geometry and other attributes may not be fully defined, which indicates that new methods of analysis may be required. Despite the difficulties, a number of attempts have been made to integrate the DFA analysis within the design process, with varying degrees of success.

A system, INSPIRE-2[51], has been presented and is shown in Figure 2.17. It combines assembly planning, DFA and redesign suggestions. A final design and its assembly operations are used to reconstruct a default design process in stages, in order to provide salient redesign suggestions. Although this system does merge DFA with redesign, it is not moving the analysis any earlier in the design process. A completely different approach to DFA is required to analyse an assembly whilst it is still developing. Much of the traditional analysis lies in the detail of the design. If this is incomplete then little of the current methodology can be used.

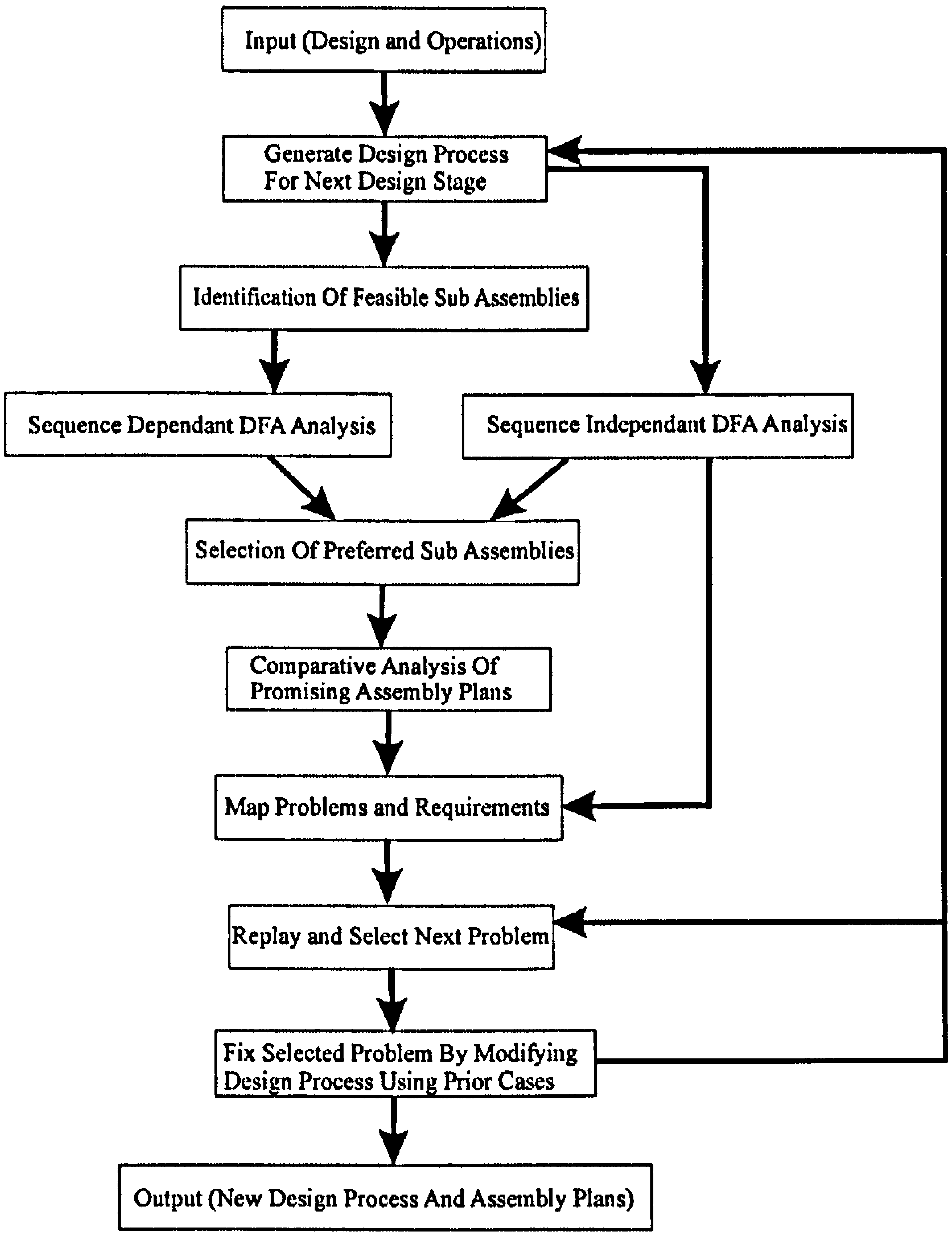


Figure 2.17: *System Architecture of INSPIRE-2*

A process for integrating the design and DFA was presented in the SCOPES project[52]. Five analyses were developed to support different stages in the product development cycle.

Product Structure Analysis - Support for rationalisation across product families into modular designs.

Handling Analysis - Offers advice for the provision of features which can facilitate ease of handling.

Feeding Analysis - Offers advice for the design of components that are to be fed by magazine.

Positioning Analysis - Checks the ease of positioning and advises on potential improvements.

Joining Analysis - Checks that the chosen joining process is suitable for the application.

The individual analyses are designed to be invoked at certain stages throughout the design process as shown in Figure 2.18, however, the user has control of this procedure. As much data as possible is extracted from the solid model and, in addition, an integrated database sits behind the analyses to minimise the amount of user input. This process seems to address many of the issues surrounding the earlier implementation of DFA by dividing the analysis into its constituent parts and identifying the appropriate times for application of these sub-analyses.

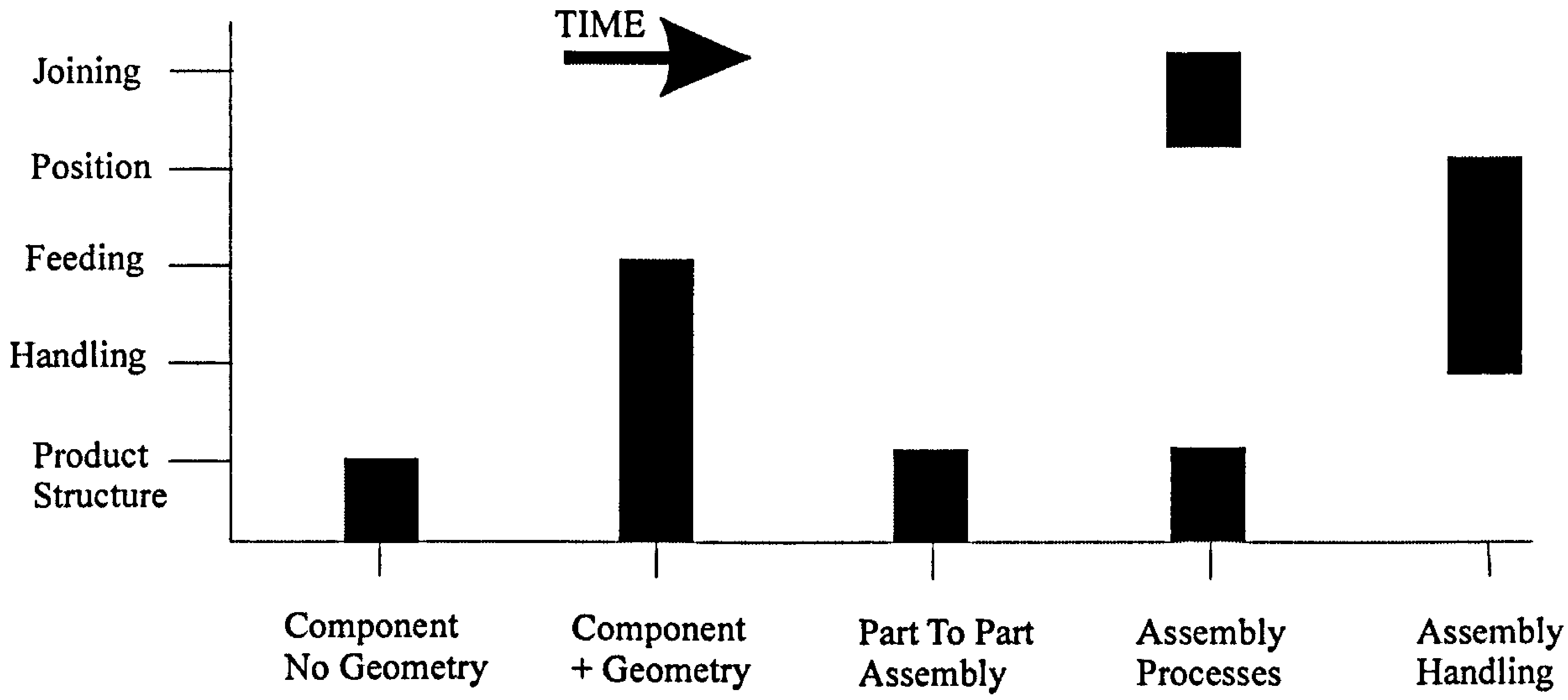


Figure 2.18: *Application of DFA Design Support Activities in SCOPES*

A similar proactive DFA methodology has been defined[53] and described[54] in the OPHIR project. This process has been developed to operate at three levels or layers of support, as shown in Figure 2.19. It differs from the SCOPES analysis as it commences from an earlier position, where even the components are unknown and the defining product family is being determined.

Product Group Support

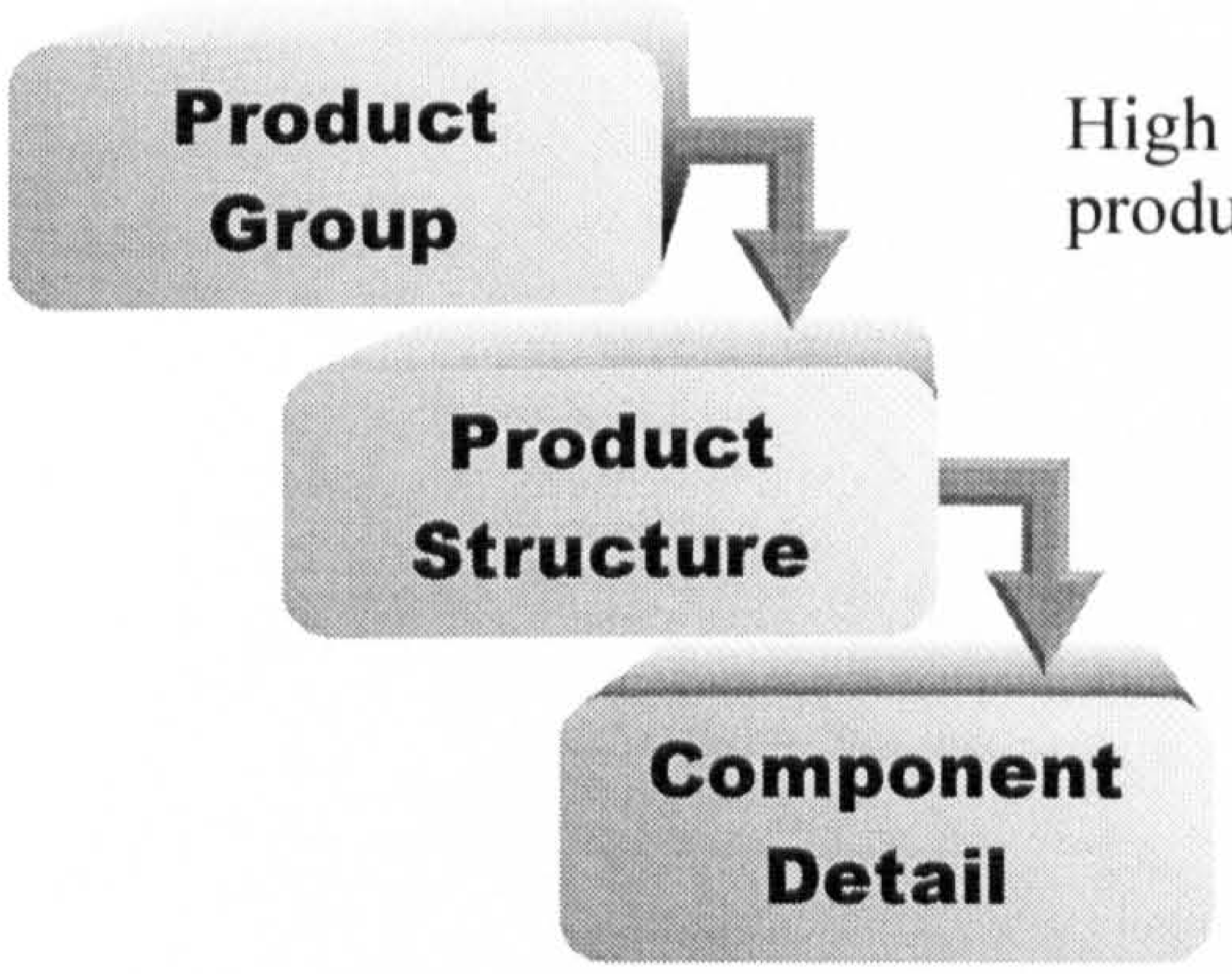
This comprises an investigation to establish a product family theme where identical components, a constant assembly sequence, and standard feeding and manufacturing features should be encouraged across a range of assemblies.

Product Structure Support

The early assessment needs have been met by direct interaction with the assembly hierarchy and the assembly sequence during the development of the design and sequence. Evaluation of the assembly structure through DFA criteria and knowledge provides an up-to-the-minute account of the quality of the product from an assemblability perspective. This layer seems to be similar to the SCOPES Product Structure Analysis.

Component Detailed Design Support

This layer is in effect an enhanced, but traditional approach to the DFA analysis that can be invoked at the earliest possible stages in the design process, whether or not CAD data is available. Inference from the component's attributes and default data is used to approximate early DFA evaluation. As the design develops and more detail is accessible, so the DFA evaluations become more reliable and accurate. Successful revised designs rely upon an understanding of the capabilities of manufacturing processes and the adoption of different materials. Thus, this knowledge has been captured and is offered at appropriate stages in the process. This layer appears to correspond to the remaining four analyses from the SCOPES project; Joining, Insertion, Feeding and Handling.



High level decision making influencing:
product families, modules, variants & standard parts

Intermediate suggestive solutions & examples
involving part counts, assembly structure, DFA
optimisation, etc.

Detailed evaluation techniques including
process capability maps, assembly ports,
manufacturing analyses, etc.

Figure 2.19: ***Proactive DFA Methodology***

Until recently, DFA was a successful, but somewhat reactive approach to improving the assemblability of designs. It has now been identified that further cost savings and assemblability improvements can be realised by the earlier implementation of the methodology. However, it is not just a matter of reapplying the existing methodologies, as much detail is required to complete the analyses. Thus, a number of approaches have been proposed which modify the traditional processes to facilitate the analysis of designs earlier in the design process where geometry and attributes are incomplete.

2.3 *Product Introduction Process (PIP)*

The quantification of the assemblability of the design and the generation of the assembly sequence are tasks that reside within an overall procedure that develop a product suitable for market. Until quite recently, these two tasks were part of distinct processes. The assemblability analysis was contained as part of the design process and the assembly planning took place within a manufacturing implementation model. Today, with the advent of concurrent engineering and interdisciplinary team working, a single process is used to define the overall development of a product, from the identification of the need, to in-service maintenance. This is generally called the Product Introduction Process (PIP). To understand these models, the early design processes must be described with their evolution into the current PIP models.

2.3.1 From Design Process Models To PIP Models

A linear design activity model[55] has been proposed as a representation of the design process where the specification bounds all other activities, and is shown in Figure 2.20. This model has been adopted by SEED, Shared Experiences In Engineering Design, which is concerned with the teaching of design in Higher Education.

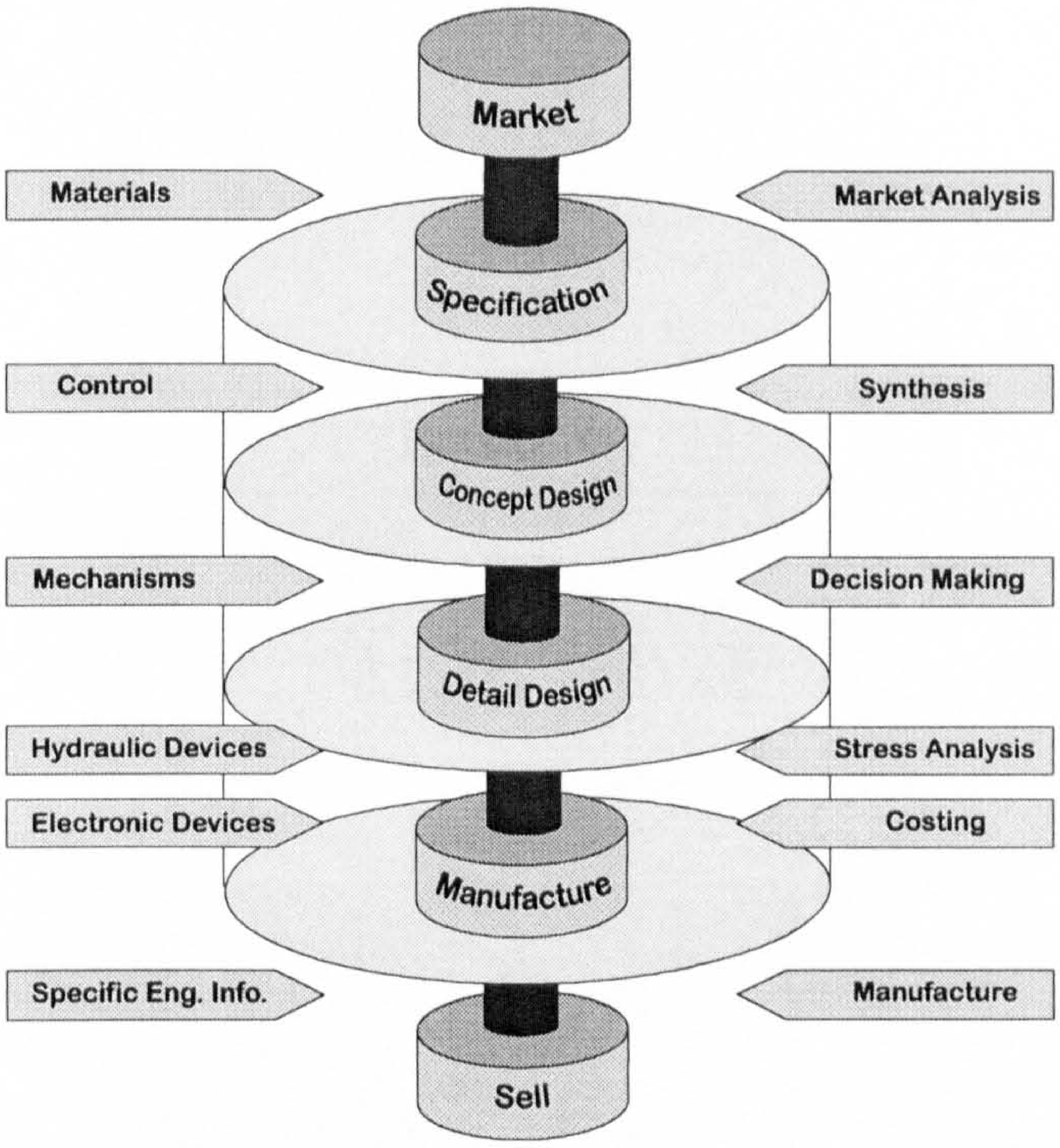


Figure 2.20: ***The Design Core Bounded By Product Specification***

Another widely accepted model of the design process[56] is shown in Figure 2.21. Again, it is an essentially sequential model, treating design as an isolated process with no links to any other business function. This model is criticised because it appears too regimented and does not allow for the lack of linearity in industrial design. It also fails to highlight the tools and techniques available to assist the designer to produce the 'optimum' design solution.

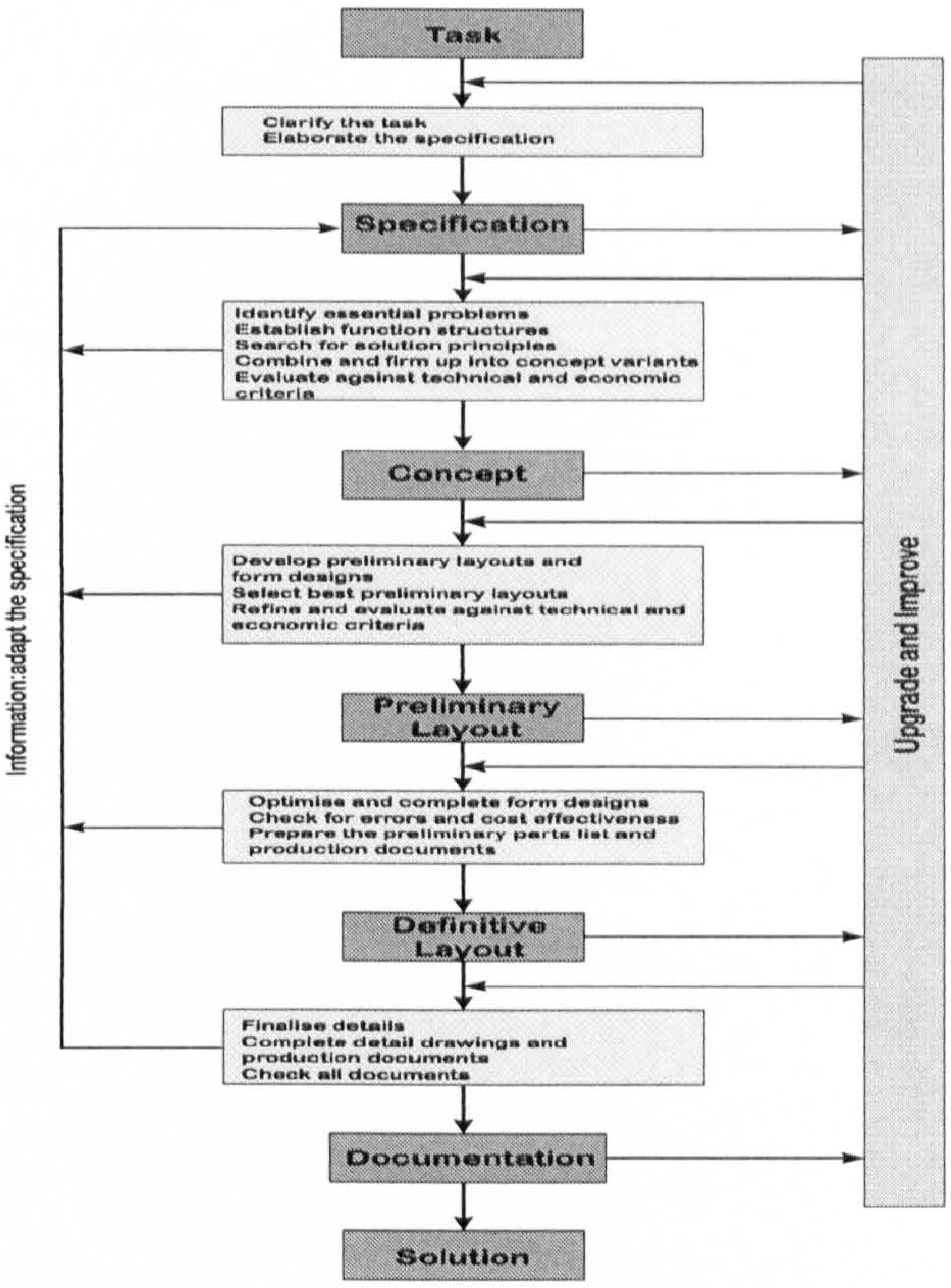


Figure 2.21: *Steps of the Design Process According To Pahl and Beitz*

Miles and Swift[57] recognised these issues and identified "an urgent need to revolutionise the way in which products are brought to market". This involved using teamwork, concurrent engineering, project management and suitable tools and techniques. They believed the design process should be based upon the Quality Function Deployment technique as shown in Figure 2.22 and integrated with other business functions.

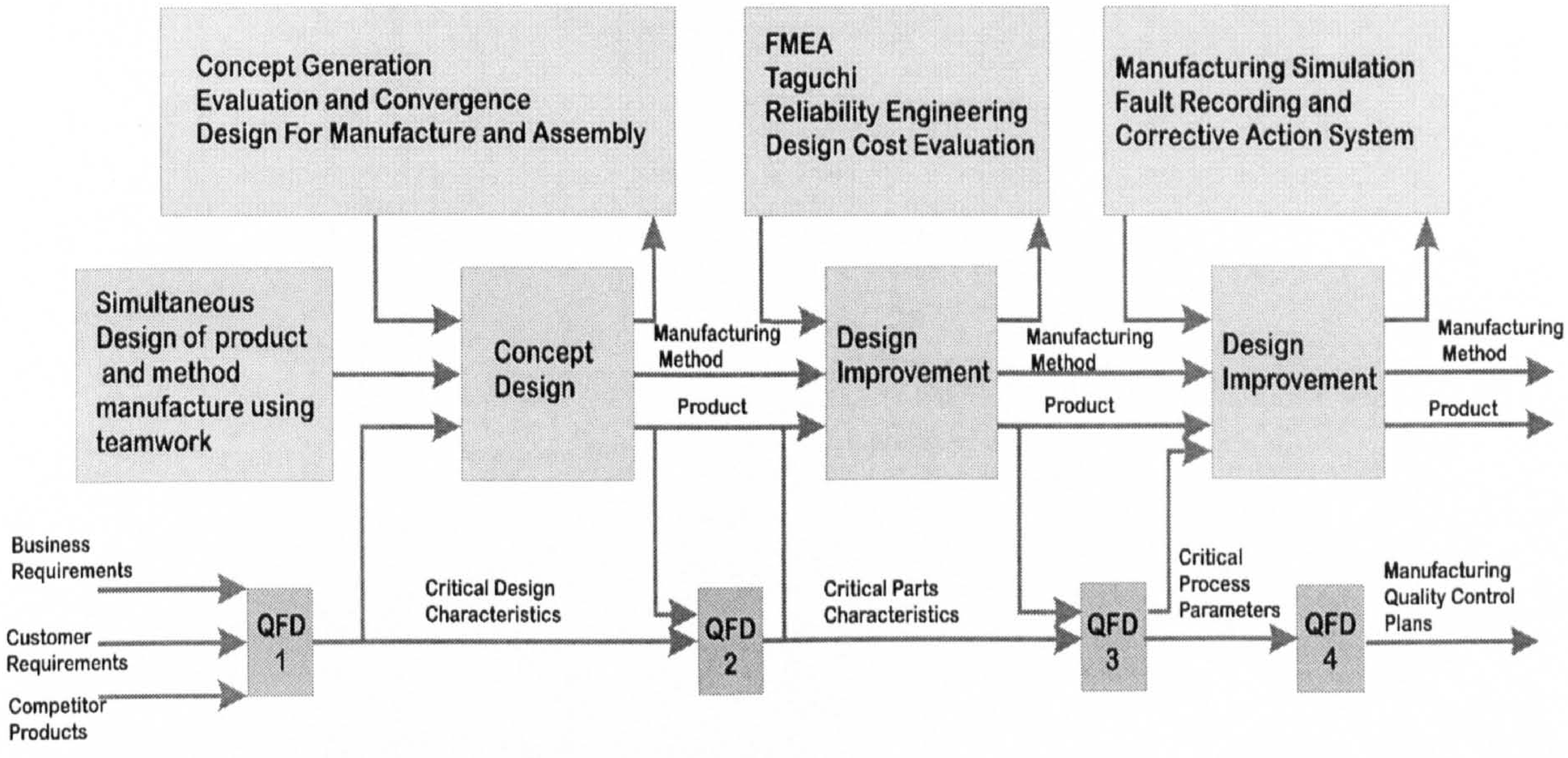


Figure 2.22: *Swift and Miles Generic Design Model*

Andreasen *et al*[58] believed that the way to reduce costs was to define simultaneously the product and processes in an Integrated Product Development environment, as shown in Figure 2.23. This environment shows links with many other disciplines (e.g. marketing, sales, and manufacture).

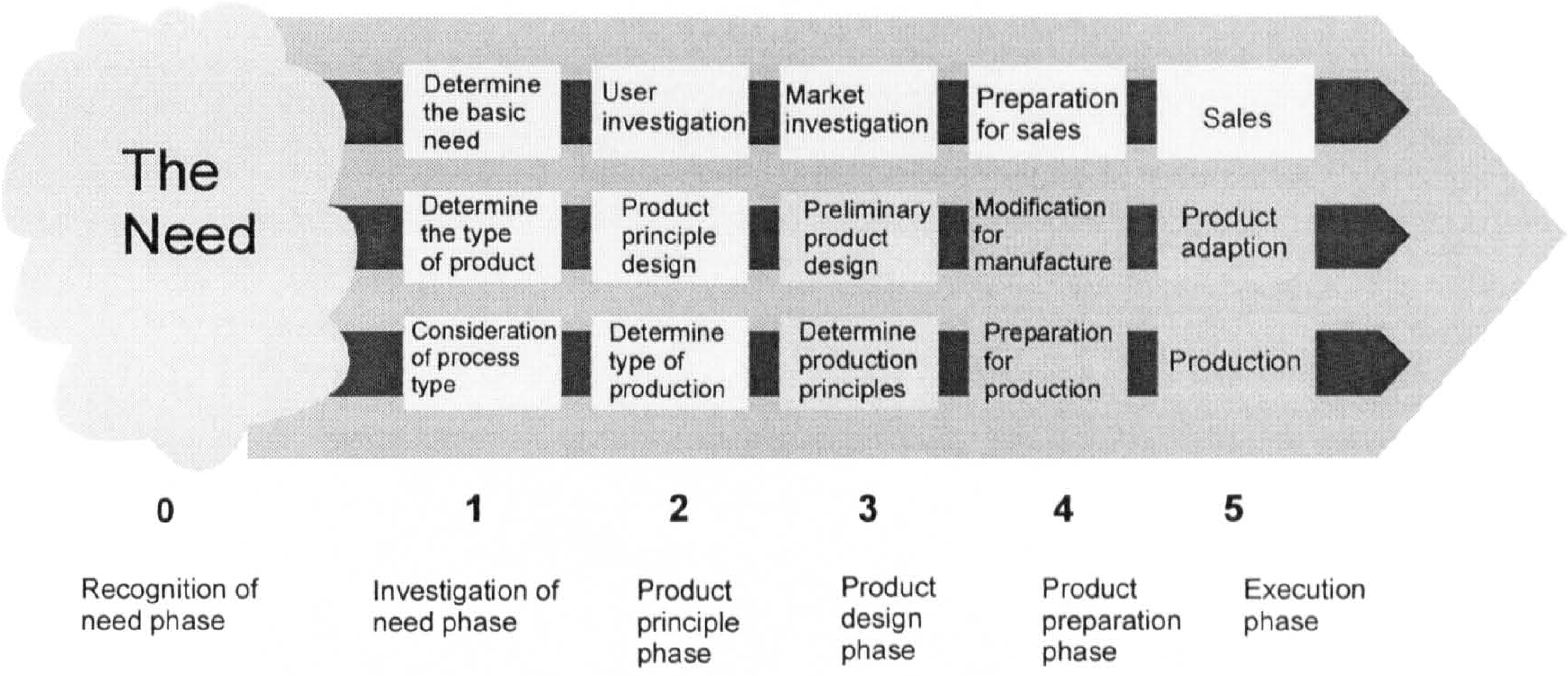


Figure 2.23: ***Andreasen's View of Integrated Product Development***

It can be seen from this brief discussion that the design process has matured from an individual-based activity, through a systemisation of procedures to a process, which is integrated with other disciplines to create PIP models. This is seen as the way to achieve the faster product introduction, lower costs and higher quality necessary in today's markets. The linearity of the discussed models, both of the design process and the PIP, do not to mirror the *actual* sequence of work. Some areas of a design can be detailed before others depending on the importance, complexity or other such factors of the assembly. Design is an iterative process and this must be reflected in the methodology for concurrent assembly sequence generation and design.

2.4 Concurrent Sequence Generation and Design

Assembly sequence generation, in general, considers the conclusion of the design process as the natural starting point. It is argued that following many of the proposed approaches can help to find a good, or perhaps even, optimum solution for the given design and thus reduce costs. However, adopting this philosophy misses a crucial opportunity to exploit the design alterations that could still further improve the assemblability and decrease costs. This attitude is similar to that seen towards the DFA methodology. Significant improvements have been made with *a posteriori* analysis, but it is now appreciated that further assemblability gains can be found from the routine application of DFA throughout the design process. The implementation of this approach creates a requirement for the assembly sequence to be generated substantially earlier in the design process, perhaps even before all the components have been decided. It is proposed that an additional benefit of early sequence generation is a better assembly-oriented view of the design, which facilitates the development of a product more suited to assembly.

A recently published literature survey identifies the "Development of ...environment for the integration of intelligent systems of design and assembly planning" as an important development trend for the future[10]. This concept was proposed as early as 1989[59], but disappointingly, little research attention has been forthcoming. Where simultaneous sequence generation and design has been considered, it is still offered as two separate processes rather than a seamless integrated implementation. To achieve true concurrency of the two tasks, the assembly sequence may necessarily have to be built interactively in stages with much incomplete product data. This area is not considered in any literature to the author's knowledge. A partially integrated approach has been developed[60] which identifies areas suitable for redesign by analysing the complete assembly sequence. The step from this method to concurrent redesign suggestions seems within reach of this approach, but not actually achieved yet. Another approach[61] has developed a method for easily generating assembly sequences when design modifications have been implemented. It decomposes the assembly sequence generation into a series of sub-problems and reuses those where the design has not changed. Thus, every time the design is changed, only a small sub-problem must be solved, considerably reducing the time taken to compute the sequence for redesigns. This method cannot be used until a design is virtually defined. However, it does enable those design modifications, which are often necessary in later design stages, to be tested quickly and efficiently. The SCOPES[52] project includes the definition of both design for assembly and assembly planning modules. This approach has the potential to provide a totally concurrent sequence generation and design environment. However, the opportunity has not been fully exploited and the sequence is still generated after the design has been fully defined. In a separate but related area, it has been recognised that there exists a need for an iterative and concurrent process when considering the design of products and their associated assembly lines. CISAL[62], shown in Figure 2.24, has been developed to provide such a tool which, in addition, assists with the design of multi-variant products.

Firstly, the PRODUCT ANALYSIS module tries to reduce the number of functional components. Once this is complete, the product is decomposed and a first set of precedence constraints generated[63]. The OPERATING MODES AND TECHNIQUES module proposes possible attachments for the liaisons identified in the previous module[64]. Finally, the LINE LAYOUT module uses an Equal Piles approach to allocate tasks to each workstation[65]. Each of the modules feed back to the others to ensure the result is optimised for the constraints imposed. This approach is a promising complementary method to the one presented in this thesis. It is a logical step from concurrent sequence generation and design to the consideration of the factory constraints.

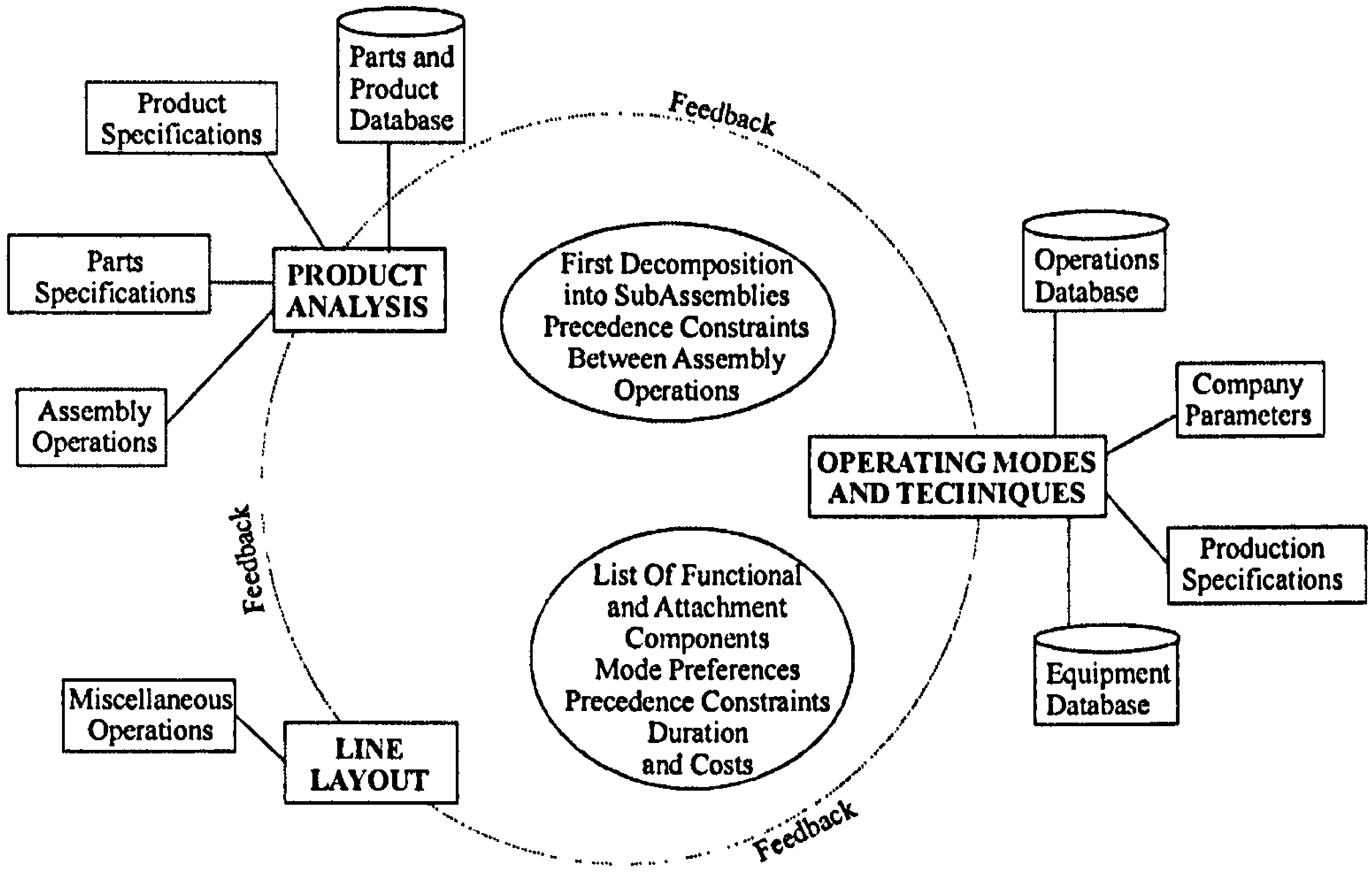


Figure 2.24: *Methodology and Information Flow In CISAL*

2.5 Summary of Findings

This literature review has shown that very little work exists that is directly applicable to the definition of a process for the concurrent generation of the design and the sequence. Because this research has covered a number of topic areas, each of these has been reviewed in order to be able to draw lessons from past work.

- *Computer Aided Assembly Planning*
  It was shown that all of the research in this area considered that the design was fixed. Whilst many innovative techniques to generate the optimum assembly sequence have been proposed, it is believed that an important opportunity has been missed. The presence of a feedback loop to the design process would allow iterative amendments to the design parameters and the sequence configurations, which could find the best overall combination for reducing assemblability costs.
- *Design For Assembly (DFA)*
  This technique has been evident in industry for a number of years and can demonstrate some success in reducing assembly costs. Current trends in this area are towards early consideration of the DFA principles. The analysis, however, requires an assembly sequence and thus provides another reason for determining a process for sequence generation early in the design process. The DFA metrics can also provide a method for quantifying the improvements gained by a concurrent process.
- *Product Introduction Process (PIP)*
  An overall model must be considered in which the methodology should operate. It was seen that design processes have evolved into product introduction processes and

that more simultaneous working processes are now operating throughout industry. This again provides some justification for following this proposal.

- *Concurrent Sequence Generation and Design.*
  Some attempts have been made to combine the tasks of design and sequence generation, but with little detail of how the lack of product data is approached. Very recently, a method for simultaneous product and assembly line design has been proposed which seems to be a complementary approach to that described in the next chapters.

In summary, the area of concurrent sequence generation and design is little explored from a research perspective. This is despite the potential costs and time saving available to any industry forward thinking enough to implement the process.

3. ASSEMBLY PLANNING PRACTICE

It has been shown in the previous chapter that the area of assembly sequence generation has received much academic interest in the last decade. Yet, few of these systems and techniques have filtered through into commercial applications and widespread business use. Three main reasons have been cited for this fact[66]:

- *Computational Efficiency* – The planning systems can only analyse assemblies with relatively few components before computation time becomes prohibitive and consequently the user input requirements increase.
- *Inadequate Evaluation Criteria* – Appropriate generic metrics for the evaluation of assembly sequences have not been researched and defined comprehensively. Cost and time are common criteria in current usage, but the calculation and inclusion of tasks varies widely. Methods suitable for industrial use need to be determined.
- *Industry Conservatism* – There is an inevitable delay in technology transfer from academia to industry.

Thus, any developer producing such a piece of software to help with the task of assembly planning must consider these points and ensure similar pitfalls are avoided. One way to improve the relevance of such a system is to define the current industrial working practices and hence identify how the computer can aid the process. In addition, discussions with potential end users can bring many issues to light and provide useful input into any piece of software. Grewel[44] when discussing the assembly planning system developed at CSIRO, said "Industry feedback ... showed that users prefer interactive planning which mimics their practice". It was for these reasons that it was felt necessary to find out what was actually happening in industrial assembly planning. Two investigations were completed and compared:

- A study of the actual assembly planning practice in industry.
- A survey of the literature to compare the findings with other such studies.

3.1 A Study To Define Industrial Assembly Planning Practice

An investigation was completed to document the assembly planning process in British industry. It was felt that it was also necessary to gain a broader understanding of the barriers to successful assembly design. In addition, the use of DFA techniques was also included in the remit of the survey as it provides a useful insight into the concurrent engineering philosophy of the company and the value placed upon the assemblability of products. The aims of the study were stated as:

- To gain an overview of the business, especially the design and assembly planning processes.
- To examine the use of DFA to evaluate assemblies.
- To identify the communication channels between design and manufacturing.
- To define the assembly planning process.

It was decided that blind questionnaires were not a suitable method to complete this study because of the detailed and potentially sensitive nature of the required answers. Actual visits to the factories were made to ensure that the results of the investigation represented reality; not the companies own perception of their processes. Hence, the aims of this survey were achieved by utilising structured interviews with relevant employees and by observation and salient questioning throughout the visit.. Appendix A contains a sample questionnaire used throughout the study.

Ten diverse companies were visited, covering a wide spectrum of British industry. Included in the list were both major multinational companies and some SMEs operating in many different marketplaces. A few of the companies were current and regular users of DFA, others often had not even heard of the technique and its potential benefits. Each company's business sector, DFA and assembly processes are defined in Table 3.1.

From Table 3.1, it can be seen that the companies visited employ a variety of assembly techniques. This ranged from one operator bench building precision electronics for defence use to semi-automated assembly lines, mass-producing consumer goods. It was felt that this was a representative perspective on the assembly issues encountered by industry today. It was assumed that the identification of similar observations would allow a generic assembly planning process model to be defined.

Half of the companies visited did not utilise formal DFA techniques, although general ease of manufacture and assembly rules were used by some of the designers. Where DFA analyses were regularly employed, it was generally towards the end of the design process or as a redesign exercise. Although some useful improvements had been implemented, many others were discounted because the cost of the alterations was too high. Although the use of the DFA analysis is said to improve communication between design and manufacturing, this was not evident in the companies visited. Conversations were generally limited to formal procedures such as design reviews or FMEA exercises where many business functions are brought together to identify and discuss issues. Whilst these processes are useful for opening channels of communication, more informal liaison between the two functions would result in a better understanding of the overall issues and thus less design revisions and assemblability problems. In general, it seems that British industry fails to appreciate that more collaborative working arrangements would improve the assemblability and manufacturability of a design and thus result in a more competitive product.

Comp	Business Sector	Assembly System	DFA Processes	Design - Manufacturing Communication
A	Defence	Bench build by one operator	Just started to implement DFA as a reactive tool	Manufacturing try to be more involved but designers wary thus generally only formal channels.
B	Aerospace	Subassemblies, bench built	DFA not used widely	More collaborative working being introduced
C	Consultancy	No assembly undertaken	DFA used extensively	Supports manufacturing and design communication
D	Medical Equipment	Bench build but many stations	DFA not considered	Little communication between design and manufacture
E	Measuring Equipment	Bench build but many stations	DFA recently successfully introduced	Where DFA used, manufacturing and design discuss issues early
F	Packaging Equipment	One operator builds assembly	DFA not considered, modular build used	Little communication between design and manufacture
G	Automotive	Bench build by one operator	DFA sporadically used, but modular design	Design and manufacture discuss issues but not early in process
H	Heating +Ventilation	Assembly line	DFA not considered	Little communication between design and manufacture
J	Heating +Ventilation	Bench build by one operator	No formal DFA but new manufacturing techniques used to reduce costs	Some communication between design and manufacture later in process, designers very aware of need to reduce assembly time
K	Automotive	Manual / automated assembly line	DFA widely used as a reactive tool	Some communication between design and manufacture

Table 3.1: *Characteristics of Visited Companies*

Table 3.2 summarises the specific assembly planning processes observed during the study. It can be seen from this table that in half the companies the sequence is determined at the end of the design process, once the product attributes are fixed. This means that the consideration of the assembly sequence cannot be used to improve the design. Only one of the ten companies employed sequence optimisation techniques to improve assembly times. The most unexpected discovery was that, in three of the businesses, the sequence was never formally defined. It was left to the assembly operators to decide. This situation is almost unbelievable in industries that have to reduce costs; a major opportunity has been missed.

This survey has identified a widespread lack of understanding of the influence of assembly within businesses today. Whilst it is generally believed that assembly improvements are a low priority for many manufacturers, the scale of the neglect gives cause for concern. Despite the negativity of these findings, in companies where sequences were generated, a common process became apparent.

Figure 3.1 shows the generic process of assembly planning in British industry. Designers do generally consider how an assembly may be built and try to create suitable subassemblies. However, because this thought process is rarely documented and there are rarely assembly experts amongst designers, this bears little relation to the final product structure and assembly sequence. Once the design is complete it is signed off and sent to the assembly planning engineers. Their first task is to collate all relevant data to enable the definition of the sequence. This data includes detail and assembly drawings, any prototypes or first production samples, similar products and factory capability information. Some information, often not explicitly available, forms part of the knowledge-based expertise gained by a planner in the course of generating many plans. It is evident that two categories of data are used to build the plan; product specific data such as geometry and materials; and generic knowledge such as factory capability, available jigs and possible joining processes. The generic knowledge imposes constraints upon the sequence variations possible. This information is examined to identify which are the most suitable subassemblies, in effect defining the assembly structure. Once this has been completed satisfactorily, the planner then takes each subassembly in turn and plans the sequence of component assembly and the associated tasks. This approach can be considered a *breadth-first, depth-second* search for feasible sequence configurations. The validation of each sub-plan is by actually disassembling the product as defined. Once each subassembly is planned, the overall plan is validated, generally by a trial run down the assembly line or on the workbench.

In summary, it was found that assembly is the poor relation of manufacturing in most businesses. The many problems found in assembly are a testament to this fact. If greater emphasis was placed upon improving this area then fewer production issues would ensue. However, it is not enough just to focus upon the actual assembly, the design has to be right in the first place. Designers do their best to create easy to assemble products, but poor communication and a lack of understanding make this less than effective. DFA can help to achieve easier to assemble products but more companies should utilise this useful technique in the first instance. However, improvements from a DFA exercise can only be implemented so far before a great amount of expense is incurred. Thus, DFA should be considered from the start of the design process. The assembly sequence, where it is formally defined at all, is generally not considered until the design is fixed. This effectively removes all possibilities for product alterations for ease of assembly.

The sequence is built by using a *breadth-first, depth-second* search and using knowledge-based rules to apply constraints on the sequence configurations. The sequences are validated by physically trying to follow the plan but rarely evaluated to define the plan quality.

Company	Sequence Generation	Assembly Planning Process
A	During prototype development	Designers specify nominal sequence. Manufacturing engineers define by disassembling the actual assembly.
B	After design is fixed	Breaks main assembly into subassemblies ensuring not too many levels of hierarchy. Work on individual subassemblies in detail.
C	Advocates early sequence consideration	Sequence determined in partnership between design and manufacturing.
D	After design is fixed	Define most appropriate subassemblies. Attempts assembly of prototype noting the order of components and required processes and tools.
E	Product modifications - after design is fixed. For new products - considered from the start of the design process.	Based upon prior sequences.
F	Designer considers sequence during design but does not document	Designer divides design into useful subassemblies. Sequence left to experience of assembly fitters, drawings often not available.
G	Sequence never defined	Sequence left to experience of assembly fitters.
H	Overview considered during FMEA but sequence developed on first production run	Assembly Planner uses drawings to define subassemblies and then find sequence by manually disassembling product. Assembly time reduced by sequence optimisation.
J	Sequence never defined	Sequence left to experience of assembly fitters.
K	Sequence defined towards the end of design process	Assembly Planners base sequence on existing methods.

Table 3.2: ***Observed Industrial Planning Process***

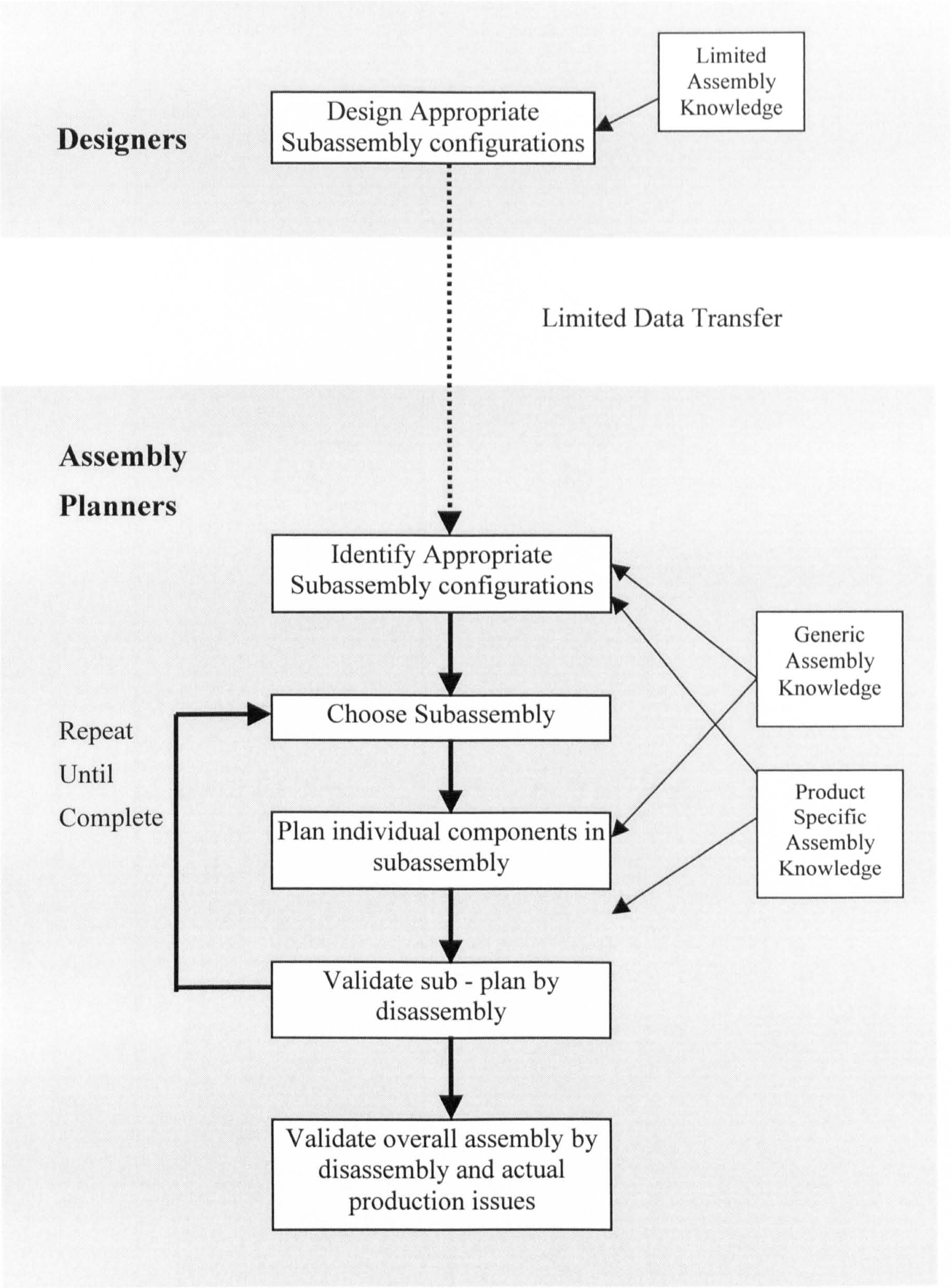


Figure 3.1: ***Industrial Assembly Planning Current Practice***

3.2 *Research In Assembly Planning Practice*

After the investigation of industrial assembly planning practice was completed, relevant literature was surveyed to compare the findings. Few published studies aim to improve our understanding of the processes involved in manual assembly sequence planning. It is also rather surprising that the human involvement in the process has been largely ignored.

An experiment was conducted[67] in the aerospace industry with four engineers to determine how the task of assembly planning is completed. The results showed a considerable difference in process from many of the automatic sequence generation systems proposed in the literature. It was found that most of the engineers used a breadth first, depth second approach. That is,

1. Breadth first - the product was decomposed into major subassemblies
2. Depth second - the subassemblies were individually planned in detail.

Many automated assembly sequence generation systems developed to date rely upon complex algorithms to generate the geometric or 'hard' constraints and thus present feasible sequences. Heuristic-based or 'soft' constraints are then implemented by the user to identify the most practical sequence based upon prior knowledge. This was not observed during this experiment. It was found that, in contrast to automated systems, planners integrate the application of the hard and soft constraints throughout the process to define a good assembly sequence.

Another knowledge engineering study[68] to develop a sequence generation expert identified a three stage planning process, similar to that previously described:

1. Decompose assembly into subassemblies.
2. Select the most suitable base part for each subassembly.
3. Complete the assembly sequence for each subassembly.

Stages 1 and 3 were identified as part of the planning process in this and the previous investigation. The additional second stage was implicitly included in the first study, a base part must be have been established to create a plan.

A third industrial survey[45] found that industrial assembly sequences are generally only generated once a design is essentially complete and fixed. It reported that these sequences are rarely validated to identify errors and almost never evaluated to determine the best sequence. No tools were available to help with sequence generation. A slightly different effect to the prior studies was also reported whereby the assembly planners took a wider view, considering assembly systems as a whole. This study reported that there were 3 stages to the planning process:

- *Geometric and Mechanical Reasoning.*
  Identification and categorisation of liaisons and precedence.

- *Assembly System Concept.*
  Recognition of the company strategy and existing equipment to define a system for product assembly

- *Assembly System Detail.*
  Allocation of individual operations to each workstation

In common with both other reports, it found that the assembly was planned in overview before the component detail was added and, in addition, company specific assembly strategy and equipment were considered.

These three studies all presented essentially the same process and was as observed during the industrial visits. Products are decomposed into relevant subassemblies and each of these subassemblies are planned in detail (breadth first - depth second). However the reported studies also discovered that hard and soft constraints were integrated into the process and not separate as in many proposed computer-based assembly planning systems. This was actually observed during the industrial visits, but not explicitly stated.

3.3 Summary Of Findings

By visiting a number of companies and comparing the findings to some published industrial surveys, a generic assembly planning process has been defined. It has been seen that the planner uses a *breadth-first depth-second* approach that identifies the best subassembly partitioning and then individually plans each subassembly in turn. The hard and soft constraints were integrated within the process and not separately implemented. In addition, it appears that validation and evaluation of the generated sequence are hardly considered in industrial situations.

One study defined the requirements for a successful assembly sequence generation system [67]. To develop an appropriate system there should be:

- High levels of user interaction throughout the planning process
- Graphical representations used as the medium between human and system
- Hard (geometric factors) and soft constraints (heuristic based) integrated within the planning process.

Thus, any sequence generation methodology and resulting computer implementation must take note of these facts to ensure that the resulting system enhances the generation process and not hinders it.

4. TWO – TIER METHODOLOGY

This chapter discusses the need for a methodology that facilitates the concurrent consideration of the design creation and the generation of the assembly sequence. It defines the support that will be required from a Computer Aided Design (CAD) environment. The literature review identified three stages of the assembly planning process, which were found to be sequence construction, validation and evaluation. These will be examined from both an automatic generation perspective and concerning the requirements of concurrent sequence generation process. The industrial investigation in Chapter 3 found that the application of the hard and soft constraints should be interwoven within these three stages for a successful planning process. The most appropriate method to achieve this interactivity will be analysed. Once these points have been established, a methodology for simultaneous consideration of both the sequence generation and the design will be briefly defined. Specific details of the proposed process and the implementation issues will be fully covered by the remainder of this thesis.

4.1 Definition Of Need

It can be seen from Figure 4.1 that the majority of the product life cycle costs are determined prior to full-scale development. Before the product reaches its manufacturing stage investment has already been put into such areas as new jig purchases and new dies due to lead times on these items. The geometry and topology, as defined by the designer, has determined the requirements for these items. In addition, the ease of manufacture and assembly of the product has been determined by the design configuration. Thus, when an assemblability issue is detected in production any necessary changes to the product are both difficult and costly to implement.

The CAAP literature review in Chapter 2 demonstrated that much of the current research considers that the conclusion of the design process as the most obvious starting point for the generation of feasible and practical assembly sequences. The design and its various attributes are assumed constant and the sequence is built, with no regard for the assemblability quality of the product. It should be noted that the identification of the optimum sequence for a given design represents a significant step forward for many companies, as discussed in Chapter 3.

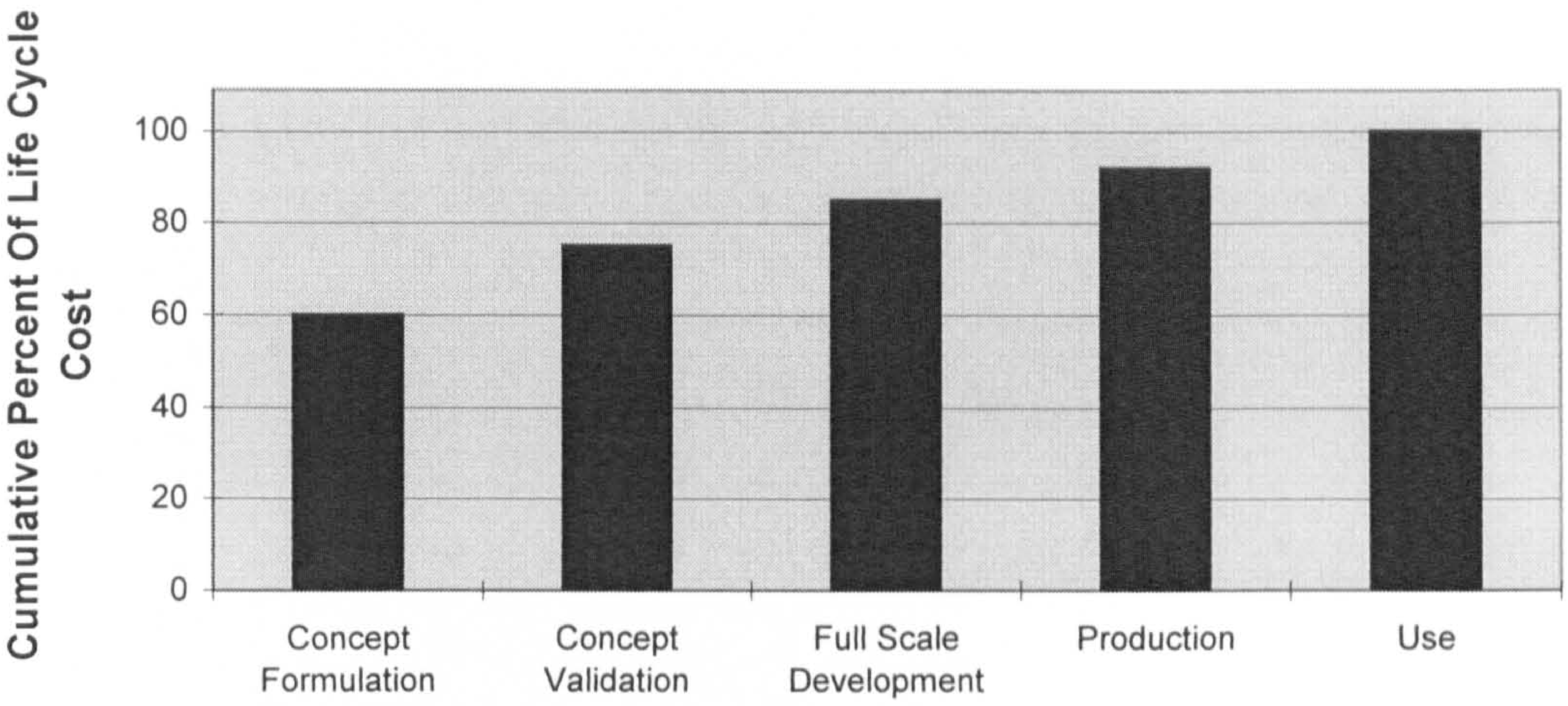


Figure 4.1: ***Life Cycle Costs in the Product Introduction Process*** [69]

It is proposed that this *a posteriori* approach misses an important cost reduction opportunity. An easier to assemble and thus less expensive product could be achieved if it was possible to alter the design configuration to find the optimum assembly sequence. This may then realise further improvements but unfortunately involves much reworking of existing designs. It may be possible to take this idea one stage further. Designing the both product and its assembly sequence at the same time, by the same person, would enable the exploration of the interrelationships and trade-offs to produce optimised designs and sequences. In this manner, the generation of the assembly sequence concurrently with the design could also afford a more assembly oriented view of the product and highlight any issues as they arise. This should reduce the need for unnecessary and expensive changes late in the PIP. Because there will be no need for a subsequent sequence generation step after the design process. Another advantage of this approach is the reduction of product lead times. However, it is noted that this benefit is offset by the extension of the design process.

4.2 Computer Aided Design Support

Appropriate support from a CAD system is essential to fully realise the benefits from a concurrent sequence generation and design methodology. A suitable CAD package must offer an assembly-oriented perspective throughout the design process. However, most commercially available systems concentrate upon a component oriented approach. Substantial functionality is provided for the modelling of individual parts. Yet only after the components are fully detailed can the assembly relationships be defined to represent the final assembled product. This approach is known as bottom-up design, and is detailed in Figure 4.2. Thus, commercial CAD systems focus the designer towards the optimisation of individual components, which in most cases does not lead to the best assembly configuration. CAD systems fail to afford an assembly-oriented view of the product which is necessary to concurrently consider the design and the sequence.

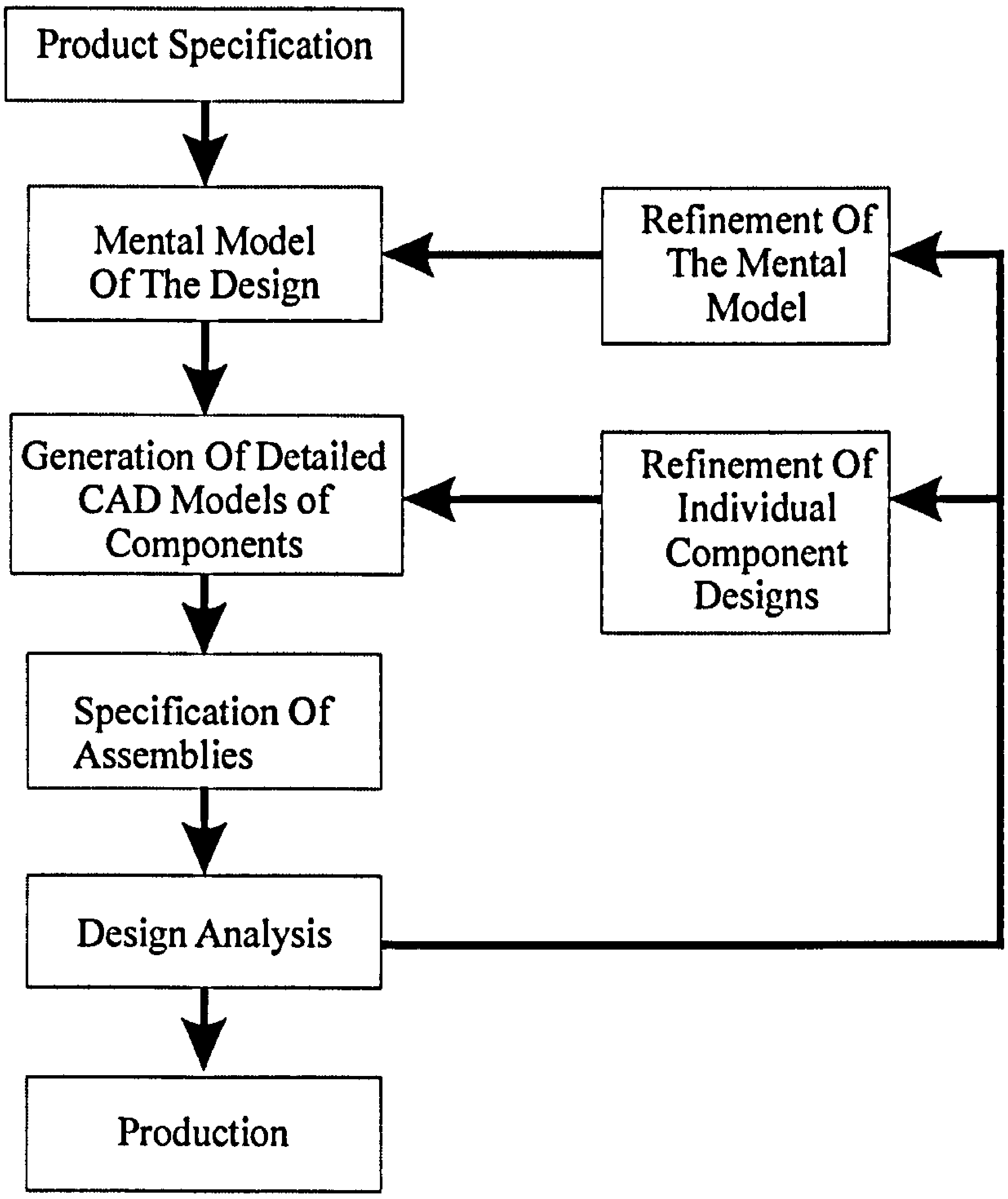


Figure 4.2: ***Bottom Up Design Process***

Top-down design has been proposed as an alternative method of designing products using CAD support[70]. This method is illustrated in Figure 4.3 and shows with the generation of a functional representation of the design. This is analysed to ensure that all the product requirements are included. Geometry can then be added to specify each component. Basic requirements for assembly-oriented CAD and top-down design support have been defined[70] to facilitate the creation of a useful software environment. The report concluded that a top-down approach is fundamental for the appropriate support of an assembly focused design process. Thus, a top-down approach to CAD support is required to facilitate concurrent generation of both the assembly sequence and the design. This necessitates a new definition of the design process using CAD support and indeed a whole new approach to the design process. This investigation is outside the scope of this thesis but it is assumed that a top-down approach to design is taken.

The representation and manipulation of data is another challenge for commercial CAD systems. Those who assume that design is merely the creation of geometry are mistaken. Focussing upon the design geometry leads to a neglect of the important data management and engineering skills[71].

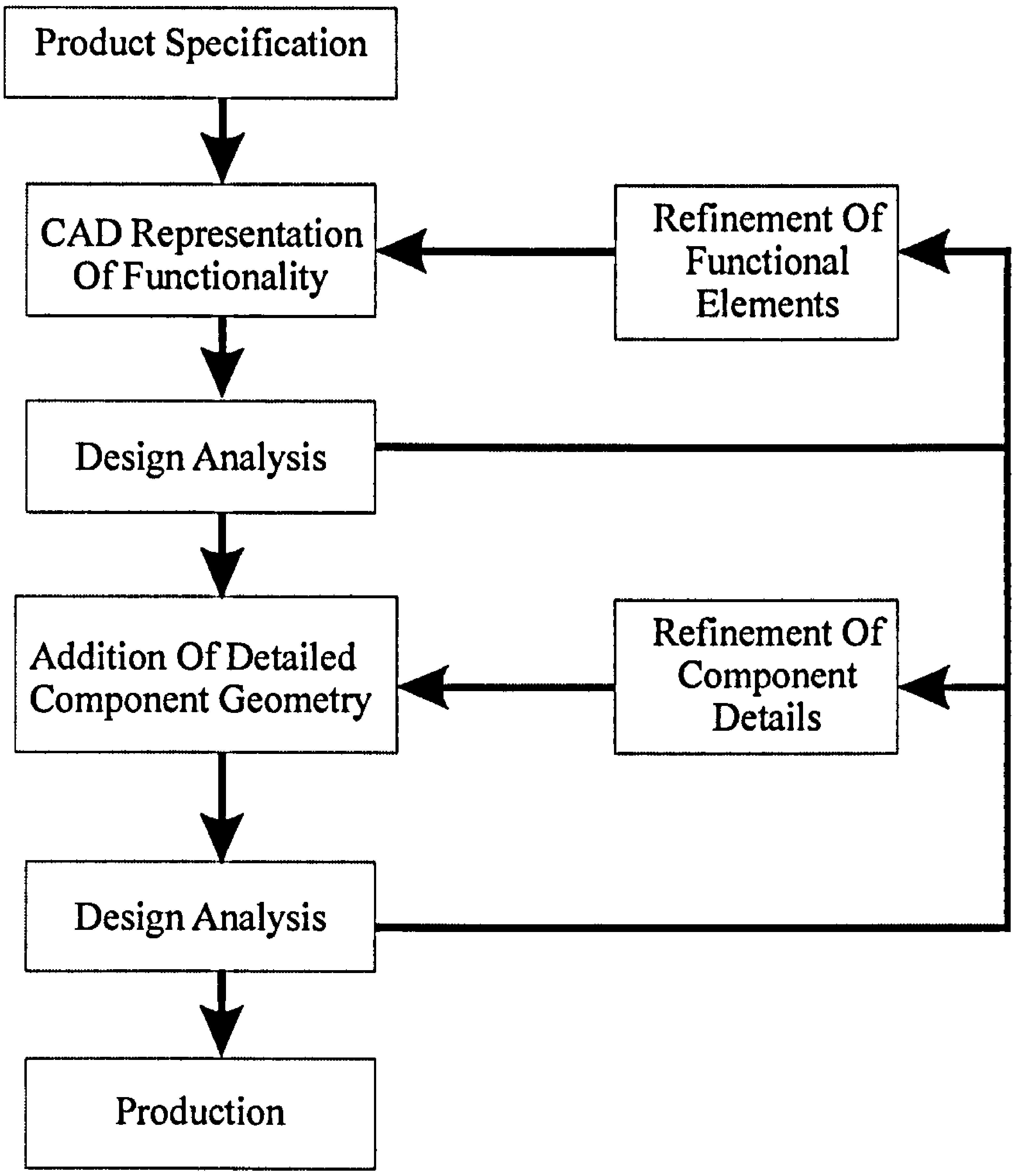


Figure 4.3*: Top Down Design Process*

As the design process tends more towards a PIP and thus includes more interdisciplinary tasks, the requirements of the CAD system becomes ever more complex and demanding. Future systems need to consider the inclusion of the following tools:

- Variation predication and management.
- Assembly interactions.
- Production issues.
- Design of product families.
- Support for design data management.

Although the redefinition of the design process is outside the scope of this thesis it is important to realise that current commercially available CAD systems force designers towards sub-optimal assemblies. It has been seen that these applications do not provide the appropriate support for the concurrent consideration of the development of a design and the generation of an assembly sequence. This requires the determination of a new process for the use of CAD software. Work towards defining and developing such an environment has taken place as part of the OPHIR project[72,53,73] and includes the implementation of the Two-Tier methodology. Chapter 10 will describe this system in detail.

4.3 *The Stages Of Assembly Planning*

In the previous section it was stated that current CAD systems fail to provide the functionality required to design assembly oriented products and to plan the sequence of assembly during the design process. It is necessary to fully understand the requirements of a methodology for concurrent sequence generation and design and define the separate stages involved in the planning of assemblies. It has been shown in Chapters 2 and 3 that the human assembly planning process is somewhat different from the research-led automatic sequence generation process. This section aims to highlight the constituent stages in both processes and shows that whilst there are many differences the separate stages are inherently similar.

The CAAP literature review in Chapter 2 showed that most research in the area of assembly planning has concentrated upon the automatic generation of an assembly sequence from a completed design. Three generic stages can be identified by analysing this research, shown diagrammatically in Figure 4.4, despite many differences in approach and search techniques.

STEP 1: ***Automatic Sequence Construction Phase:***

This phase comprises the building of the set of all feasible assembly sequences. In many automated sequence generation systems this involves the first draft construction of a liaison diagram[13]or the AND/OR graph[15]. Hard constraints are invoked to define the set of geometrically feasible sequences. Many different methods are used to build these data structures, a representative selection has been described in Section 2.1.

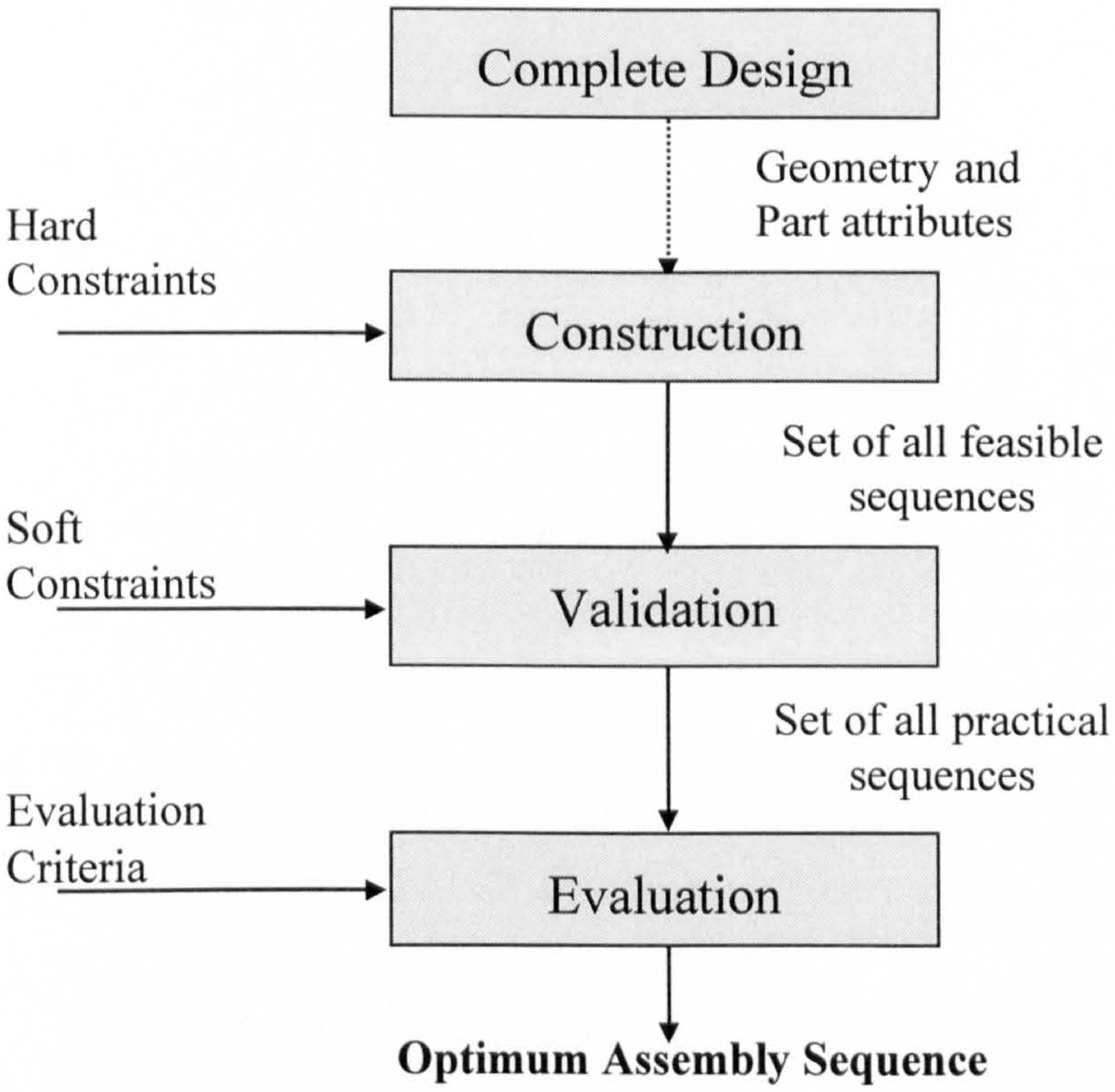


Figure 4.4: ***Automatic Sequence Generation Procedure***

STEP 2: *Automatic Sequence Validation Phase:*

Once the set of sequences has been defined, invalid or inappropriate actions and liaisons must be removed. This should leave only those sequences that are both practical and feasible. Soft or technological constraints are used to validate sequences during this stage. These are usually suggestions for 'best practice' which often require further user validation to ensure correct application.

STEP 3: *Automatic Sequence Evaluation Phase:*

Those sequences remaining after the validation stage should be evaluated using some appropriate metrics to determine the optimum sequence for the given design and situation. This is the least well explored of the three areas and one which few sequence generation systems consider in depth. The most common evaluation metric is a cost calculation, however there are many different definitions of sequence cost. When the literature is examined, it becomes apparent that many of the systems that claim to evaluate sequences are only ranking validation criteria. For example, many systems use a stability constraint to validate sequences. This rejects particular liaisons in the sequence which do not conform to the particular definition of stability; a pass/fail state. However, stability can also be quantified to give a value to the stability criteria and this is used to evaluate the sequence.

These same three stages are also apparent when analysing the manual planning procedure, as shown in Figure 4.5. However, the contents of the steps are different from the computer-based automatic sequence generation process.

STEP 1: *Manual Sequence Construction Phase:*

The first task in this step is the collation of all the relevant information required for successful planning. Once this is completed, the planner must decide upon a suitable subassembly configuration, the *Breadth-First* approach. Each subassembly is considered in turn and the sequence of component assembly and the associated tasks are planned. This can be considered the *depth-second* search for feasible sequence configurations. Hard and soft heuristics are applied at this stage to output a plan that is both feasible and practical. In contrast to the automatic process, only one sequence is constructed.

STEP 2: *Manual Sequence Validation Phase:*

In general, disassembling the product as per the defined plan validates each subassembly plan. Once these plans are deemed satisfactory, the overall plan is validated, often by using a trial run on the assembly line or the workbench.

STEP 3: *Manual Sequence Evaluation Phase:*

Figure 4.5 shows that no sequence evaluation is considered. During this research programme's industrial investigations, no plan evaluation was observed except general line balancing techniques.

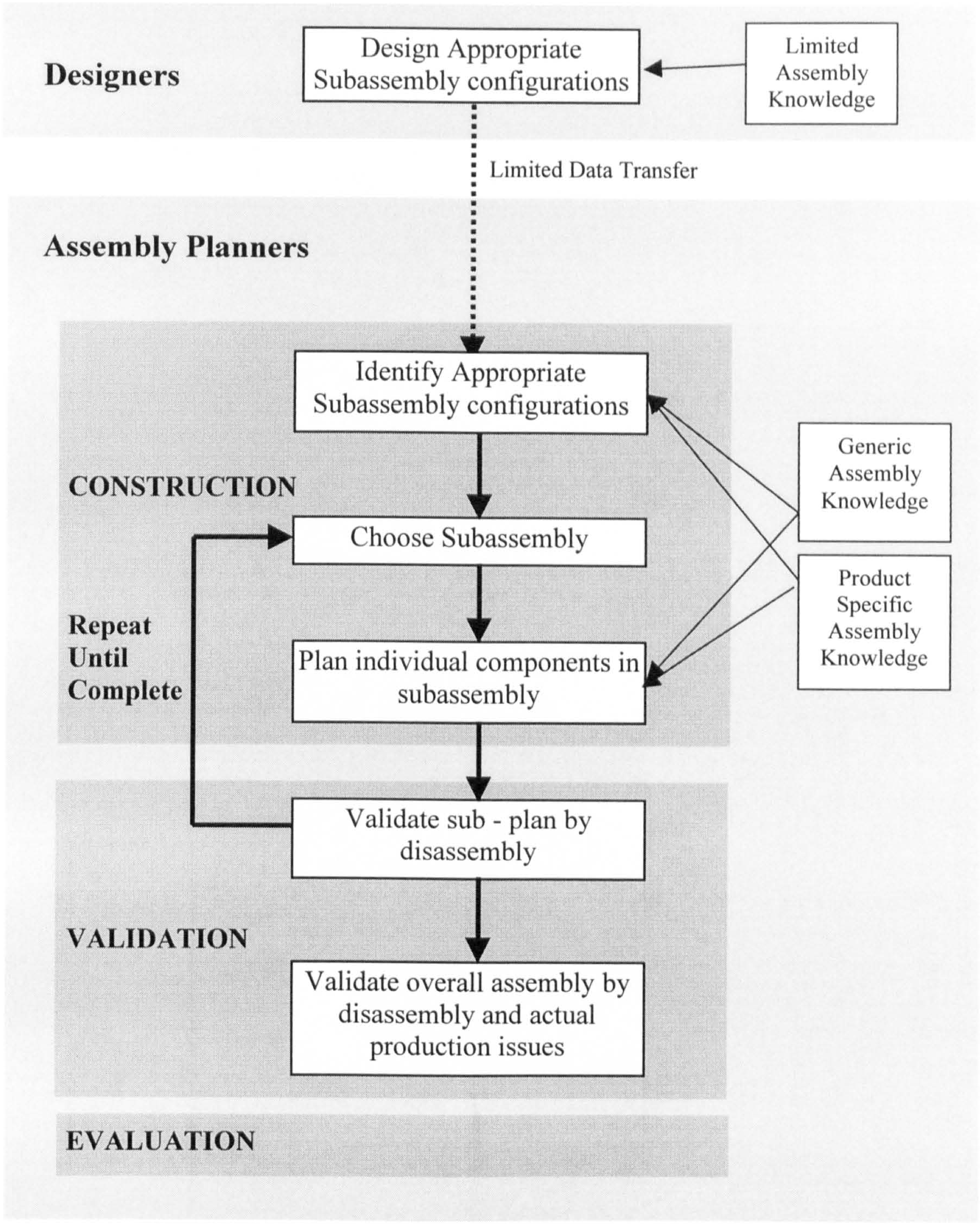


Figure 4.5: ***Manual Assembly Planning Practice***

An examination of the steps involved in the automatic sequence generation and the human assembly planning process shows that the same three steps are involved, but their content is somewhat different. The automatic generation procedure concentrates upon finding the set of all the geometrically possible sequences in the construction phase, only to prune this in the validation stage. The human process, on the other hand, focuses effort on finding one good sequence that is validated by disassembly analysis.

These two methods must be examined to identify a process that will enable the generation of an assembly sequence concurrently with the design.

4.4 Concurrent Sequence Generation Process

Building an assembly sequence in parallel with the developing design requires the definition of a new process. Neither of the two approaches detailed in the previous section is directly transferable into a method for the concurrent consideration of the sequence and the design. Thus, a new methodology needs to be defined, which is based upon a top down approach to design, as discussed in section 4.2. For comparison purposes, it is useful to outline this new process in the same three steps as the prior section.

STEP 1: ***Concurrent Sequence Construction Phase:***

> It has been seen that the human planning process uses a *Breadth-First, Depth - Second* approach to sequence generation. It is proposed that this should be implemented in the concurrent sequence generation methodology. To achieve this, a facility must be provided for decomposing the assembly into appropriate subassemblies and constituent components before the actual sequence construction. The parts and processes can then be interactively added to the sequence. The building of the sequence can commence at any time, even if only some of the assembly is currently determined. As more components and attributes are developed then they can be added to the sequence. No constraints are applied to stop parts being added to the sequence although appropriate suggestions can assist with component choice. The various aspects of the construction of the assembly sequence are discussed in greater depth in Chapters 5, 6 and 7.

STEP 2: ***Concurrent Sequence Validation Phase:***

> Validation criteria can be applied at each liaison level as the parts are added to the sequence. Both hard and soft constraints can be invoked at this time. This approach integrates the application of the criteria as identified in the human planning process. The validation of each step ensures that, as the sequence is generated, it tends towards the optimal as no impractical or invalid actions or liaisons are included, (it is not claimed that this method will produce an optimal sequence). In a practical implementation, this validation process may prove to be computationally expensive and alternatives may be necessary. Further sequence validation details are to be found in Chapter 8.

STEP 3: ***Concurrent Sequence Evaluation Phase:***

> When the methodology constructs only one sequence, the evaluation of that sequence is imperative. It must be possible to understand the quality of this sequence during and after construction to decide if more work is needed to find a good sequence. The evaluation metrics must be such that it is possible to determine the sequence value absolutely. Design evaluation is also important as assemblability and sequence quality are intrinsically linked to geometry. In addition, comparative sequence evaluation can be a useful tool if more than one design and/or sequence have been constructed. However, the nature of the

methodology means that only one sequence is built and thus it is important to know the its suitability. This is discussed in detail in Chapter 9.

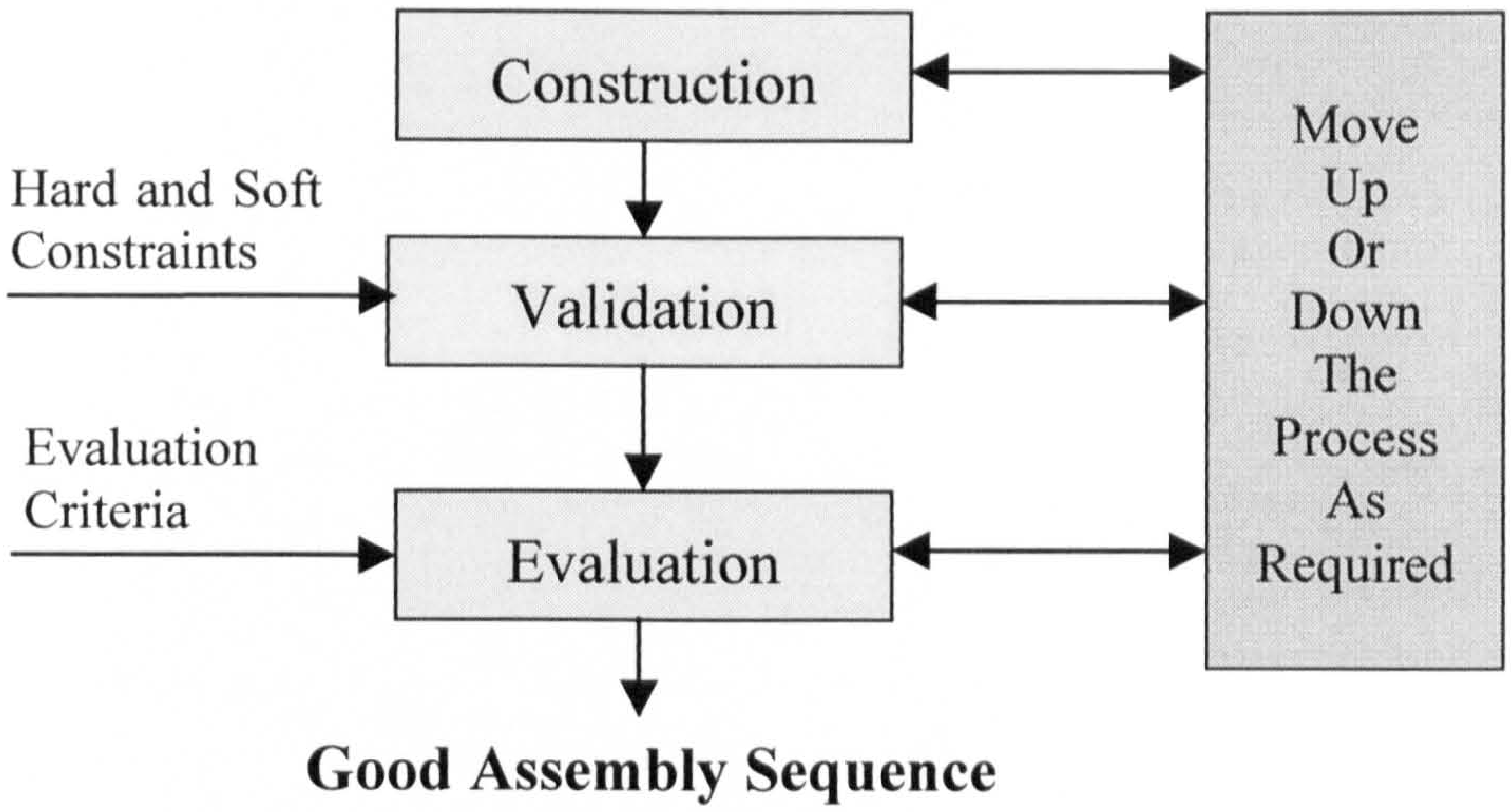


Figure 4.6: ***Concurrent Sequence Generation Process***

4.5 Definition Of Two-Tier Methodology

The three-step process described in overview in Figure 4.6 has been developed into a Two-Tier methodology for concurrent design and sequence generation. Support is provided which allows the generation of an assembly sequence in parallel with the design process, see Figure 4.7. The top tier of the methodology supports the definition of a suitable assembly hierarchy, *Structure Definition*, and is described in more detail in Chapter 5. The tier facilitates the partitioning of appropriate subassemblies and implements the breadth first approach. Assistance to build assembly sequences is provided by the second tier, *Sequence Construction*, which is dealt with in Chapter 6. *Validation* and *Evaluation* Modules are available to ensure feasible and practical solutions are explored, see Chapters 8 and 9 for further information. *An Expert Assembler* discussed in Chapter 7, works behind the scenes to offer timely advice and suggestions to ensure that a good sequence is built. This is necessary because designers are, in general, not manufacturing and assembly experts. The provision and appropriate accessing of expert knowledge will help with the generation process. The described tiers are discrete, but intrinsically linked, which allows the design to be completed concurrently, but separately from, the consideration of subassembly partitioning and sequence generation. The methodology aims to ensure that assemblability issues are highlighted during the design process and solutions found before they cause manufacturing 'headaches'.

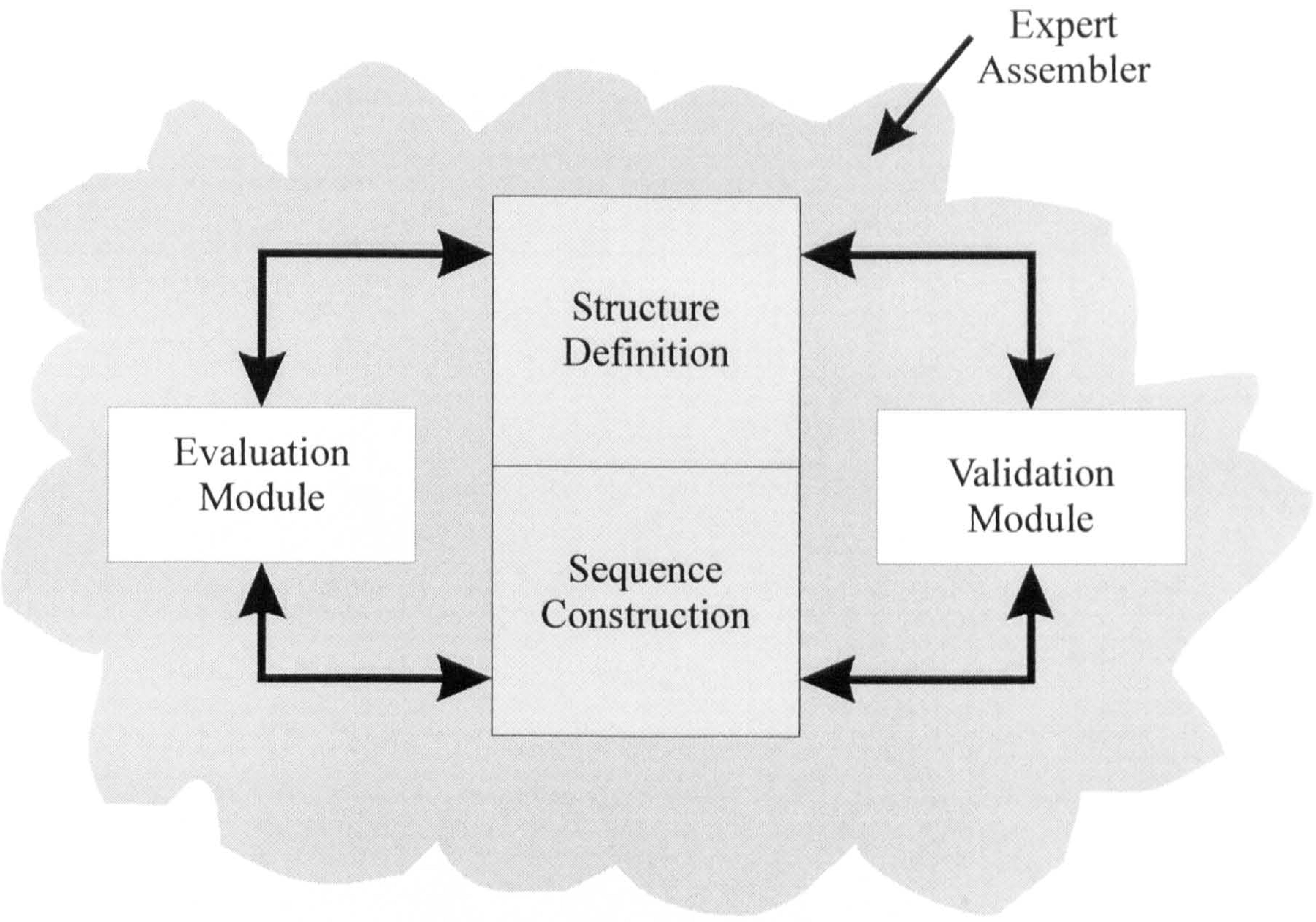


Figure 4.7: ***Two-Tier Sequence Generation Methodology***

The methodology should be used as an integral part of the Product Introduction Process (PIP). Figure 4.8 shows the relationship between the PIP and this sequence generation methodology. Early in the design process, little specific data is available, thus the *Structure Definition* module will be the most utilised. As the design becomes further defined, the *Sequence Construction* module will be increasingly used, as the designer finalises the assembly sequence. The Two-Tier methodology should be employed throughout the design and development cycle, alongside the more conventional design processes, providing further data regarding the assemblability merits. The output of the process is a finished design and working assembly sequence, which can then be used by manufacturing to plan the production of the product.

4.6 Concluding Remarks

A need has been identified for a process that can construct, validate and evaluate assembly sequences during the design process. It was found that current CAD systems do not support assembly design. Although redefinition of the design process is outside the scope of this thesis, new ways of implementing CAD systems must be considered. It was seen that a top-down approach afforded a more assembly focused design.

The three stages of sequence generation, construction, validation and evaluation, have been defined for both an automatic approach to sequence generation, and the manual planning process. A Two-Tier methodology for concurrent sequence generation and design was developed with its foundations in these processes. This will be discussed in more detail in the following chapters.

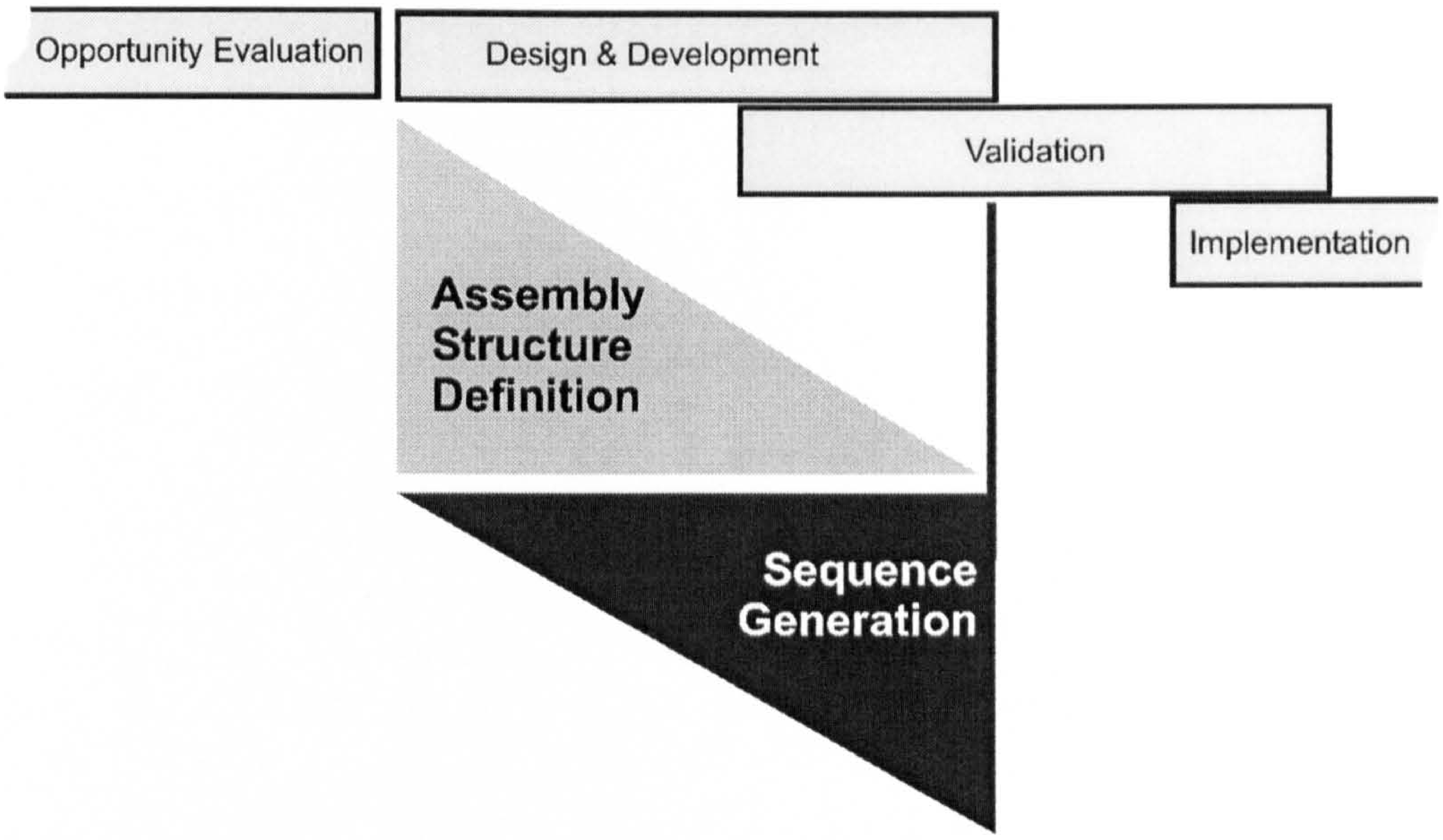


Figure 4.8: ***Structure Definition and Sequence Generation in the PIP***

5. STRUCTURE DEFINITION TIER

The previous chapter proposed that significant benefits could be gained from implementing a Two-Tier methodology, which supports the concurrent generation of assembly sequences and designs. The *Structure Definition* tier is the top tier of this methodology and realises the *breadth-first* philosophy. It provides support for the early definition of the product structure and partitioning into appropriate subassemblies. The assembly structure of the product is generally based upon the function structure[e]. This latter type of structure and the process of moving from function to assembly structure is beyond the scope of this thesis. However, it is believed that it is necessary to consider product structure optimisation because only limited assemblability improvements can be realised if just the individual components are analysed[58]. An additional benefit of this early documentation of the structure is that it allows other business processes to utilise this information before previously possible.

To determine the requirements of the *Structure Definition* tier, the different models of product structures are explored and defined in this chapter. The proposed process for the definition of the product/assembly structure is detailed followed by a definition of the functionality provided by the top tier of the Two-Tier methodology.

5.1 Product Structures

Once the function structure has been constructed, the designer must translate these ideas into the tangible components and subassemblies that become the physical manifestation of the design solution. The examination and inclusion of this process is outside the scope of the thesis although in reality the completion of this task is unavoidable if the ideas are to be developed into a workable hierarchy of components and subassemblies. The consideration of the assembly structure before the design of each individual component is an integral part of the top-down design approach and fulfils the *breadth first* philosophy of the proposed Two-Tier methodology. It is by following the procedure that the construction and documentation of the included components and subassembly partitions can be completed. However, there are many definitions of a product structure and it must be clear what is necessary in this case for successful

---

[e] A hierarchy of functional requirements

sequence generation. This section investigates the different types of product structures and defines the required form for the *Structure Definition* tier.

Both relational and hierarchical models have been used as types of product structure[70]. The relational model consists of nodes that correspond to the components and links that represent the relationships between the components as shown in Figure 5.1. However, this is a 1-level structure representation; a hierarchical structure is believed to be the more appropriate for assembly-related data and the links to functional intent. This type of structure is derived by adding sequential constraints to the relational model. Whatever the user's perspective, the relational model is constant. However, the hierarchical model can be different depending upon the application. Figure 5.2 shows a selection of hierarchical models used to represent a design in different situations.

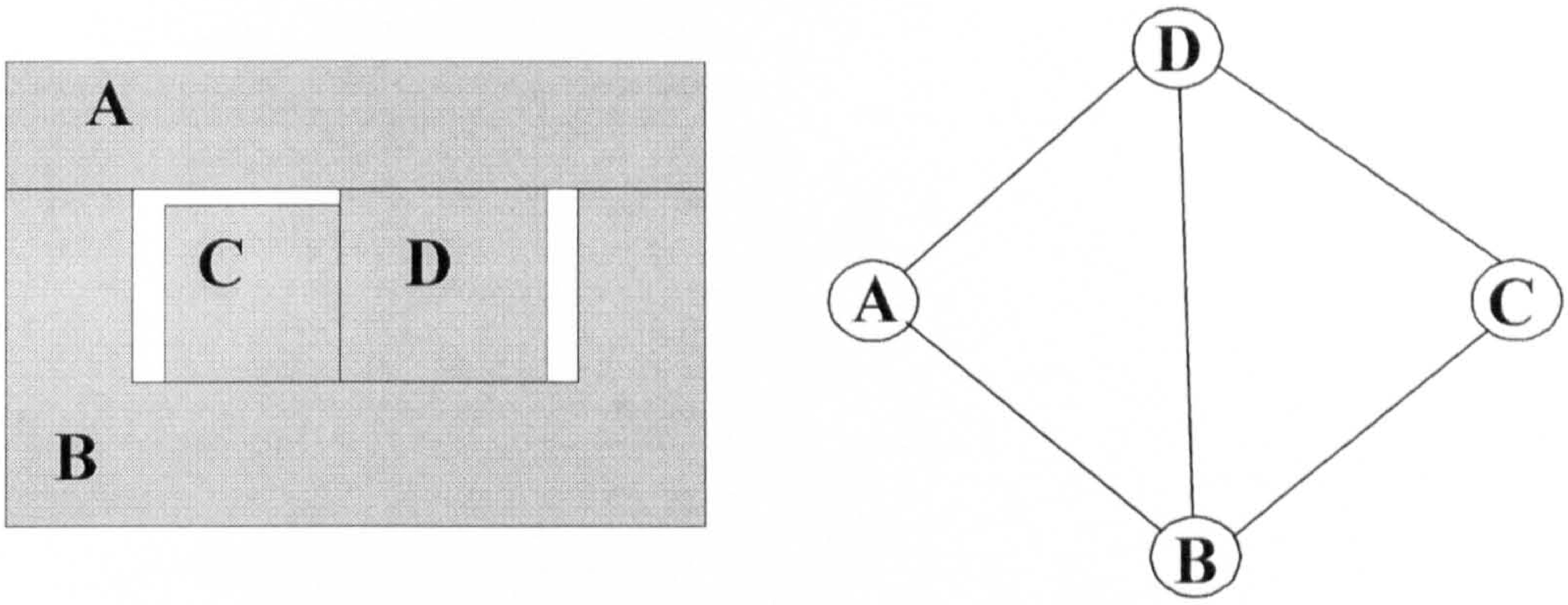


Figure 5.1: ***An Assembly and Relational Model***

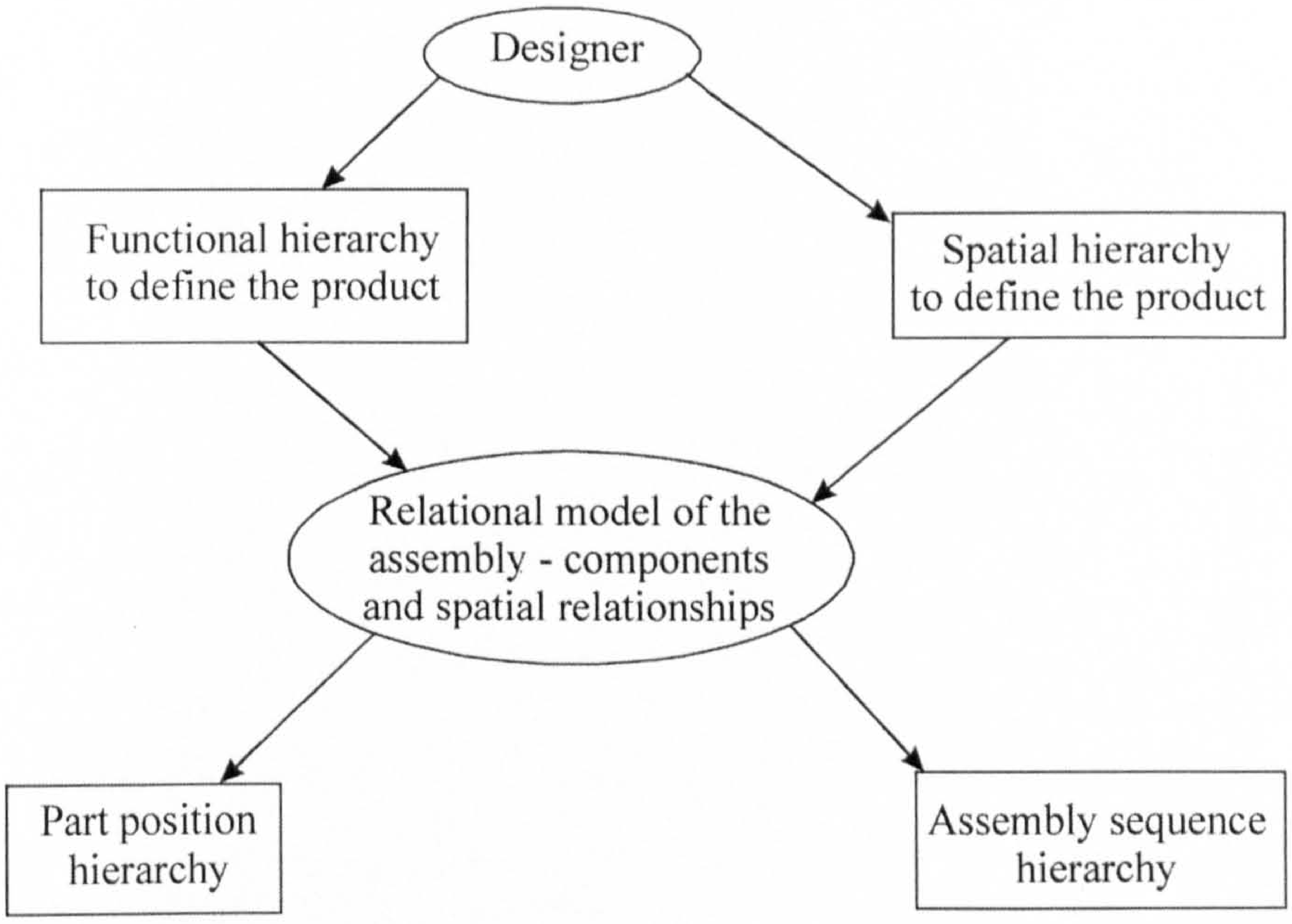


Figure 5.2: ***A Selection of Different Types of Hierarchy Models***

Any product structure, relational or hierarchical, must contain two types of entities, elements and relationships[74]. By definition, the elements are all of the same type and the relationships are defined as composition (hierarchical models) or connectivity (relational models) links. Data can be attached to both the elements and the relationships within the structure. This is explained further in Figure 5.3, which shows the partially completed product structure of a Compact Disc (CD) case assembly. From the model it can be seen that the CD case assembly *is composed of* a CD, front case assembly and rear case assembly and the CD *connects to* the rear case assembly, illustrating the two types of relationships. The nodes conventionally represent the elements (all of type part) and the attached data currently consists of the part name, as shown. Other attributes that could be attached include material, manufacturing process, part number. The composition and connectivity relationships can also have data attached such as sequence of assembly, joining process and mating faces. The *Structure Definition* Tier will support the construction of this type of hierarchical model. The exact relationships required will be determined in the next section.

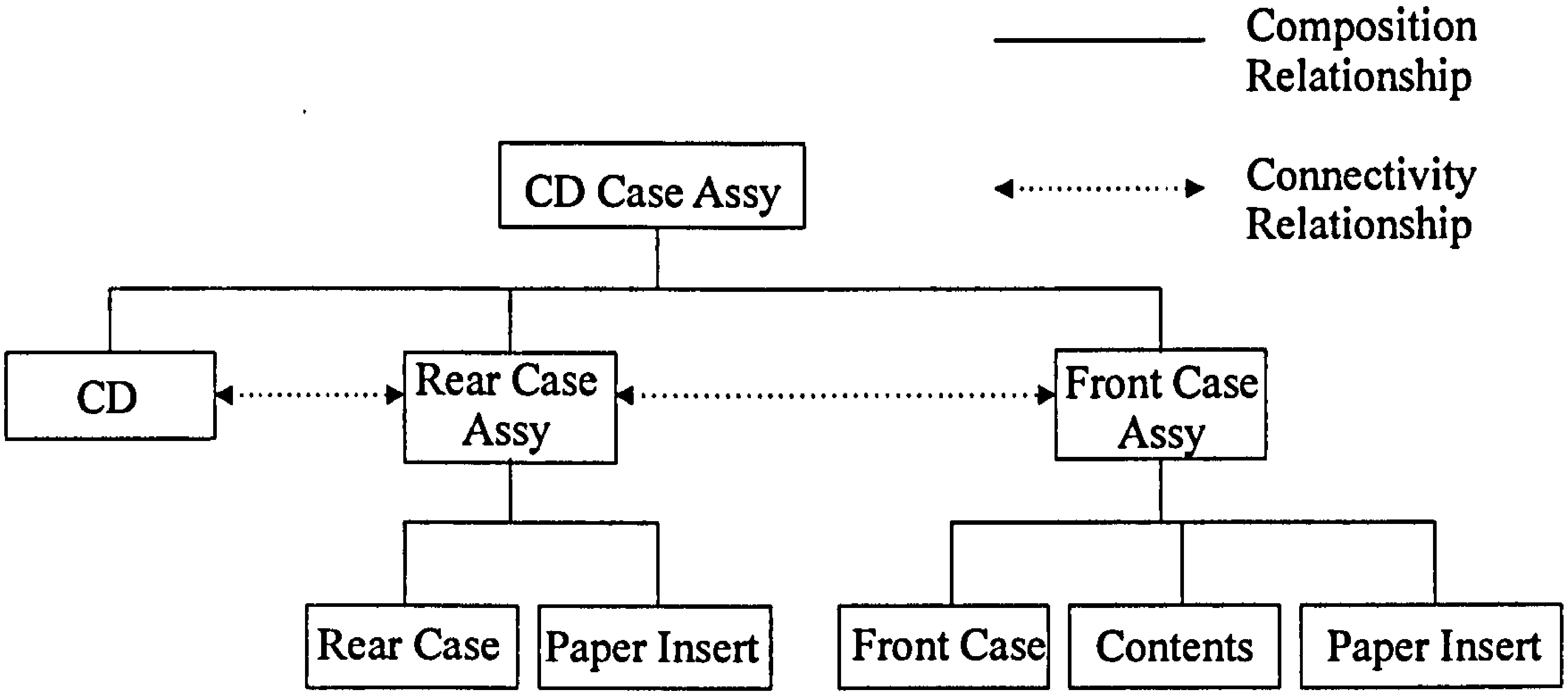


Figure 5.3: ***Product Structure for CD Case Assembly***

5.2 Structure Definition Tier Requirements

A hierarchical product structure will be used to represent the assembly in the *Structure Definition* Tier, as defined in the previous section. However, conventional CAD, operating a bottom-up design philosophy, rarely allows the user to construct the product structure. Thus to incorporate the necessary top-down design focus, this tier must provide the functionality to complete this task. Specifically, it is necessary to facilitate the clustering of components into subassemblies that are suited, both positionally and technologically, to the particular product and the available assembly processes. However, the development methods must be generically applicable for all types of design processes. Thus, three design activities[56] must be considered:

- *Original Design*: providing an original solution principle for a given system.
- *Adaptive Design*: the adaptation of known solution principle to a changed task.
- *Variant Design:* The variation of size or arrangement of an existing system.

In an original design, the designer starts from a blank sheet of paper. Many of the constituent components and subassemblies are designed specifically for this product. In today's businesses, this type of design is rarely undertaken. Companies tend to specialise in a range of similar products and rarely venture into the uncharted territory of this type of design. In general, much design is adaptive, where a known solution principle is applied to a particular design specification. This re-uses many existing components and subassemblies, but does require that some new parts be created. The re-use of standard parts and subassemblies is standard practice in variant design, where new part development is scarce. This type of design is becoming more prevalent as companies try to reduce costs by removing variation in their product range.

These three design activities have different requirements of an assembly structure definition. Consideration must be given to the design of completely new components whilst enabling, or perhaps even encouraging, the use of existing parts. For each type of design, it must be possible to handle the different parts. The product models and attributes must be controlled accordingly. For example, it must not be possible to alter existing parts as this may have implications in other product designs. It is necessary to identify and define the different component groups, the methods of handling their attribute data and any other structure related information:

New Component:

Definition: A component designed specifically for a product and can only be a member of that product.

Methods: Full access to the component model is available.

Structure: Terminates a composition link.

Existing Component:

Definition: A component that can be a member of many products. It could be either a bought-in item or part of a standard in-house range.

Methods: Only the assembly position and orientation can be edited.

Structure: Terminates a composition link.

New Subassembly:

Definition: A collection of two or more components that only exist within a particular product. The incorporated components can be either or both the *New Component* or *Existing Component* types.

Methods: Full access is given to the product model to make changes. However, any changes to individual components can only alter the respective product models if it is the *New Component* type.

Structure: Must have n composition linked nodes of group *New Component/ Existing Component/Existing Subassembly*, where $n>1$.

Existing Subassembly:

Definition: A collection of components that together form a subassembly that can be a member of many products. Again, this may be a bought-in component, part of a standard in-house range or a standard module.

Methods: Only the assembly position and orientation can be edited.

Structure: Terminates a composition link.

Because the defined assembly structure is a hierarchical model, there is the potential for an unmanageably large number of connectivity relationships in even a relatively simple assembly. Thus, it is not intended to include the mating face data in the structure representation. However, it will be necessary to somehow represent part to part connections for the sequence generation process. This will be achieved by data held in the product model but not visually represented.

Composition relationships and components are represented in the assembly constructed in the *Structure Definition* Tier and are shown in Figure 5.4. The nodes of the model signify one of the component groups as defined above and the links correspond to the composition relationships. Components can be clustered into subassemblies and these and individual parts are grouped to form the overall assembly. The terminal node of every link should not be a member of the component group, *New Subassembly*. The hierarchy consists of *n* levels where level 0 represents the finished assembly and level n must only consist of terminal nodes.

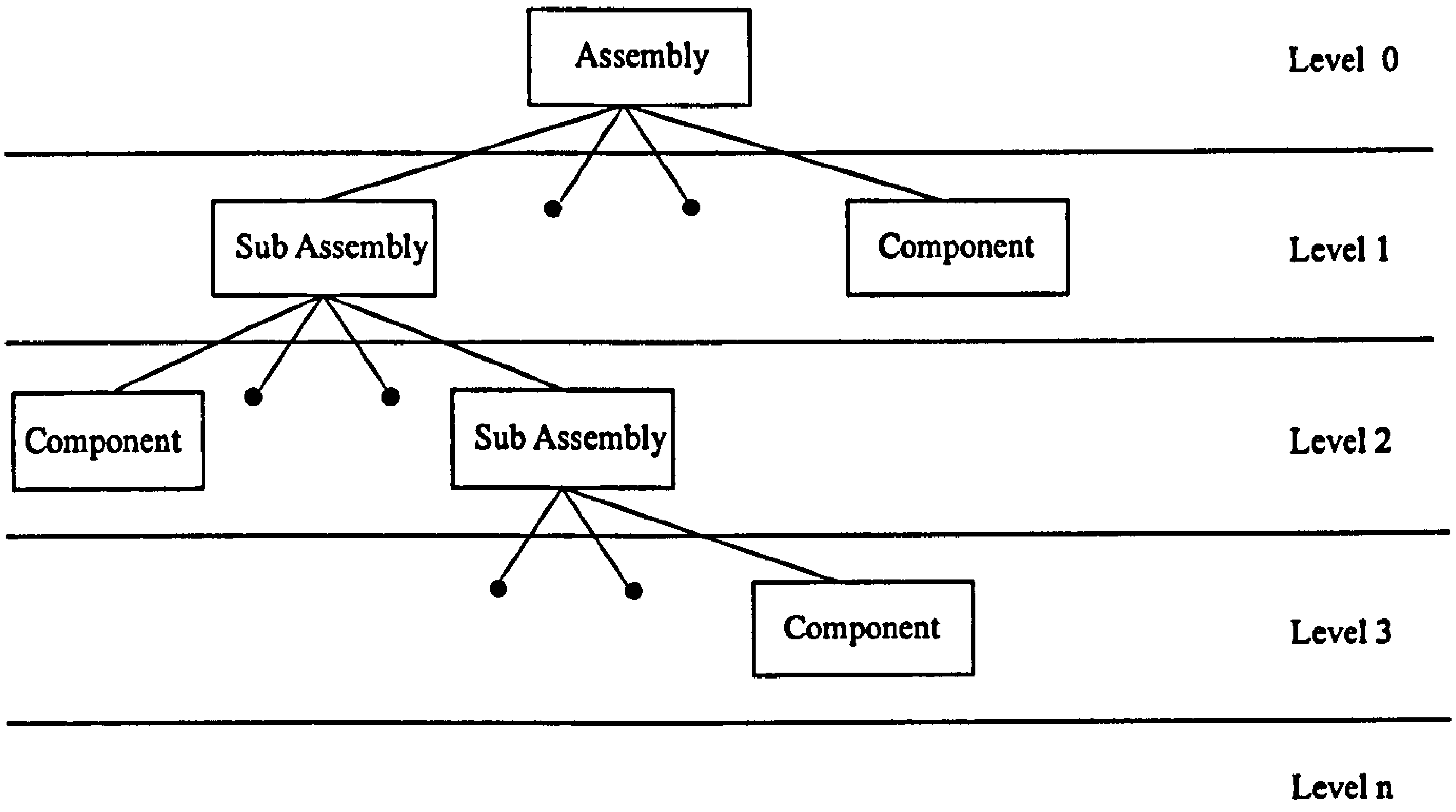


Figure 5.4: ***Structure Definition Tier Hierarchical Model Representation***

Because the methodology requires the structure to be defined before a complete description of the product model is available, it must be possible to add new components without a full geometric description. Hence, it is only necessary to define the part name and number attributes when adding a component to the structure. As the structure is further developed and the design configuration includes more geometry, attributes can be attached to the nodes of the assembly structure. These attributes can include materials, manufacturing processes and costs. Data can also be attached to the composition links during the sequence generation process, which will be discussed in detail in the next chapter.

The process of building this assembly structure adds parts to the underlying product model, described in Chapter 10. The component group is defined, predetermined procedures add the part to the structure and appropriate rules determine how the component is treated throughout the generation of the design and sequence. This is detailed in Figure 5.5. At any time, the structure can be readily rearranged to explore and analyse different hierarchies and thus alternative levels of parallelism in the assembly sequence. This functionality can help with the optimisation of the assembly sequence as will be seen in later chapters.

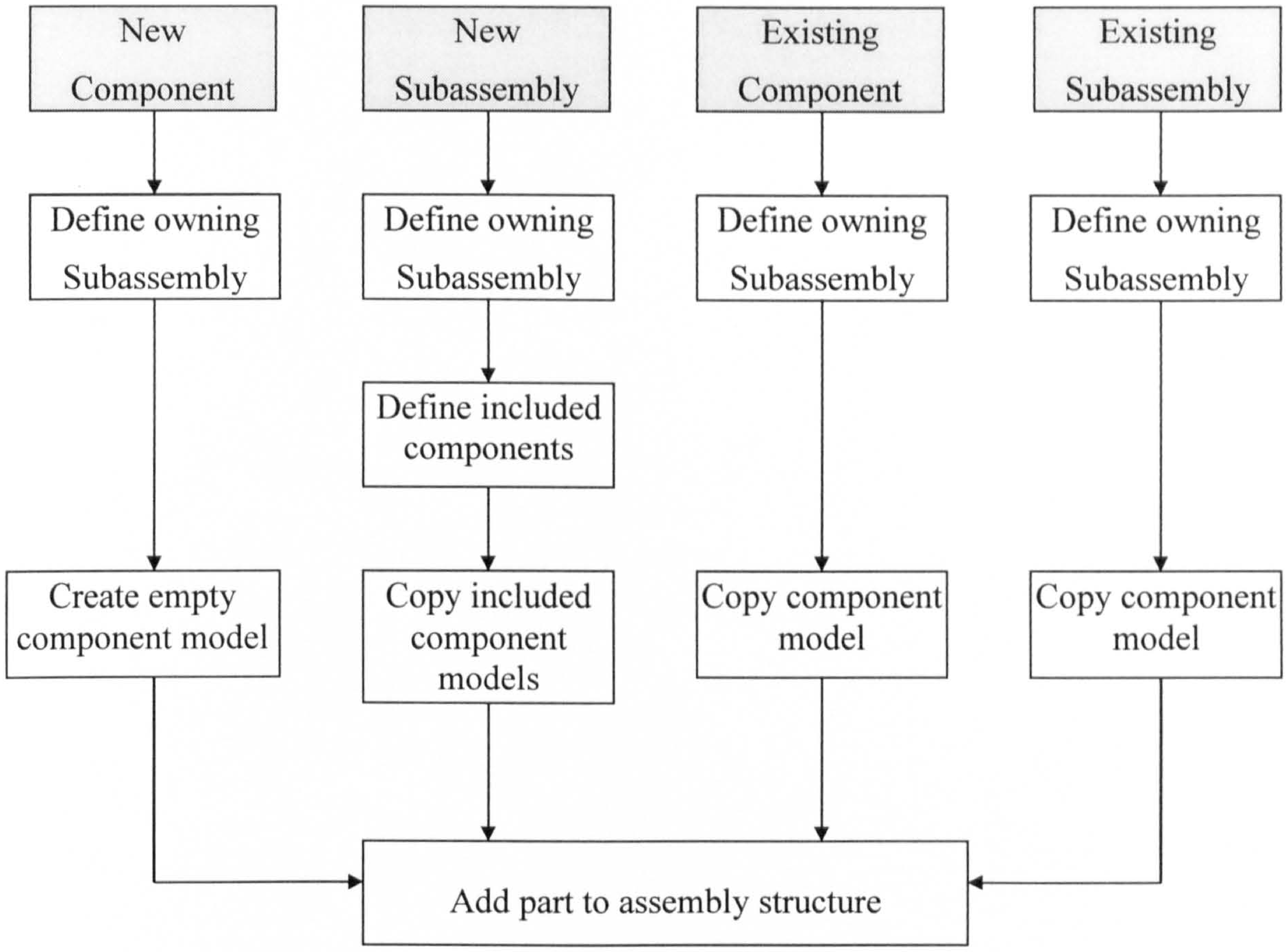


Figure 5.5: ***The Process of Adding a Part to the Assembly Structure***

5.3 Concluding Remarks

This chapter has described in detail the *Structure Definition* tier, which forms the top layer of the Two-Tier methodology. It has been found that a hierarchical model is the most suitable representation for the assembly structure. This is because components can be shown by nodes and composition relationships can be defined by the links. The different design processes that exist mean it is necessary to define a number of component groups and rules for the inclusion in the structure. Chapter 10 will illustrate the implementation of this process showing how the different parts can be added and analysed.

6. SEQUENCE CONSTRUCTION TIER

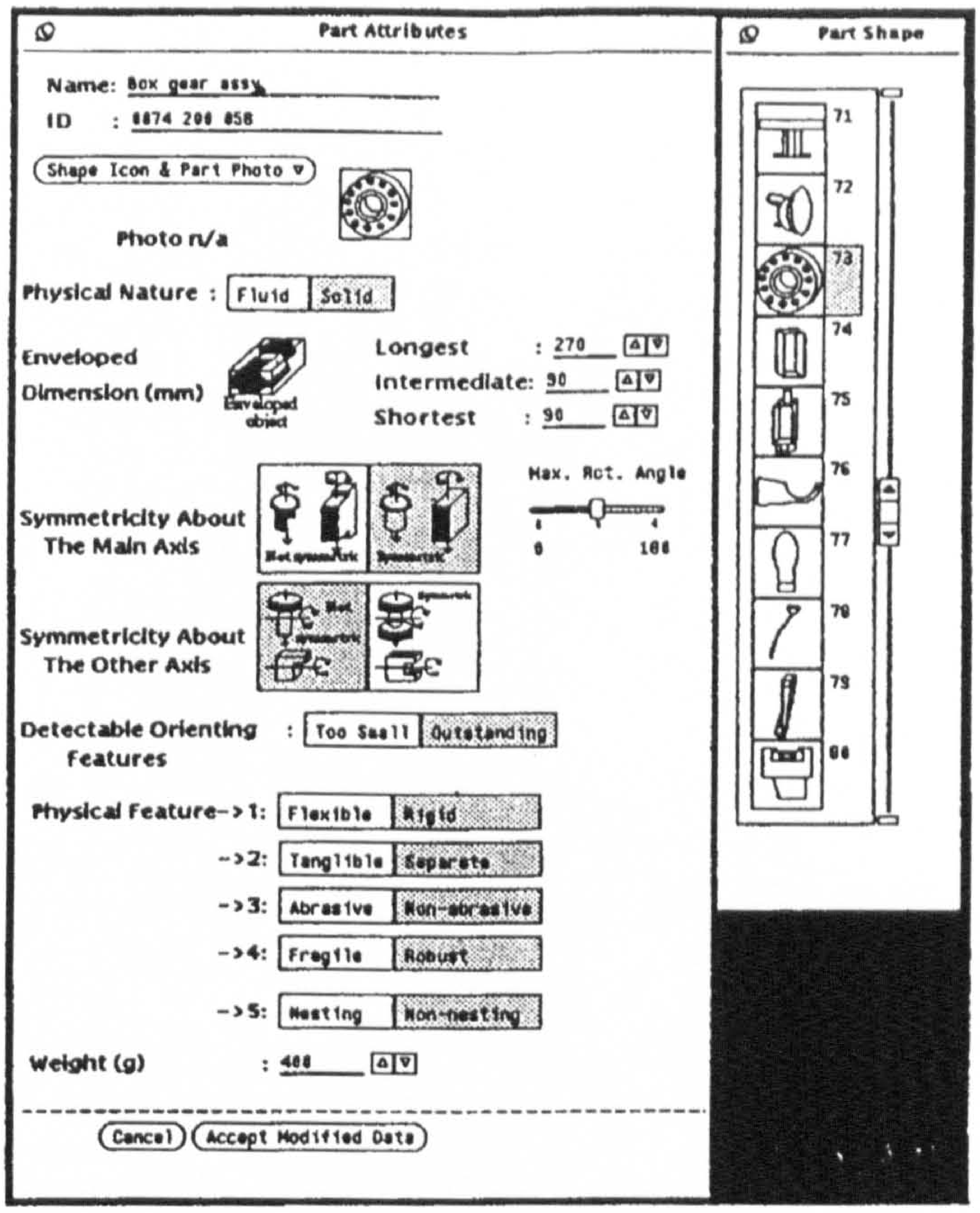
The lower tier of the Two-Tier methodology is called *Sequence Construction* and it comprises the necessary tools to build the sequence. This chapter defines the construction process and shows how the *depth-second* philosophy is included. To fully describe the functionality included in this section, four areas are considered in detail:

- The process of building the sequence.
- The visual representation of the sequence during and after construction.
- The level of detail that can be attached as attributes to the sequence
- The attributes which can be attached to the liaison link relationships

6.1 Sequence Construction Process

The results of the investigation to define the industrial planning process, as reported in Chapter 3, found that it was invariably a manual task which employed a breadth-first depth-second strategy. It was also observed that both the hard and soft constraints were applied simultaneously throughout the planning process. This manual approach was refined into the Two-Tier methodology as proposed in Chapter 4. This section discusses the issues involved in the building of the sequence and proposes a method to be included in the *Sequence Construction* Tier.

Much of the sequence generation literature reports progress towards automatic planning. Thus, there is little reported work available which can help to develop an interactive process for sequence generation. However, a planning system has been developed at CSIRO[42,43], which uses shape icons or 'glyphs' to represent parts as shown in Figure 6.1. Each part is defined using the icons to represent similar part shapes. These are then used to identify the part throughout the planning process. Appropriate assembly attributes are attached to this glyph to enable assembly times to be calculated. Once the definition of all these glyphs has been completed, precedence relationships are added to the part glyphs. The interactive sequence construction can now commence by marrying part and process glyphs, as shown in Figure 6.2. This process constitutes a rapid and easy way to define an assembly plan.



Name: Box gear assy

ID : 0074 200 058

Physical Nature : Fluid [✓ Solid]

Enveloped Dimension (mm)

Longest : 270

Intermediate: 90

Shortest : 90

Symmetricity About The Main Axis

Symmetricity About The Other Axis

Detectable Orienting Features : Too Small [✓ Outstanding]

Physical Feature->1: Flexible [✓ Rigid]

->2: Tangible [✓ Separate]

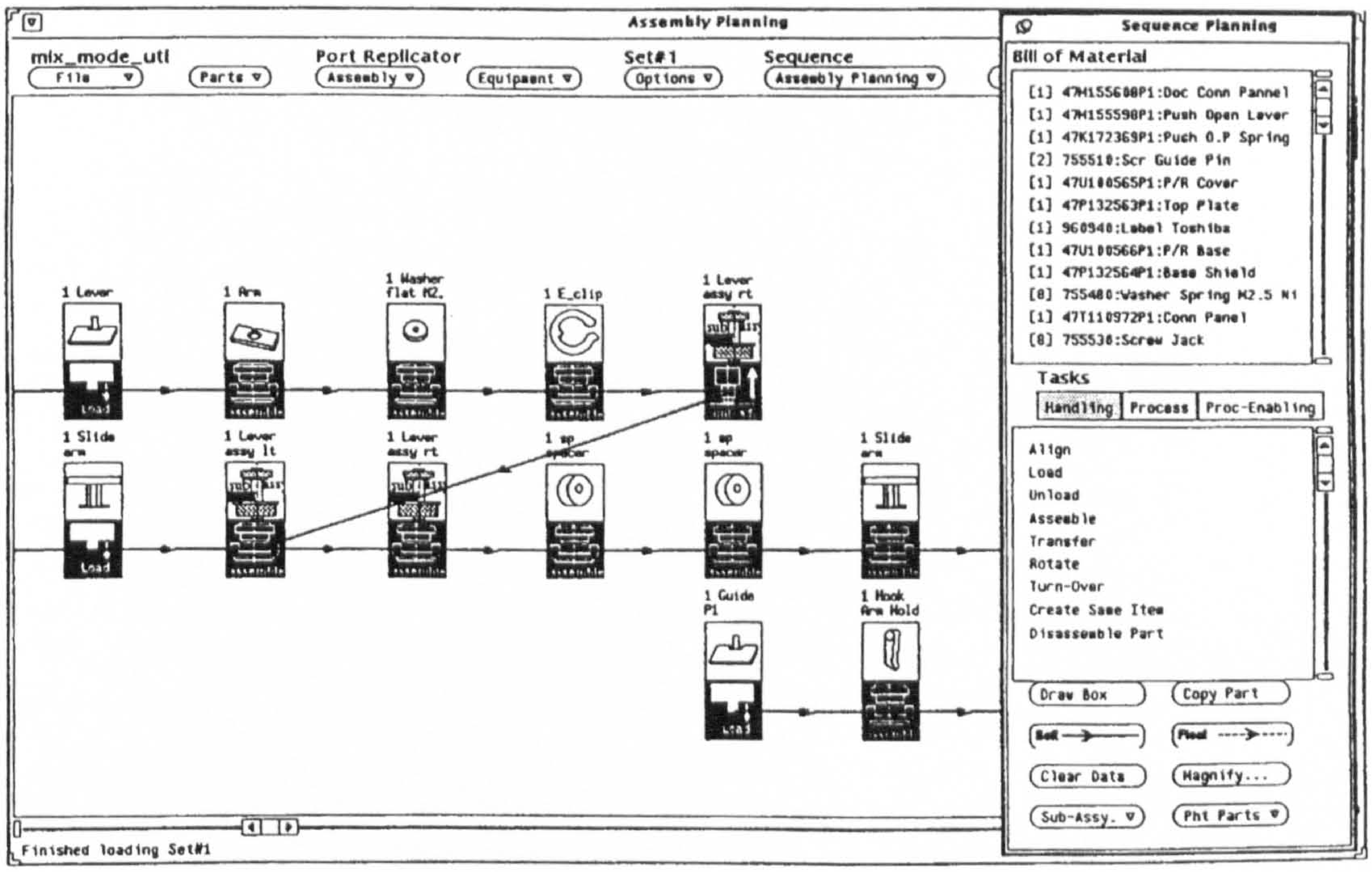
->3: Abrasive [✓ Non-abrasive]

->4: Fragile [✓ Robust]

->5: Nesting [✓ Non-nesting]

Weight (g) : 400

Figure 6.1: *Defining the Part Attributes For Assembly In CSIRO Sequence Generation System*



Finished loading Set#1

Bill of Material

[1] 47M155600P1:Doc Conn Pannel
[1] 47M155590P1:Push Open Lever
[1] 47K172369P1:Puch O.P Spring
[2] 755510:Scr Guide Pin
[1] 47U100565P1:P/R Cover
[1] 47P132563P1:Top Plate
[1] 960940:Label Toshiba
[1] 47U100566P1:P/R Base
[1] 47P132564P1:Base Shield
[0] 755480:Washer Spring M2.5 Ni
[1] 47T110972P1:Conn Panel
[0] 755530:Screw Jack

Tasks

[✓ Handling] Process Proc-Enabling

Align
Load
Unload
Assemble
Transfer
Rotate
Turn-Over
Create Same Item
Disassemble Part

Figure 6.2: *Sequence Generation Process In CSIRO Sequence Generation System*

A similar process is applied to the concurrent construction of the sequence within the Two-Tier methodology and is defined in Figure 6.3. Parts are added to the assembly structure using the *Structure Definition* Tier and arranged into a suitable subassembly hierarchy, as described in the previous chapter, formalising the breadth first approach. These parts are also added to a holding area that identifies which components must still be planned into the current assembly sequence. The sequence construction can then commence at any time, but ought to start before the design is complete to facilitate early assemblability consideration. This means that the part definition can contain little specified geometry and attributes or conversely can be fully defined. The overall process takes no account of the level of detail to which a component is described.

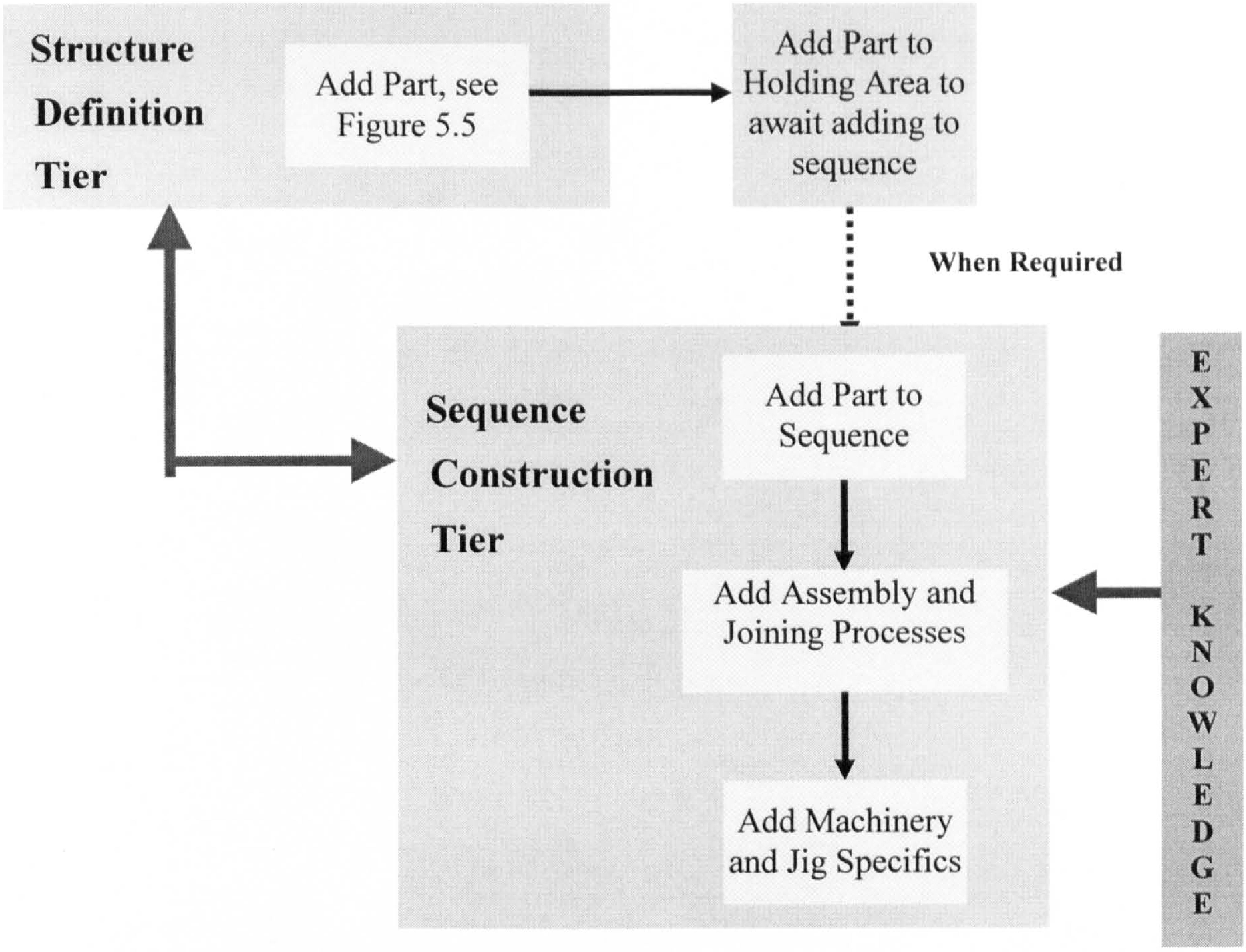


Figure 6.3: ***Process for Constructing the Assembly Sequence***

When it is believed that the design and assembly structure are sufficiently developed to allow the consideration of the sequence, the *Sequence Construction* Tier functions can be invoked to plan the components in detail. The first decision to be made when starting to build a sequence is which component to use as the base for the plan. It is imperative that this part is chosen carefully because the quality of the whole sequence usually depends upon a suitable selection. Once an appropriate base component has been decided, the sequence can be built by interactively adding components and subassemblies from the holding area. It is recognised that the user may not have the necessary assembly knowledge to make the right decision at the right time. Thus, an integral "Expert Assembler" offers suggestions regarding the best options for both the base part and the next part. This is discussed in greater depth in Chapter 7. The addition of sequence attributes such as assembly processes and necessary jigs will be covered in later sections of this chapter

To ensure that the inherent creativity of the design process is not impeded, the assembly sequence does not have to be constructed chronologically. It is possible to add parts to the sequence in any order. The user can also consider the whole sequence or just a subset of the sequence, dealing with a single subassembly. Additionally, a number of sequences for a given product structure can be constructed to explore the numerous assembling possibilities. The Validation and Evaluation Modules help the designer to choose the best sequence for any given situation. These will be outlined in more detail in Chapters 8 and 9 respectively.

6.2 Visual Representation Of Sequence

Any assembly sequence representation involves the embodiment of much data. It is extremely important that a suitable representation is defined to allow easy interpretation of the information. There are two forms of sequence representation. The sequence data has to be stored and some form of representation is required for this purpose. This has been discussed in Chapter 2 where the different sequence generation systems were compared and contrasted. Furthermore, Chapter 10 will detail the data structure used for the computer implementation of this methodology. However, of equal importance is the definition of an appropriate visual representation that allows the user to readily develop the sequence and easily interpret the results.

There have been many visual representations for assembly sequences proposed which are graphical descriptions of the underlying data structure. Diamond graphs[13], shown in Figure 6.4, represent the state of the assembly by a rectangle filled with smaller rectangles, which indicates the individual liaisons. A white cell indicates the liaison has not happened and a black cell shows a complete liaison. The lines connecting the boxes represent the state transitions.

The graph shows all possible assembly sequences by the number of different paths possible through the state transitions. This representation, whilst offering completeness, can quickly become difficult to interpret. It would become even more unwieldy if other data was shown in the sequence, such as assembly operations and joining processes. However, the proposed *Sequence Construction* Tier only considers a single sequence at any one time. This means that the Diamond Graph might remain comprehensible when handling this limited amount of data. Operating at the liaison level is not an intuitive way to interpret real assembly tasks and so has been rejected as the visual sequence representation.

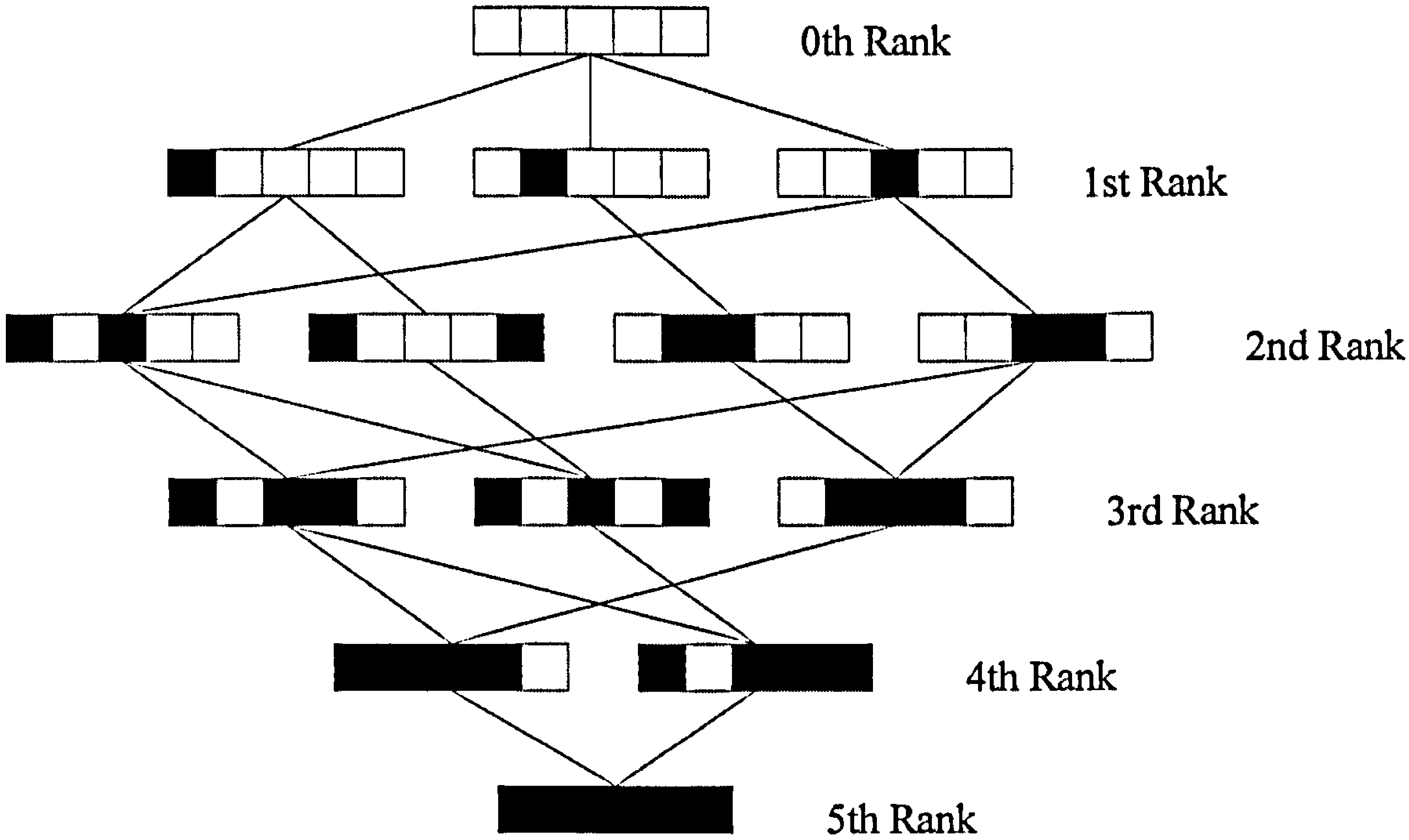


Figure 6.4: ***Diamond Graph Sequence Representation***

Another representation which has been often used is the AND/OR graph[15], see Figure 6.5. This uses a node to define a database that describes a single state of the product being assembled.

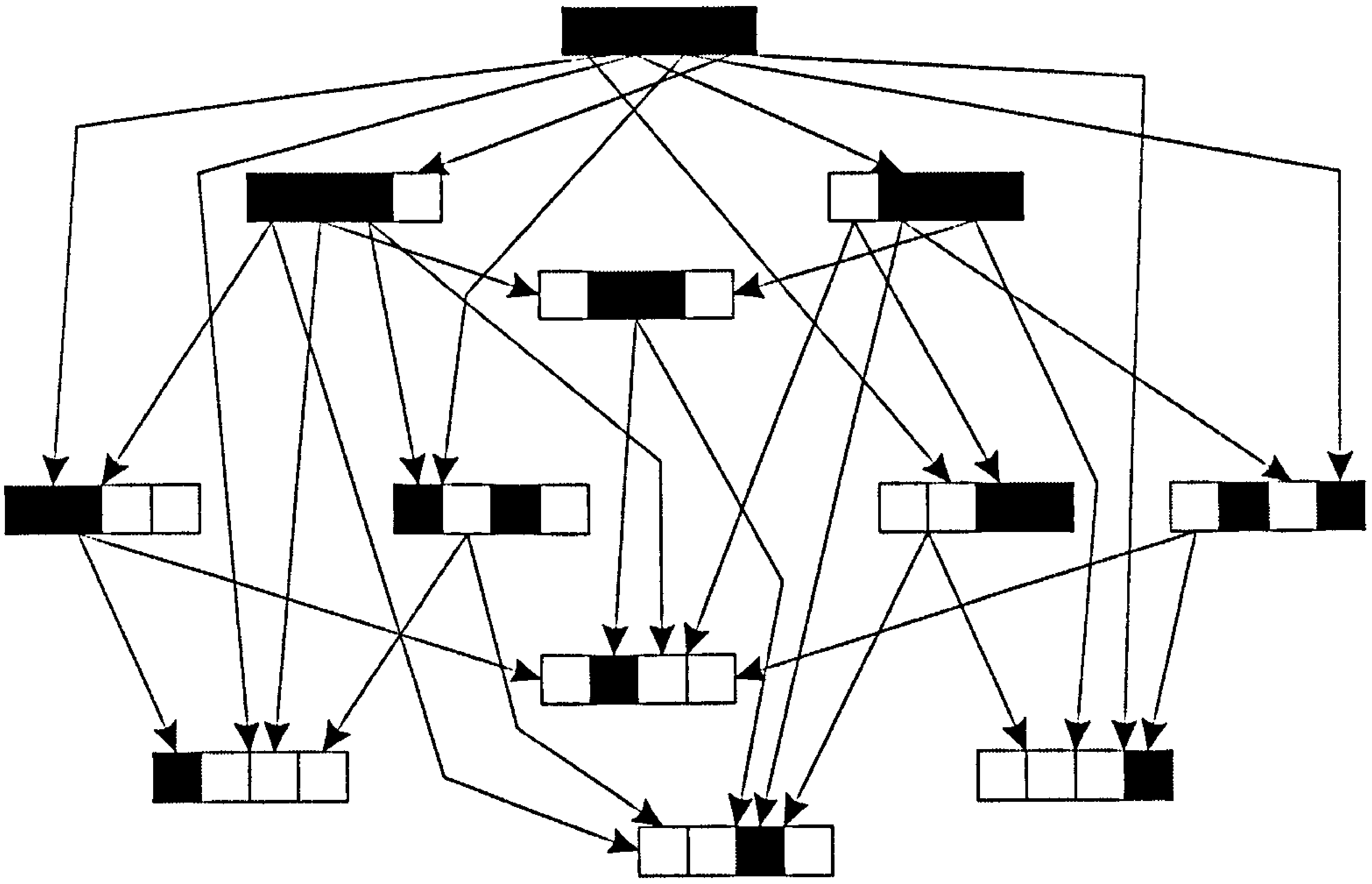


Figure 6.5: ***AND/OR Graph Representation of Assembly Sequences***

Each hyperarc leaving a particular node corresponds to one disassembly method for that partial assembly. The hyperarc then points to the resulting two partial assemblies remaining from that disassembly operation. Again, this representation offers a complete view of all possible assembly sequences for a particular product, but can prove difficult to interpret for anything but the simplest of assemblies. Limiting the number of sequences being considered would reduce the complexity of the diagram. However, the Two-Tier methodology deals with concurrent generation. It would often be impossible to define both nodes of a hyperarc if the assembly was only partial defined and thus this representation is discounted.

Another sequence generation system, XAP/1[18], bases the generated plan upon insertion operations and represents these as subassembly trees, see Figure 6.6. This seems to be a rather more tangible diagram for a designer to understand. Each node relates to a part or subassembly to be inserted. The horizontal links define the order of insertion and the other lines show children of the nodes, or parts constituting the subassembly. This clear representation can easily show one sequence and other operational data. However, it is only possible to define linear plans that restricts the user unnecessarily and makes the representation of reality difficult.

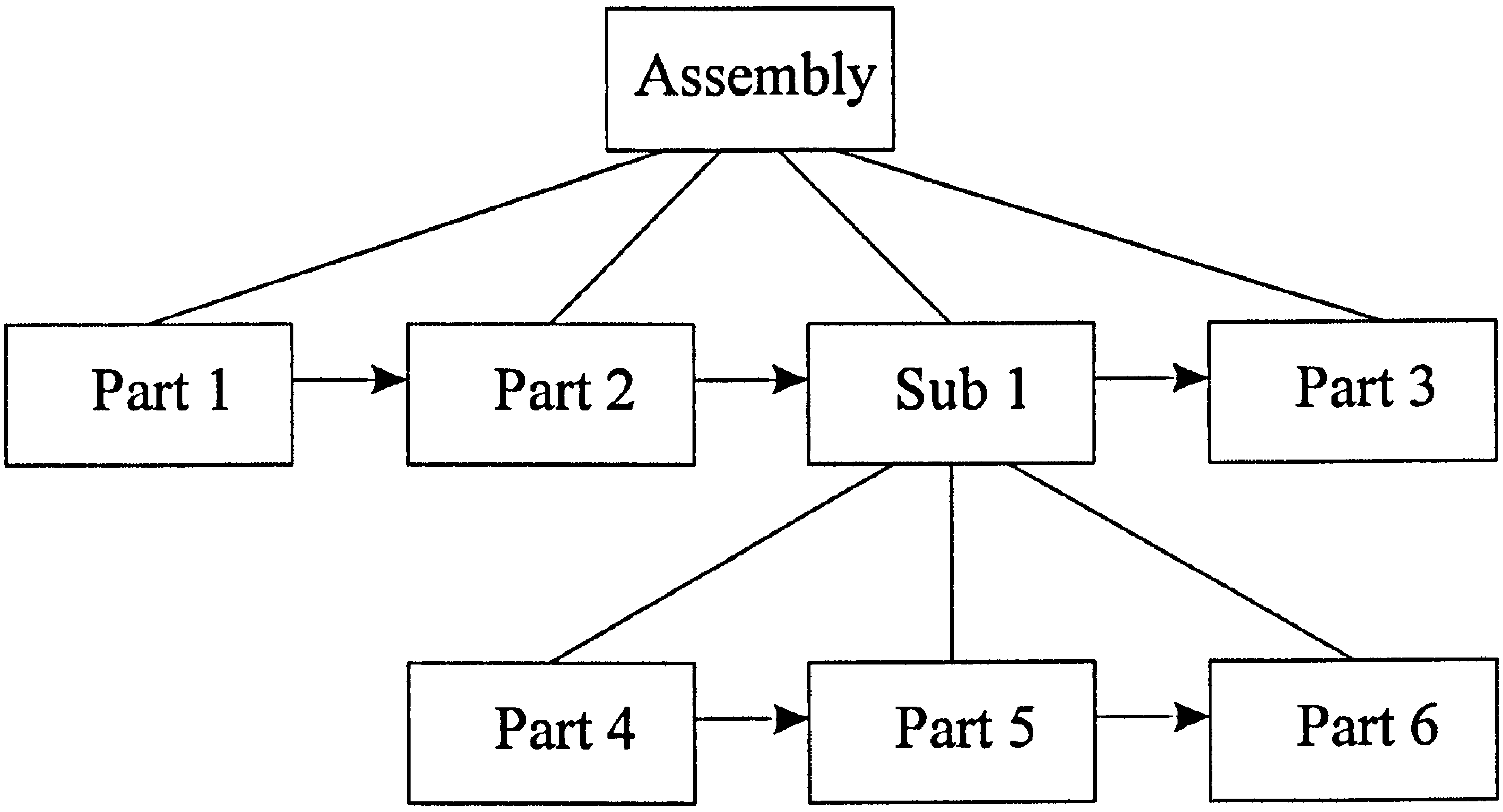
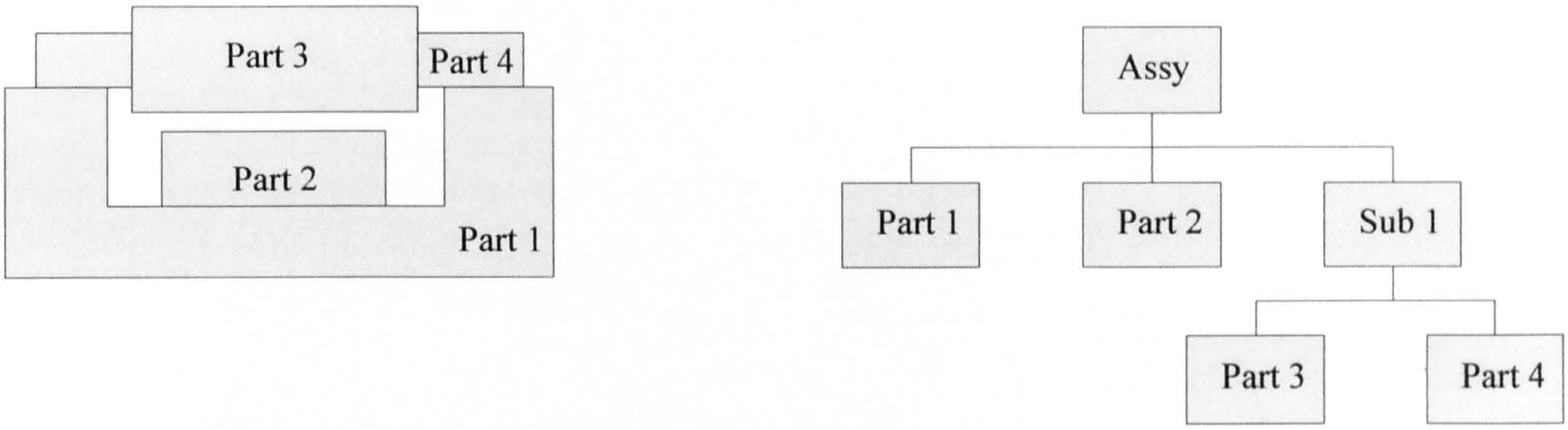


Figure 6.6: ***Using Subassembly Trees To Define An Assembly Sequence***

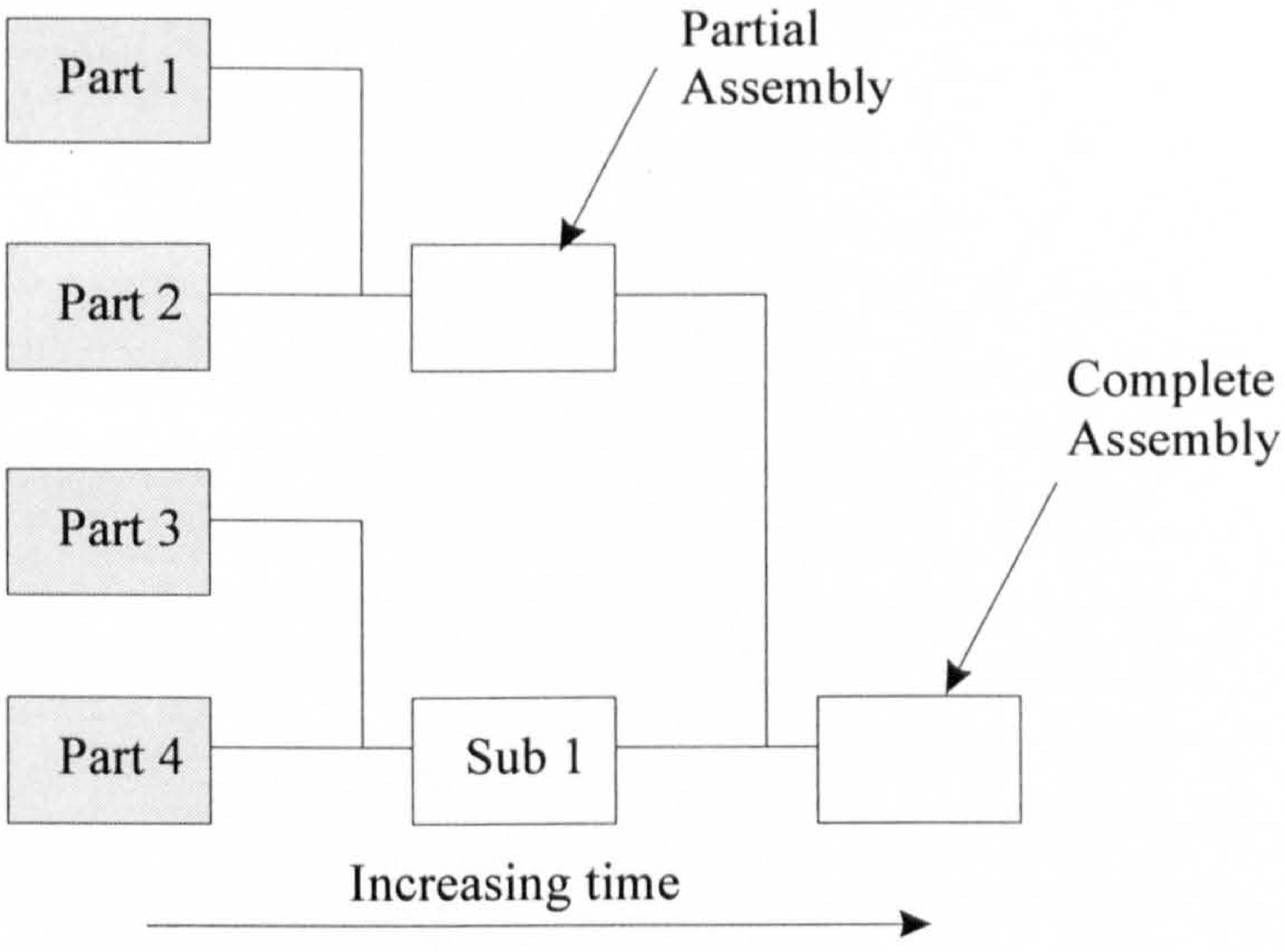
The representation scheme for the Two-Tier methodology was defined by building upon the idea of using insertion operations to define the sequence representation. In addition to the data included in the subassembly trees, other assembly operations and joining processes are to be represented. It must also be possible to include parallel operations. The interpretation of the plan should be as intuitive as possible to facilitate ease of understanding. The representation used in the *Sequence Construction* Tier is shown in Figure 6.7(c) relating to the assembly shown in Figure 6.7(a) and the assembly structure, Figure 6.7(b).

The shaded nodes of the graph in Figure 6.7(c) represent individual parts. These are linked to an unshaded node that defines the partial assembly, which has been created from the liaison of the two parts or part and partial/subassembly. Conventionally, the temporal data is represented by the order in which the components are shown from left to right. As illustrated in Figure 6.7(c), parallel plans can also be shown alongside the original sequence and linked into the main planning strand as appropriate. The partial assembly node will contain icons representing those additional assembly attributes which must be included, e.g. joining processes, reorientations. This, however, does not allow for the representation of assembly operations that occur outside of the actual liaison process. Workholding actions, gripping operations and pre-contact adhesive applications cannot be shown in this way as they happen before the actual insertion. It is also apparent the same action applied in a different context requires alternative attributes. For example, the reorientation of a part between presentation to the partial assembly and its insertion operation has different requirements and considerations to the reorientation of the whole assembly between liaisons.



(a) Actual Assembly

(b) Assembly Structure



(c) Sequence Representation

Figure 6.7: ***Defined Assembly Sequence Representation***

This issue was also identified during an investigation to determine a suitable representation of tooling operations and characteristics in an assembly planning system[28]. It was reported that tools could have a different set of attributes depending on where they are applied in a sequence. To represent this, the following classification was defined:

Pre Tools:	- applied before a liaison.
In Tools:	- applied during a liaison.
Post Tools:	- applied after the liaison is complete.

This can be translated into the Two-Tier methodology sequence representation, although in this representation, it is not the tool itself that is to be shown, but the operation associated with that tool. Thus, three different types of processes are defined and used in the *Sequence Construction* Tier:

Pre Processes:

Those tasks that must be completed prior to the insertion of a component. This includes actions such as the use of a workholder or the application of an adhesive.

Insertion Processes:

Those tasks that are completed as part of the insertion process. This includes actions such as 'screw together' or 'snap into place'.

Post Processes:

Those tasks that must be completed after the insertion operation. This includes actions such as welding, painting or reorienting the partial assembly.

Consequently, the sequence representation must allow for the inclusion of these three types of processes. Figure 6.8 modifies the original notation to include the attachment of attributes at the pre and post insertion level. It should be noted that, by definition, pre processes pertain to a particular part and post processes relate to the whole partial assembly.

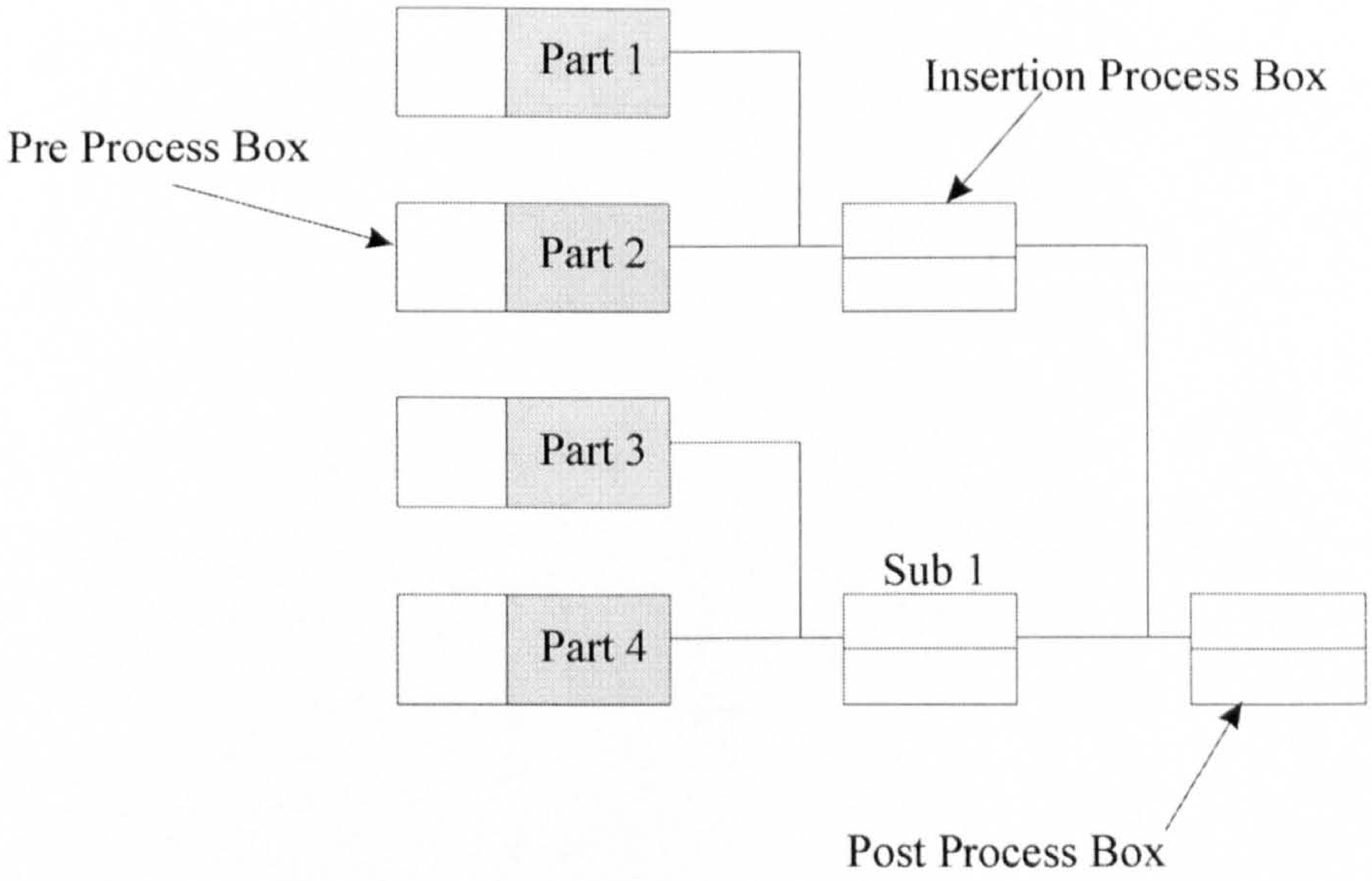
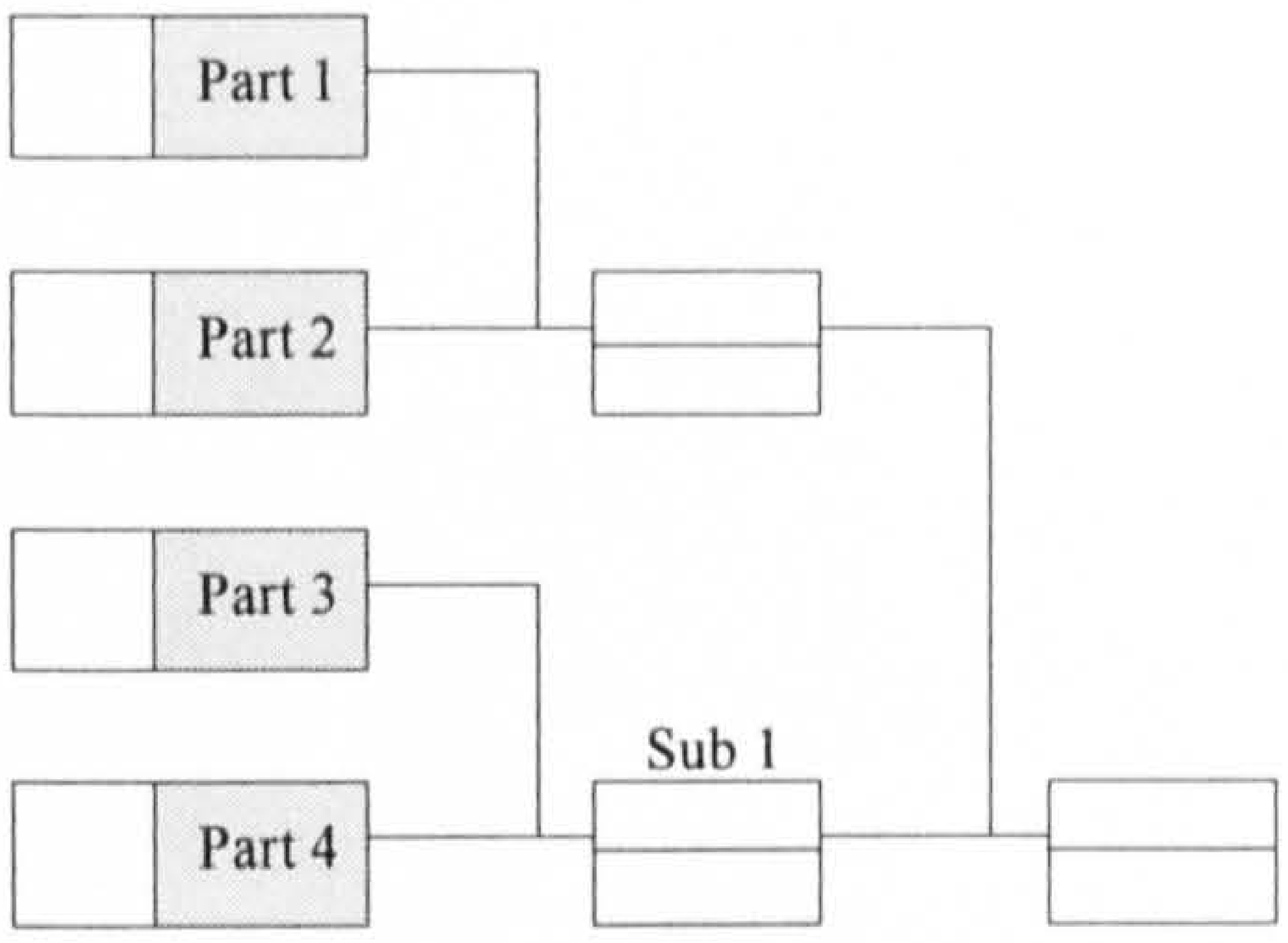


Figure 6.8: ***Sequence Representation Showing Pre, Insertion and Post Assembly Processes***

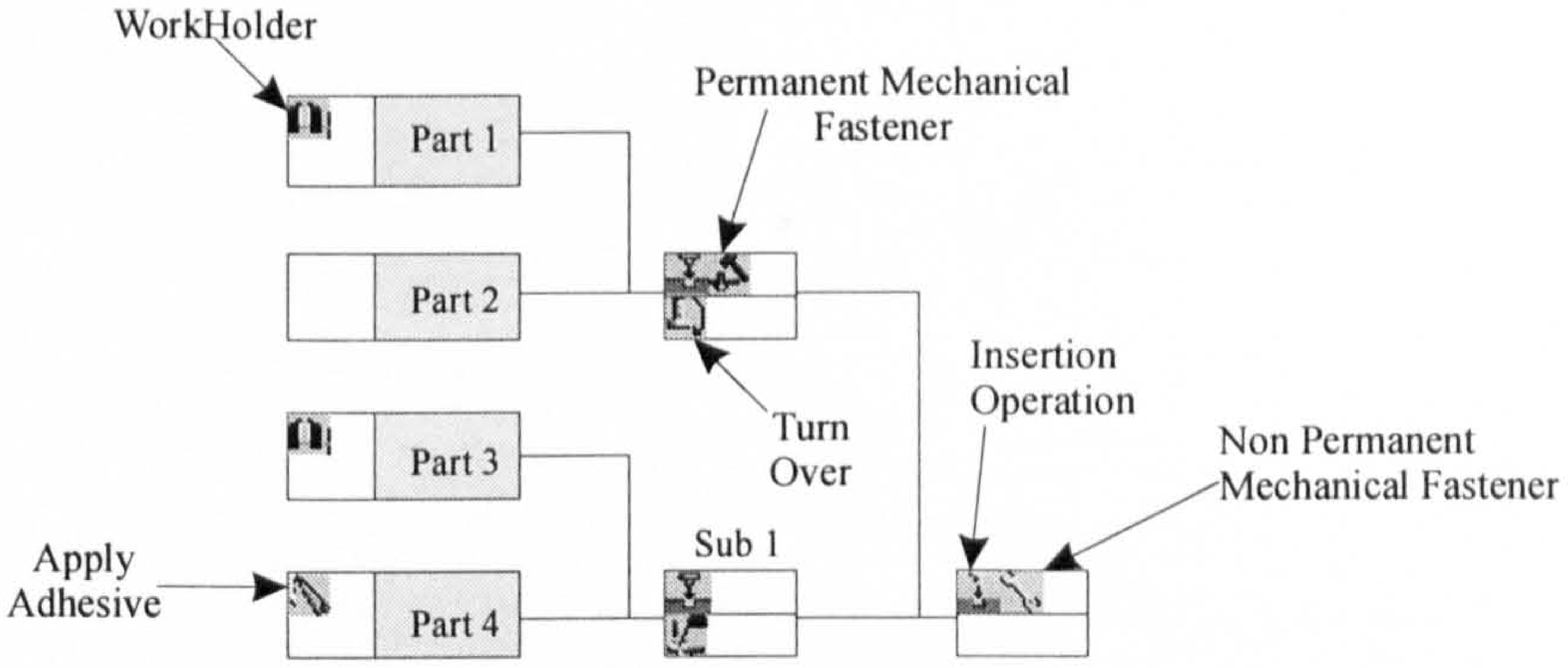
6.3 *Levels of Sequence Detail*

The sequence should be built as a part of the design development, so it is impractical to assume that the sequence be immediately defined to a high level of detail and accuracy. However, at some point it will be necessary to add more detail and further constrain the sequence to allow meaningful analyses. To facilitate this, it is possible to define the sequence representation at several levels of detail. Level 1, the highest level of sequence abstraction shown in Figure 6.9, only contains components and subassemblies with no assembly actions. It is possible to start building the sequence at this level as soon as there are parts in the assembly structure. Level 2 develops the plan by adding any known assembly operations and joining processes. When the product design has been defined to a high degree of detail, the factory planning specifics can be added, as shown in Level 3.

(a) Level 1 - Part Detail



(b) Level 2 - Process Level



(c) Level 3 - Planning Level

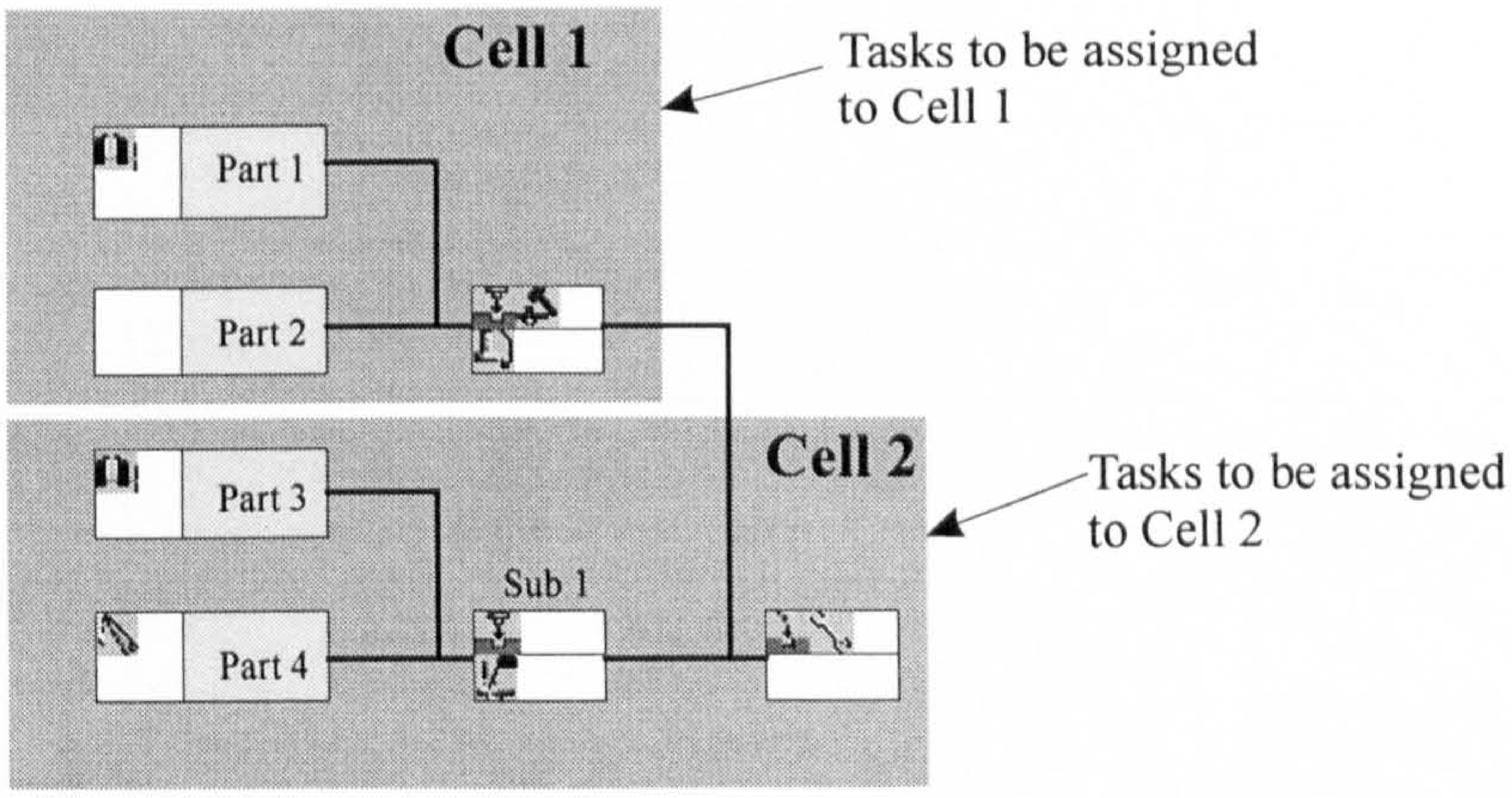


Figure 6.9: ***Available Levels Of Sequence Detail***

6.4 Liaison Attributes

Assemblies consist of two types of entity; components and liaisons. Components, and clusters of these called subassemblies, are defined in the *Structure Definition* Tier. The liaisons between the components are defined in the *Sequence Construction* Tier. Three different attributes are required to fully define a liaison:

Mating Joint Type	- The type of mating joint at the liaison
Assembly Action	- The assembly action required to complete the liaison
Joining Process	- The joining process required to stabilise the liaison

This section defines each of these required attributes and shows how these can be used to fully determine a feasible and practical assembly sequence within the *Sequence Construction* Tier.

6.4.1 Mating Joint Type Definition

Even during the early stages of design, some information may be known about the joint type and thus the *Mating Joint Type* of the liaison can be identified. However, not all the data may be known so it may not be possible to define it fully. For example, the designer may know that a particular liaison has a requirement for a permanent joint, but as yet, no other details are known. Thus, it should be possible to add the attribute "Permanent" *Mating Joint Type* attribute with a view to adding a more detailed description later in the design process. The availability of a hierarchy that defines the many different joint types in decreasing levels of abstraction would assist with this early definition task. As more details become apparent, the joint can be further classified corresponding to the joint types defined in this hierarchy. This early definition of the *Mating Joint Type* can also facilitate some validation of the developing sequence to be completed, as knowledge about other assembly attributes is embedded in the joint type. This will be discussed in detail in Chapter 8.

The use of the *Mating Joint Type* as a means to embed assembly knowledge and thus enable the inference of other assembly related data has been proposed previously[75,76]. A hierarchy of mating joints has been developed for use in a sequence generation system[75] and is shown in Figure 6.10. It can be seen that this is a complicated and comprehensive hierarchy including many joint types. It is divided into Physical and Virtual joint types and these are further defined by a breakdown of the different types. Despite this extensive level of detail, in some instances it is still inadequate. To illustrate this point, consider a welded joint. The five types of joint that are commonly welded together are butt, lap, corner, edge and tee, as shown in Figure 6.11. The mating joint hierarchy in Figure 6.10 does not breakdown the joints into this level of detail. A welded joint can only be described as a Clearance or Transitional Contact. To enable the inference of a specific *Joining Process* from the *Mating Joint Type* and vice versa, modifications to this hierarchy are necessary to enable adequate mapping between the two pieces of data.

The highest level of joint data that can be determined is its permanence or non-permanence. Early in the design process, it is often apparent whether a joint will need to be broken for access, maintenance or other such reason. Thus, this becomes the first level of the mating joint hierarchy. At a greater level of detail, joints can be of type fit, contact or moving, (NB by definition a permanent joint cannot be kinematic). This data may again be discernible long before specific geometry is defined. Finally, the greatest level of detail explores the different permutations of these fits, contacts and kinematic joints. Figure 6.12 shows the hierarchy implemented into the Two-Tier methodology. From this, a direct mapping to *Joining Processes* and indeed some *Assembly Actions* can be devised. For example, if a 'screw' fit is attached to the liaison then it can be inferred that some tool, (e.g. allen key, screwdriver, spanner) will be necessary. Of course, exceptions will always occur. A wingnut would have a 'screw' fit specified but a tool is not necessary. Thus, any inference from the data input would have to be checked by the user for correctness.

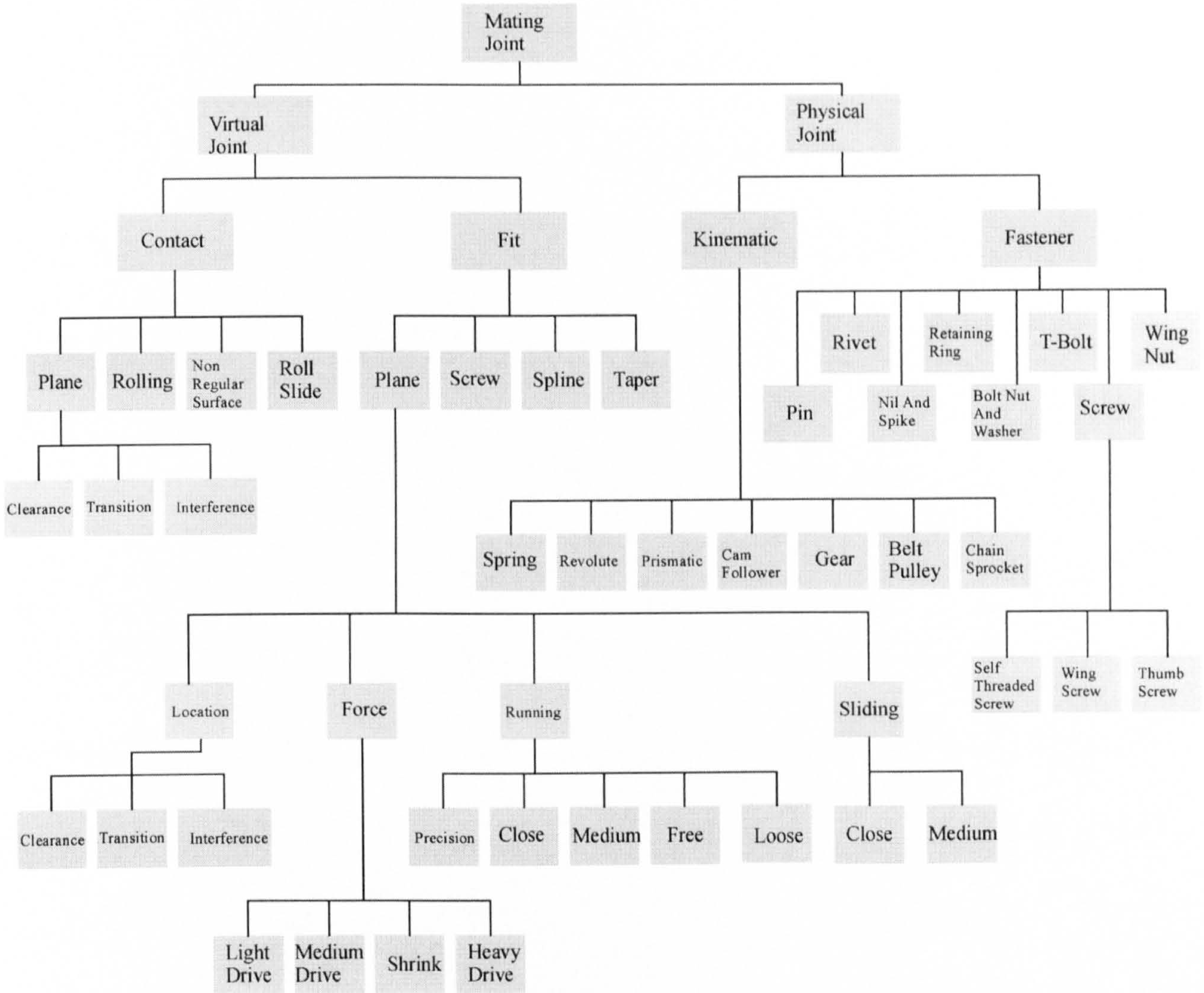


Figure 6.10: ***Mating Joint Hierarchy***

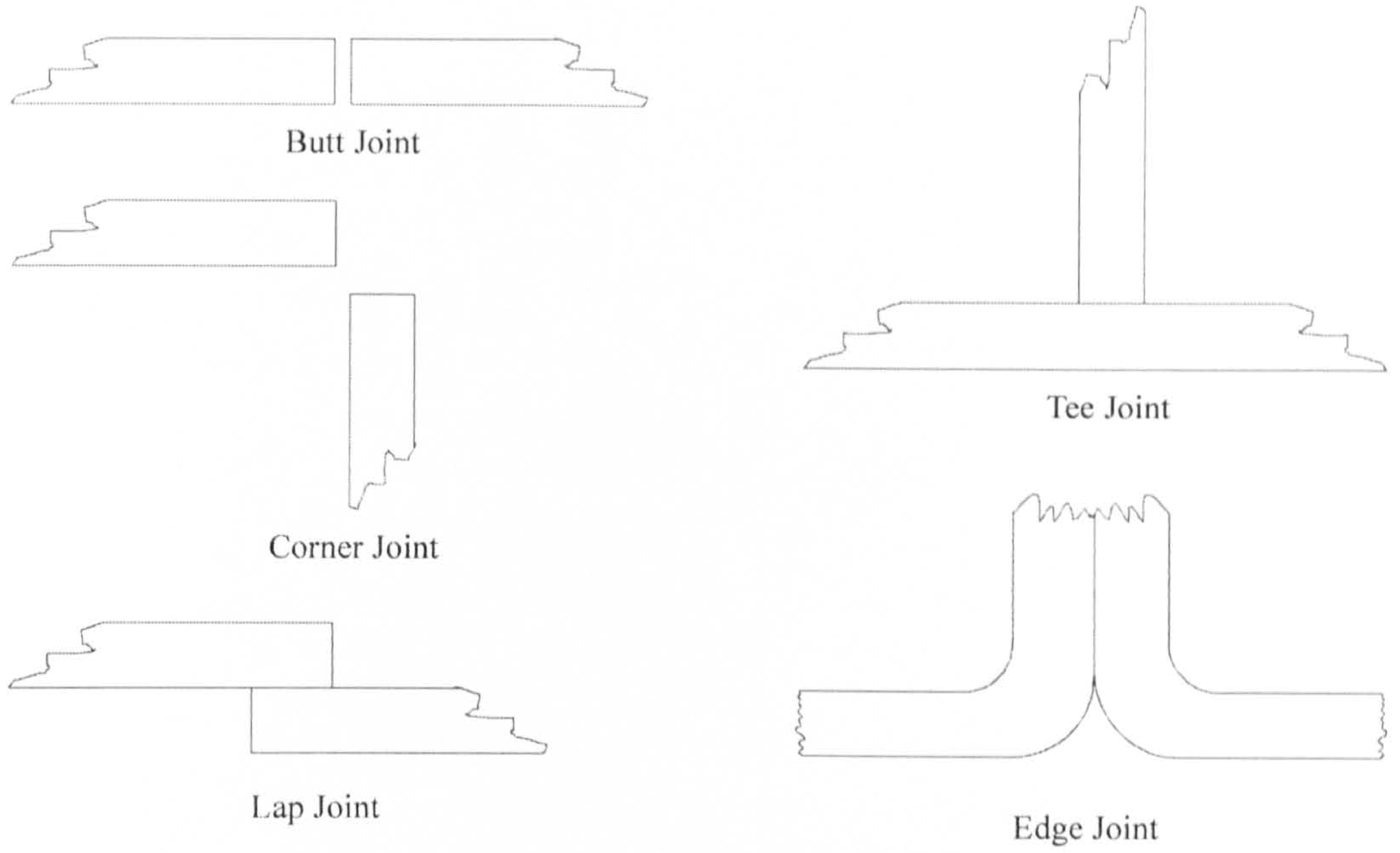


Figure 6.11: ***Types of Welded Joints*** [77]

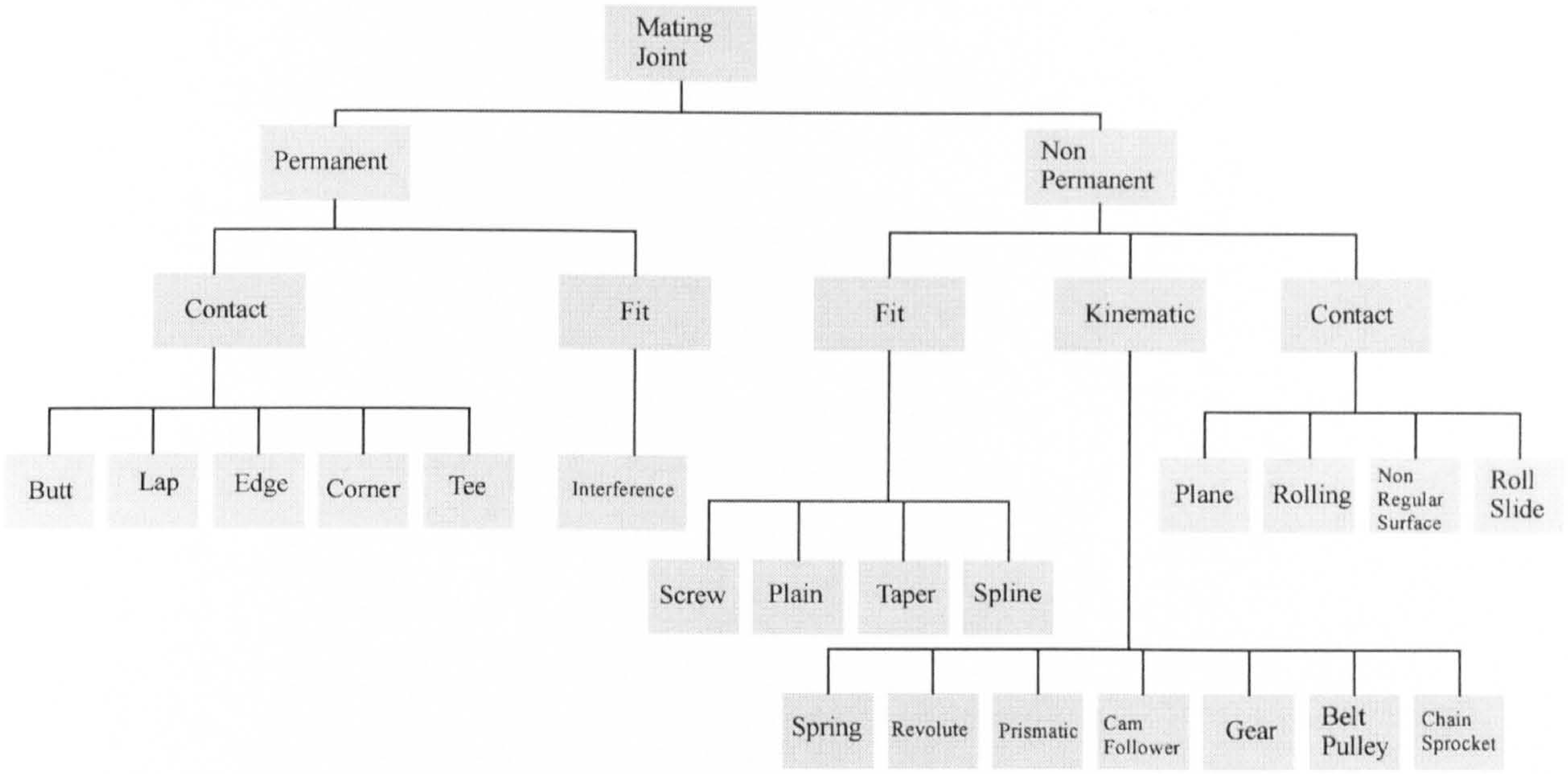


Figure 6.12: ***Hierarchy of Mating Joints Used in the Sequence Construction Tier***

6.4.2 Assembly Actions Definition

It has been stated that the tasks involved in a liaison can be sub-divided into *Assembly Actions* and *Joining Processes.* This section considers the *Assembly Actions*, which can be defined as those actions needed to join two parts/subassemblies. The *Assembly Actions* can be broken down into eight different types:

Insert	The act of bringing two parts / subassemblies together to complete a liaison.
Grip	Achieving a suitable hold upon a component before completing a liaison. This can be either using a manual grip or some form of component transfer mechanism such as a robot.
Workholder	The placement of a part into a workholder to increase/maintain stability.
Disassemble	The removing of part(s) e.g. for testing.
Reorientation	Turning over the partial assembly to change the direction of insertion.
Testing	Performing functional or quality tests on a part or subassembly.
Fill	Adding liquid or gaseous components.
Other	The use of any other operations not included in the above categories.

As stated in Section 6.2, *Assembly Actions* are added to the sequence as *Pre Processes, Insertion Processes* or *Post Processes.* When a component or subassembly is added, an insertion process is included by default, because an insertion operation is always needed at this point in the sequence. However, the user must specify other *Assembly Actions.*

It is apparent that some combinations of *Assembly Actions* and other attributes are unfeasible or impractical and thus checks are implemented to ensure that it is impossible to add these to a sequence. These rudimentary heuristics include:

- an **insert** process must be in an Insertion Box
- a **disassembly** process must be in an Insertion or Post Process Box
- a **grip** process must be in an Insertion Box unless the preceding part is a subassembly

6.4.3 Joining Processes Definition

Joining Processes are the tasks that constrain two components and have validation links to the *Mating Joint Type* and materials. There are many possible *Joining Processes* and they are divided into five categories:

- Non-permanent mechanical fastening
- Permanent mechanical fasteners
- Welded joints
- Adhesives
- Soldered and brazed joints

If this above classification is all that is known, then the *Joining Process* definition can be left at this level. However, further definition into specific types of process is possible if more detailed information is known. Table 6.1 shows the full list of *Joining Process* included in the *Sequence Construction* Tier. More data about these *Joining Processes* is contained in a knowledge base and is accessible to the user at any time. The data is used to validate the sequence, see Chapter 8, and ensures a suitable process has been chosen.

Main Joining Process	**Specific Joining Process**
Non Permanent Mechanical Fastening	Screw Snap Fit Press Fit
Permanent Mechanical Fasteners	Rivet Staple Nail Seam Crimp Press Fit Shrink Fit Expansion Fit
Welded Joints	TIG Weld MIG Weld MMA Weld Submerged Arc Weld Resistance Spot Weld Resistance Seam Weld Projection Weld Flash Weld Gas Weld
Adhesives	Epoxy Resin / Hardener Animal Glue Vegetable Glue Anaerobic Bond Cyanoacrylate Bond Hot Melt Glue Phenolic Bond Plastisol Bond Polyurethane Adhesive Rubber Adhesive Toughened Adhesive Pressure Sensitive Tape Epoxy - Single Part
Soldered and Brazed Joints	Gas Braze Dip Braze Furnace Braze Braze Weld Reflow Solder Wave Solder Hand Solder Induction Braze Resistance Braze

Table 6.1: *Table of Available Joining Processes*

6.5 Concluding Remarks

This chapter has outlined the requirements for the *Sequence Construction* Tier. The process for building the assembly plan and for visually representing the sequence have been discussed. It was found that three types of processes exist within an assembly plan, *Pre Processes, Insertion Processes* and *Post Process.* These were defined and the representations defined. It was also noted that because of the evolving nature of the design, it is necessary to represent the sequence in a multi-level view.

Any assembly sequence contains both the parts and the liaisons between those parts. Part attributes are commonly used and thus are not detailed. However, liaison attributes are not so often considered and thus a discussion of the requirements of these attributes was completed. For this methodology, it was stated that three attributes are needed for the full description of a liaison, in addition to the parts involved. These are *Mating Joint Type, Assembly Actions* and *Joining Process.* The chapter concludes with a detailed description of these attributes and their usage.

7. EXPERT ASSEMBLER

It is clear that a designer will need help to construct a good sequence and thus, the idea has been proposed to use the assistance of an assembly expert system. Since it is anticipated that the Two-Tier methodology will be implemented into a computer-based application, it will be possible to develop on-line expert help. This chapter discusses the development of such an integrated "Expert Assembler", which assists the user throughout the process of concurrent sequence generation and design.

Advice on many different topics could help the designer to build a sequence that is both feasible and practical. It is believed that it is imperative to choose the best base component for the assembly plan. It is also important that, once a good base component is chosen, each subsequent component is suitable for the current circumstances. To help with these decisions, it was decided to implement a number of mini-advisors within the overall framework of the "Expert Assembler". Currently two of these mini-advisors have been developed to provide assistance to the user. The *Starting Component Advisor* suggests candidates for the most suitable base component for the sequence and the *Next Component Advisor* proposes appropriate components to add into the sequence next. It is believed that the use of these two advisors will provide the user with the majority of the information needed to construct a feasible and practical sequence. However, other areas of assistance could also provide sensible advice to the designer. A *Joining Process Selector* could suggest the suitable processes to secure the components; a *Jig Designer* may be able to determine whether a jig can be used and, perhaps even, design one for the user. These ideas are outside the scope of this thesis but offer possibilities for future work.

The two developed advisors are discussed in detail in this chapter. An industrial knowledge engineering exercise, a review of the literature and an analysis of a set of case studies were completed as part of this research. These have identified some heuristic-based rules suitable for use in these expert advisors. The implementation algorithms and procedures are also are described in this chapter.

The author completed the knowledge engineering exercise, the literature survey and the case study analysis, which enabled the definition of the rules. The implementation of the advisors was a collaborative exercise, for which the assistance of Ms H. Mei is acknowledged.

7.1 Heuristic Based Assembly Sequence Generation

The use of knowledge-based systems for assembly planning is not a new idea. It is because the generation of feasible and practical sequences involve "rules of thumb" that it lends itself well to the application of expert knowledge. This knowledge has been applied at many different stages in the sequence generation process. Heuristics have been widely used to extract precedence information and identify feasible plans from the geometry and topology of the assembly[15,18,21]. They have also been used to find the most practical plans and optimise the assembly sequence[78,79]. In addition, many systems operate a constraint-based approach to sequence generation and selection. These constraints are generally expressed as rules to help define a suitable sequence from the many possible configurations. A comprehensive constraint survey has been presented[31,32], which outlines many of the different approaches used in assembly planners. The Two-Tier methodology operates an interactive and concurrent approach to sequence generation and thus, represents a significant departure from conventional approaches. Because of this, it is not possible to directly apply the rules found in the literature. However, the attributes of a good sequence are the same whatever the generation method. Thus, the knowledge can be extracted from the rules reported in the literature, integrated with rules developed from other sources and modified for implementation in the two advisors described later in this chapter.

7.2 Starting Component Advisor

It could be said that, when constructing an assembly sequence, the most important decision is which component should be the base part. It is from this choice that all other selections are made. An unsuitable component at the start of the sequence can mean the whole assembly plan becomes impractical. It is for this reason that the *Starting Component Advisor* has been developed which is able to provide relevant and timely suggestions to eliminate the possibility of an inappropriate choice. In any assembly, some parts are obviously unsuitable as base components and some components exhibit the correct characteristics. Hence, this advisor offers suggestions that determines both which part or parts *should* and which *should not* be used as the base component. However, the module only offers advice, it is not a dictator because of the many possible exceptions to any rule-based system.

The industrial knowledge elicitation surveys, completed as part of this work, have identified those rules which assembly planning experts use to decide which component best suited to be the base part. These are developed in the next section. Once the rules are set, algorithms can then be defined which allow the implementation of these rules in an appropriate assembly oriented CAD environment.

7.2.1 Development Of Starting Component Rules

The importance of the attributes that constitute a suitable component to start an assembly sequence have been considered in some assembly sequence research. The author of one assembly planning system believes that the user will choose the most appropriate part[22]. The sequence base part has been explicitly defined as the heaviest and/or largest component[80,37,67,38] in some systems and as the one with the most mating links to other components[37,38]. However, these two rules are still rather too general to allow the identification of the starting component. Specific rules to determine the starting part were defined from the analysis of thirty-four automotive electromechanical case studies. The second column in Table 7.1 shows the results of this exercise. Surprisingly, in only half of the cases was the starting component heavy and large in relation to the rest of the components. However, it was observed that most of the base components were not light or small. In addition, the base component was not fragile or flexible and did not have dynamic connections with adjoining parts. The first part was also unlikely to be a fastener.

The relevance and applicability of these rules was tested with industrial experts. Experienced assembly planning engineers from six diverse companies were given the rules identified from the case study analysis and asked to score them relative to how often they were used in their sequence generation process. The results of this exercise are shown in the third column of Table 7.1. It can be seen that generally the same rules were valid as in the case studies. The only significant difference was that, in industry, it was believed that the heaviest and largest part was always used as the base component, confirming the assumption from the literature.

Rule Used To Find Base Component	**Case Study % Times Used**	**Industrial Survey % Times Used**
Use a heavy and large part	46%	100%
Not a light part	83%	81%
Not a small part	83%	95%
Not a free moving/loose part	97%	100%
Not a flexible part	100%	100%
Not a fragile part	100%	100%
Not an expensive part	0%*	0%
Part positioned relative to a datum	8%	5%
Part with mating faces only on one side	14%	52%
Most mating faces	38%	62%
Not a fastener	94%	100%

* Insufficient Data to Determine

Table 7.1: ***The Determination of Rules for Base Part in Sequence***

It can be reasonably concluded that it is possible to define rules that are generically applicable for the determination of the starting component for any assembly sequence. No rules require specific geometrical attributes to enable the application as early as possible in the design process. Thus, the rules that can be used to identify the base component in any assembly sequence are defined as follows:

Rule 1. It should be large and heavy in relation to other parts.
Rule 2. It must not be light or small in relation to other parts.
Rule 3. It cannot be a free moving part.
Rule 4. It should not be flexible.
Rule 5. It should not be fragile.
Rule 6. It should not be a fastener.

These rules can now be translated into suitable algorithmic form and incorporated into an expert system shell. However, it is apparent that these rules will often not find a single candidate for the base component, especially as the underlying product model may be incomplete. The designer will be offered a shortlist of parts which narrows down the search space and indeed all of these may be suitable candidates for this crucial position in the sequence.

7.2.2 Implementation of Starting Component Rules

These rules have been implemented in the CLIPS expert system shell to produce the *Starting Component Advisor.* A flowchart of the implementation is shown in Figure 7.1. The search for the most suitable base component starts by adding all the defined parts into a list. Each part is checked against the rules before an analysis of the next part in the list commences. The rule order has been determined to allow easy elimination of as many components as possible without the need for expensive computation. Thus, the first rule eliminates all standard fasteners, (Rule 6). If this returns TRUE then the part is removed from the list of potential starting components and the next part is checked. Otherwise, calculations are invoked which determine whether the part is small or light in relation to the rest of the assembly, (Rule 2). A positive identification at this point means the part is eliminated. If this rule returns FALSE then the mass and volume of the part (as calculated for the previous rule) are analysed to see if the large and heavy rule (Rule 1) returns TRUE. Again, if this returns FALSE then this part is very unlikely to be the most suitable base component. However, if the rule returns TRUE then, providing the checks for kinematic linkages (Rule 3), flexibility (Rule 4) and fragility (Rule 5) return either UNKNOWN or FALSE, the part is recommended as the most suitable starting component.

If, after all the components have been checked using this rule system, no one part emerges as the most likely contender, the threshold value for Large and Heavy (Rule 1) is gradually decreased to try to find a suitable candidate. This may still not identify a base component if, for example, all parts have kinematic linkages or much part data is undefined. In these situations, three options are offered to the user at this point:

1. Modify a part
2. Add a new part into the assembly structure
3. Find the most suitable part from the current list

Options 1 and 2 are self-explanatory and result in the new or modified part being analysed according to the rule set. Option 3 requires further computational analysis, completed by considering rule precedence. Initially, rule 6 is removed and the assembly is checked against the remaining rules. If a base part candidate is not found then Rule 2 is eliminated and the parts are checked again. Finally, if this still has not identified a suitable candidate, rules 3,4 and 5 are eliminated before the reanalysis of the assembly. In most cases, this will result in a base component being found.

It is also apparent that due to this interactive approach, a component more suited to be the base part might be declared after the sequence generation has commenced. Hence, each component is analysed for base part suitability on addition to the product model and the user is alerted if a candidate is found. However, the replacement of the component is at the user's discretion.

7.3 Next Component Advisor

Most planning systems compute a data structure, (e.g. AND/OR Diagram, Liaison Graph) to identify the most suitable next part(s) according to geometric rules and component precedence relationships. When the sequence is generated concurrently with the design this computationally, expensive task is both impractical and probably impossible to complete. Lack of complete geometric part descriptions, unknown attributes and missing parts mean that such a data structure is not suitable for this application. Thus, another method of identifying candidates for the next part is needed. The *Next Component Advisor* is able to use any available data to reason which part *may* or *may not* be appended to the sequence. The suggestions are based upon component group data in the assembly structure, the assembly strategy (e.g. bottom up, inside out), and rules extracted from case studies and industrial experts.

7.3.1 Identification Of Next Component Rules

To define the rules that can determine the next component, thirty-four automotive electromechanical case studies were analysed, as before. The second column of Table 7.2 shows the results of this exercise. It can be seen that the analysis of these case studies proved inconclusive. It was found that parts are always inserted one by one and generally the parts with the same insertion direction (minimising turnovers) and same locations are inserted consecutively. However, this gives few definite rules for an expert system implementation. The same six companies were used to test the usage of the identified rules. The planning engineers were again asked to score the rules according to relevance and usage, the results are shown in column three of Table 7.2.

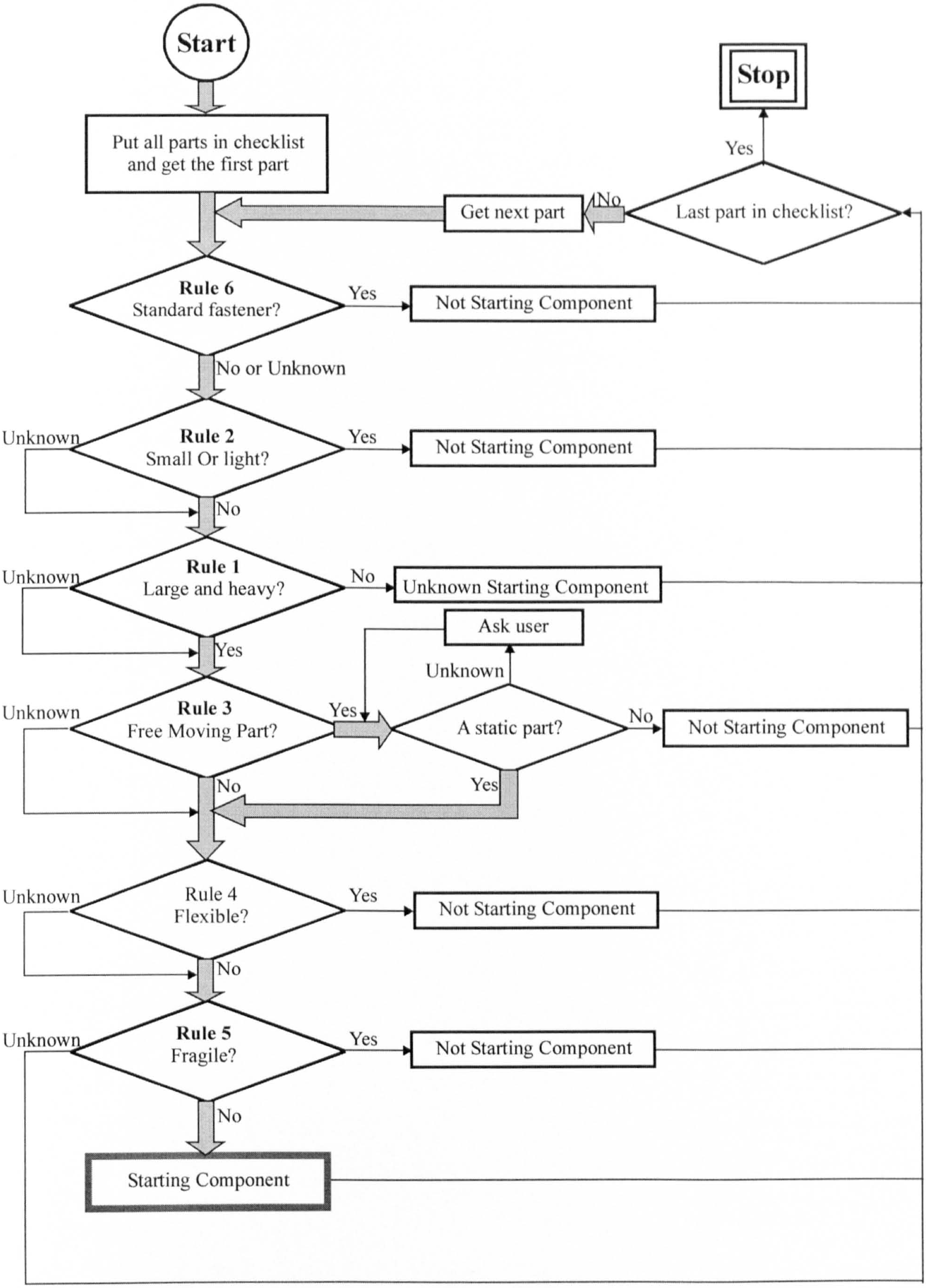


Figure 7.1: ***Starting Component Advisor Flow Chart***

Table 7.2 shows that the discussions and observations of industrial practice provided a more complete story. The rules that had been identified from the case studies were still valid, but the industrial investigations identified an implicit decision that was taken before building the sequence. This was found to be the definition of the overall assembly strategy to decide the main build direction. These strategies are defined as:

- Top Down
- Bottom Up
- Inside Out
- Outside In.

Next Component Rule	**Case Study Results**	**Industrial Survey**
Identical parts inserted consecutively	30%	86%
Secure unstable part immediately	65%	81%
Flexible parts late in sequence	0%	0%
Fragile parts late in sequence	9%	57%
Expensive parts late in sequence	0%	24%
Free moving / loose parts late in sequence	8%	19%
Access same tools consecutively	5%	62%
Complex subassemblies early in sequence	10%	62%
Work to the riveting side	0%	33%
Install parts individually	100%	100%
Light parts secured immediately	4%	95%
Small parts secured immediately	4%	95%
Work bottom up	50%	76%
Work inside out	41%	52%
Work outside in	0%	48%
Similar joining processes consecutively	4%	81%
Same insertion direction consecutively	95%	100%
Insert parts in same location consecutively	95%	81%
Separate dirty and clean jobs	8%	71%

Table 7.2: ***Determination Of For The Next Part In Sequence***

This decision is taken before the construction of the sequence commences. It assists with the build because a selection of appropriate liaisons in the sequence can be determined from the defined strategy. For example in a bottom up sequence, the base part can be found by searching the final assembly locations of the parts and finding the bottom component. The next component is then one which mates with the first but has a higher final location. Now this is a trivial example but serves to show the use of the assembly strategy. It was observed during the industrial visits that a company's product range tended to utilise similar assembly strategies. This was due to the different products having similarities in the geometry and topology and the same assembly systems. Because of this it probably would also be possible to identify rules that automatically determined the strategy without the need for user input. This was deemed outside the scope of the work.

The stability of the assembly was identified as an important consideration throughout the determination of the sequence. This was apparent in the widespread use of rules such as "secure unstable parts immediately" and "light and small parts secured immediately". Obviously, precedence of parts played an important role (e.g. "retained parts before retainer"). Ease of assembly was also considered as identical parts were inserted consecutively where possible. Dirty and clean assembly operations were separated and similar joining processes were performed consecutively wherever possible. A number of rules have now been determined for implementation into an expert system that will become the *Next Component Advisor*:

Rule 1. The next part must mate with part(s) in the sequence.
Rule 2. The next part should be secured immediately if unstable, small or light
Rule 3. Dirty and clean processes should be separated.
Rule 4. Cluster similar insertion paths
Rule 5. Cluster similar final locations.
Rule 6. Cluster similar parts.
Rule 7. Cluster similar joining processes.

It is apparent that these rules will often not result in a single component as the candidate for the next part, especially when the underlying product model may be incomplete. However, the designer will be given a shortlist of parts which narrows down the search space and indeed all of these may be suitable candidates for the next position in the sequence.

7.3.2 Implementation Of Next Component Rules

The *Next Component Advisor* commences the search for the most appropriate next component(s) using the attributes of the last part added to the sequence, as shown in Figure 7.2. A set of components in an assembly of *m* components is defined, Aset = $\{p_1, p_2, \ldots, p_m\}$ and a set of all suitable next parts, Pset, such that Pset $\subset$ Aset. Lset_i is a set of all parts on level *i*, ($i >= 0$) of the hierarchy where $\text{Lset}_i \subset$ Aset. Let x be the last part added to the assembly sequence such that $x \in \text{Aset}$ and $x \in \text{Lset}_i$. Nset is the set that contains all those parts which have not been added to the developing assembly sequence, where Nset $\subset$ Aset. All parts not in the assembly sequence, which are from the same level, *i* in the assembly hierarchy are added to Pset, thus:

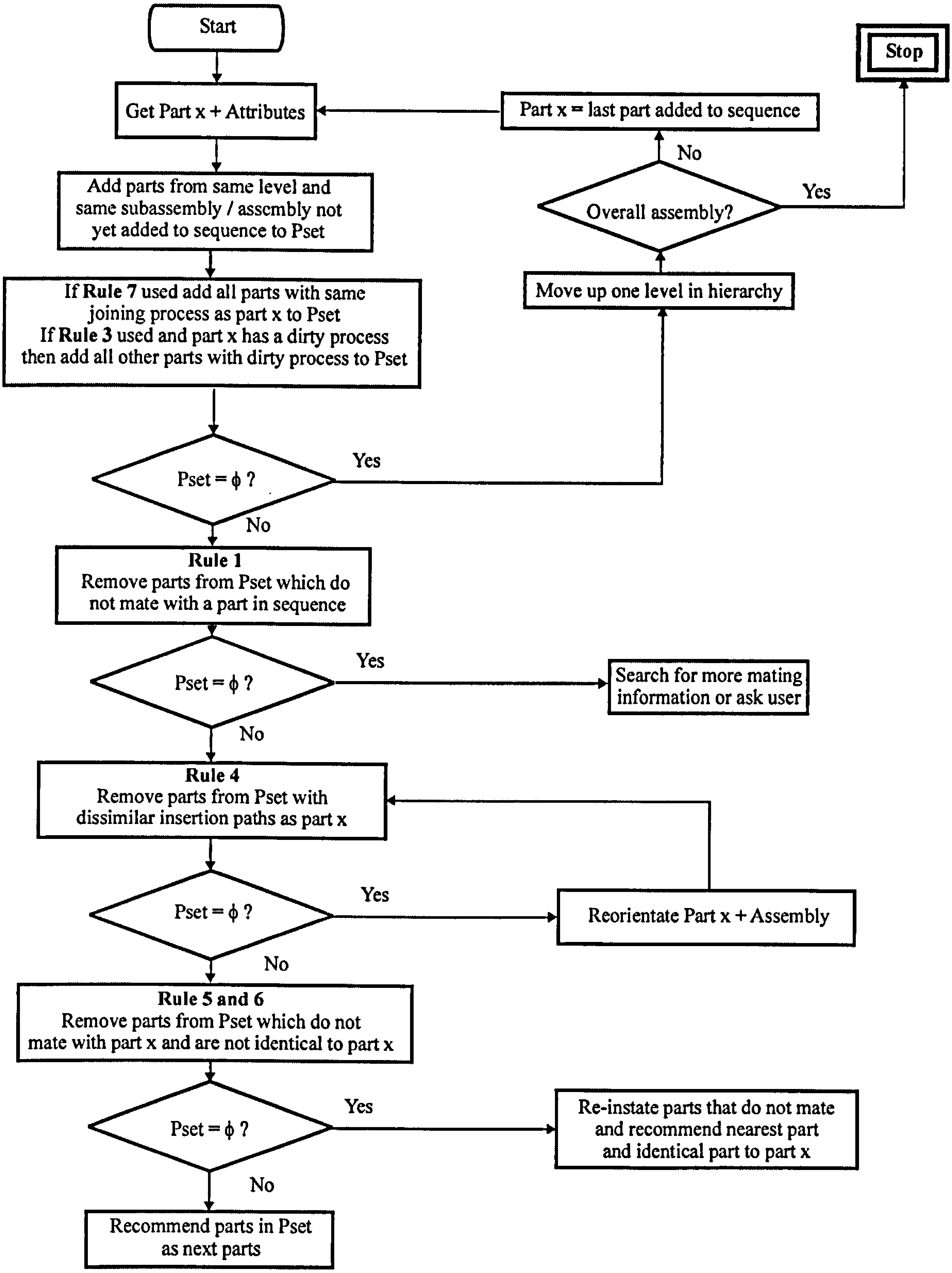


Figure 7.2: *The Next Component Advisor Flowchart*

$Pset = Lset_n \cap Nset;$

If $Pset = Lset_i \cap Nset = \phi$ and $i > 1$,

$Pset = Lset_{i-1} \cap Nset;$

Else If $Pset = \phi$, Stop.

Rules 3 and 7 are implemented as options that must be selected before the sequence construction commences:

Rule 7: **Cluster similar joining processes**

JPset is the set of all parts with the same joining process as x and not added to the sequence, $JPset \subset Nset$. This set of components is added to Pset:

$$Pset = Pset \cup JPset$$

Rule 3: **Dirty and clean processes should be separated.**

Let Dset be the set of parts that have dirty process attributes but are not yet added to the sequence, $Dset \subset Nset$. If x has a dirty process attribute then all other parts with a dirty process attribute are added to Pset:

If $x \in Dset$, $Pset = Pset \cup Dset$

Else $Pset = Pset \cap Dset'$

The use of mandatory rules are now used to select the next component(s).

Rule 6: **Cluster similar parts.**

Let Sset be the set of all parts identical to x and not added to the sequence, $Sset \subset Nset$. All these identical parts are added to Pset:

$$Pset = Pset \cup Sset$$

Rule 1: **The next part must mate with part(s) in the sequence.**

Let Mset be the set of all parts not in the sequence, which mate with any in the sequence, $Mset \subset Nset$. Any parts in Pset which do not mate with a part in the sequence are removed:

$$Pset = Pset \cap Mset$$

Rule 4: **Cluster similar insertion paths:**

If x has insertion vector, **A**, and Iset is the set of all parts not added to sequence which have insertion vector, **B**, where $\angle BA = \theta$, and $90^\circ >= \theta >= 0^\circ$. Remove all parts from Pset which require a reorientation for insertion.

$Iset \subset Nset.$

$Pset = Pset \cap Iset$

If $Pset = \phi$, $\theta = \theta + 180^\circ$, $Pset = Pset \cap Iset$

***Rule 5:* Cluster similar final locations:**

Let Fset be the set of all parts nearest to x in final assembly and not added to sequence, Fset ⊂ Nset. Parts with a final location a long distance from x are removed from Pset:

$$\text{Pset} = \text{Pset} \cap \text{Fset}$$

Pset now contains those parts that, according to the defined rules, are suitable to be added to the sequence as the next component. If any of these recommended parts are subassemblies, the NCA triggers the SCA to determine which is the best part for commencing the assembly of this subassembly.

Rule 2 has not been included as stability considerations are covered in the validation rules, Chapter 8, and duplication of this complex calculation is unnecessary.

7.4 Example Of The Advisors in Action

The *Starting Component Advisor* has been tested manually on 16 case studies. In over 80% of cases, the correct base component was included in the short list generated. This has shown that, although the defined rules are simplistic and generic, the use of the *Starting Component Advisor* can assist with the important decision of which component to use at the start of the sequence.

The use of the two advisors is illustrated by the development of an oil pump case study, as shown in Figure 7.3, and is reported in this section. The results obtained by the advisors were validated by comparison to the actual sequence as used in industry. The approach demonstrated here uses a manual implementation of the rules contained within the advisors and follows the rule flowcharts shown in Figures 7.1and 7.2. The example demonstrates the advisors working with a fully defined product for clarity purposes. It is noted that fewer definitive answers would be given by the advisors if the product model is only sparsely populated.

The rules embedded within the *Starting Component Advisor* were used to analyse the components and attributes of the oil pump and find the most suitable base components. These were defined as the Body[f] and the Cover. Nine other components, mainly fasteners, were found totally inappropriate as starting points. The remaining components had no reason to remove them from consideration but were not as suitable as Body and Cover.

It is assumed that the user has selected Body as the base component. The rules contained within the *Next Component Advisor* are now used to find the best candidate for the following part. This decision considers both the assembly structure of the oil pump, as defined in Figure 7.4 and the given attributes of Body.

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[f] Used as the base part for the industrial assembly plan

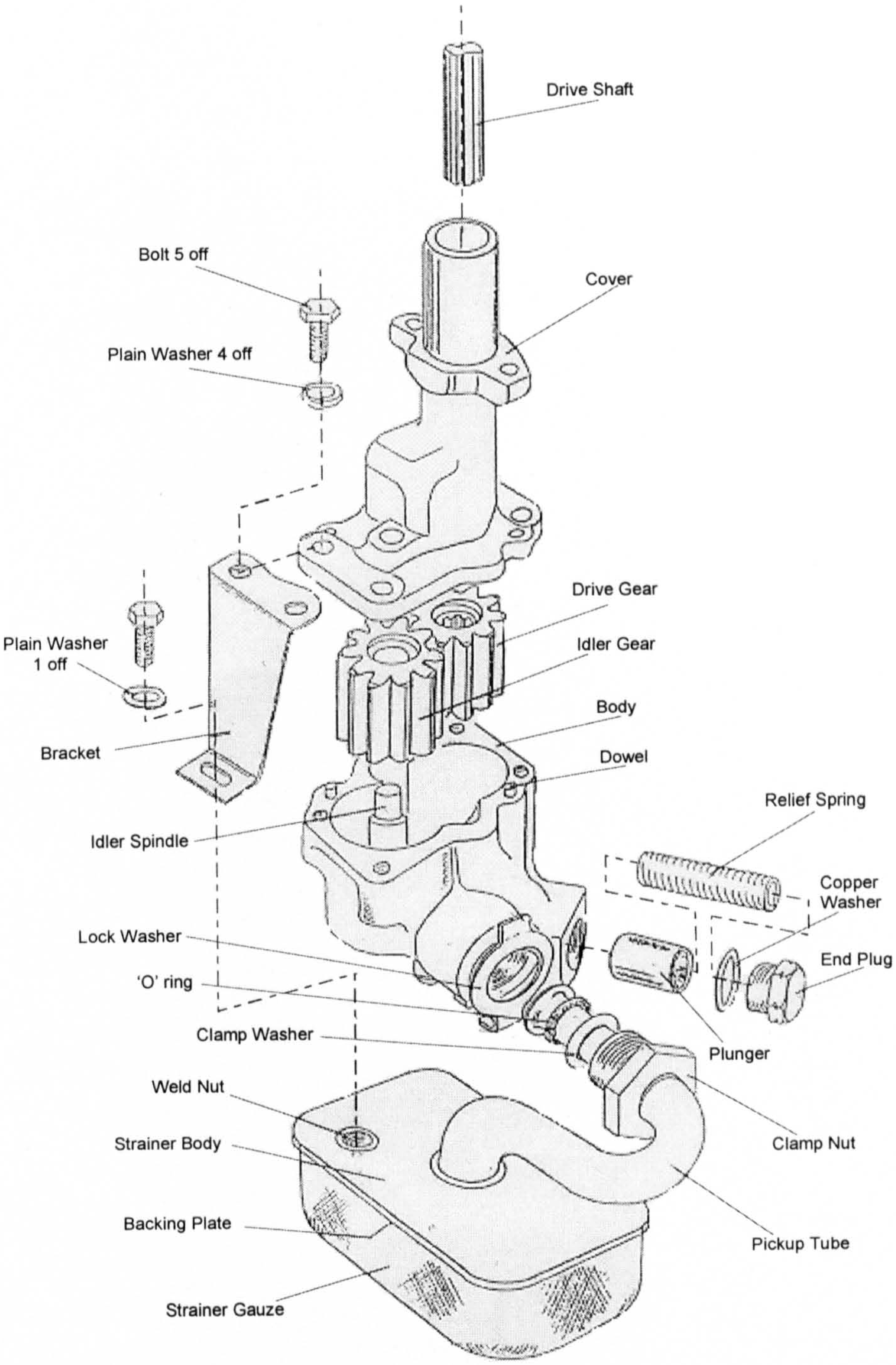
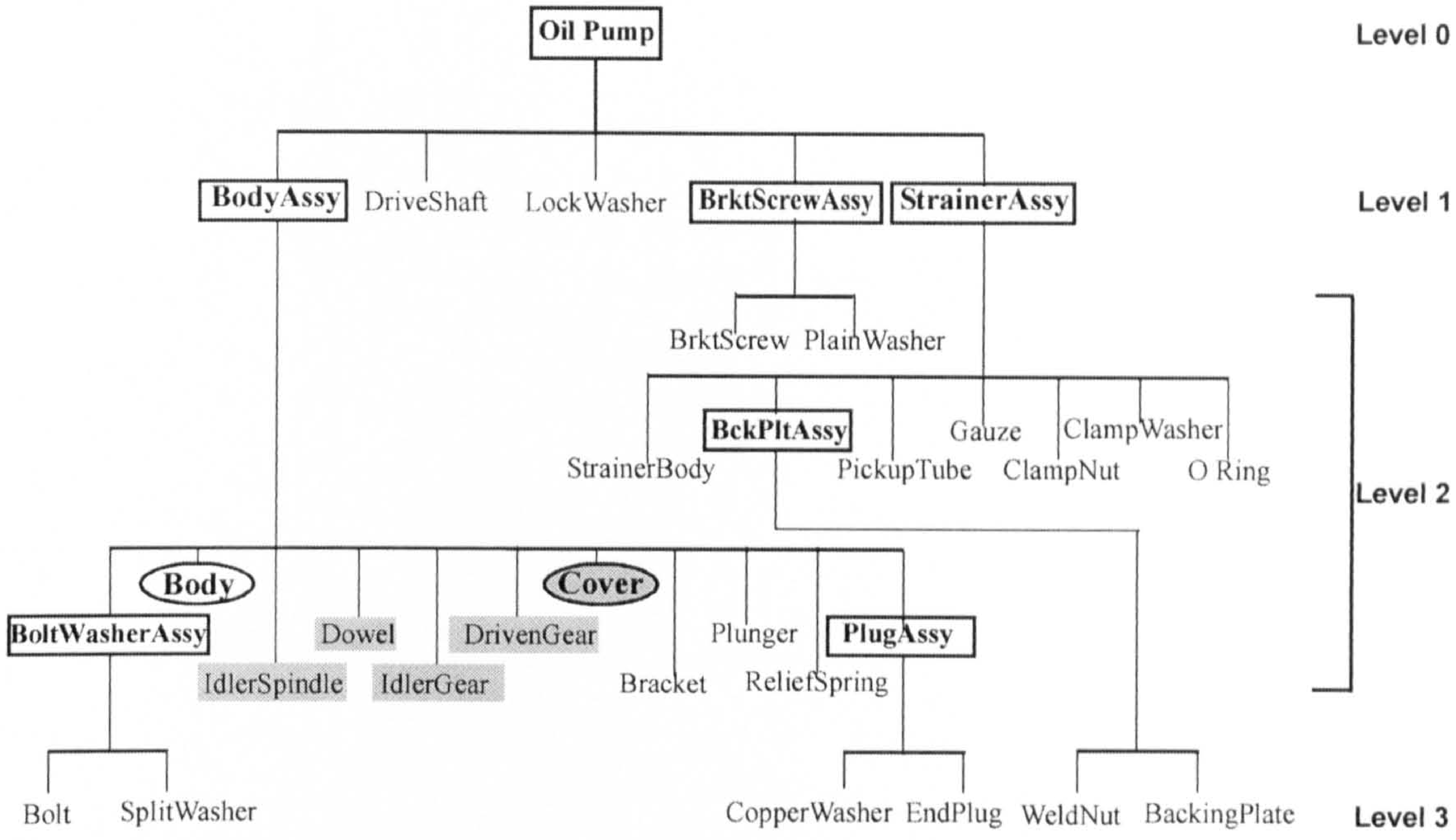


Figure 7.3: ***Oil Pump***



Body, Cover -- *Starting Component Advisor* recommended Starting Component.

▨ Shaded parts -- *Next Component Advisor* recommended next components after user choosing Body as Starting Component.

Figure 7.4: ***Assembly Structure Of The Oil Pump***

Five candidate components are found to be the most appropriate next parts. These are the Idler Spindle[g], the Dowel, the Idler Gear, the Driven Gear and the Cover, and are highlighted in Figure 7.4. The user selects the Idler Spindle for insertion into the sequence.

It is assumed, now, that the other four components stated above and the Bracket have been added to the sequence. The rules within the *Next Component Advisor* offer the suggestion that the following part should be Bolt. On first inspection, this may seem like an error. However, there are good reasons for this seemingly incorrect suggestion. The advisor initially identified the owning subassembly of Bolt, BoltWasherAssy, as the most suitable next part as it has the same insertion direction and mates with the last part selected. The subassembly must be built before it can be added to the partial assembly. Thus, the rules within the *Starting Component Advisor* are used to identify that the most appropriate base component for the subassembly happens to be Bolt. Bolt is defined as small and light and a standard fastener, as is the other part in BoltWasherAssy. The rule precedence, described in Section 7.3.2, is invoked to define the starting component. It finds that that the suggested Bolt is the larger and heavier of the two parts, is not free moving, not flexible and not fragile.

In this example, the rules contained within the *Next Component Advisor* and the *Starting Component Advisor* have offered suggestions regarding the most suitable components

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[g] Also chosen as the next part in the industrial assembly plan

for the start of the sequence and then the best next parts. This only represents one simple example and further testing is required to determine the general success rate of the *Starting Component Advisor* and *Next Component Advisor*. As previously stated, this example is based upon a complete product model. This is not representative of the situation when generating assembly sequences during the design process. In this case, the product model will only be partially defined. Thus, suggestions offered by the *Starting Component Advisor* and the *Next Component Advisor* may be incomplete and the sequence construction is more reliant upon the designer's judgements.

7.5 Concluding Remarks

It has been stated that appropriate assistance is necessary in a system that expects a designer to build feasible and practical assembly sequences. This is for two reasons, designers are rarely assembly experts and so the embedded knowledge will help with the decision making process. However, even if the user is an expert in the area of assembly, timely advice may reduce the human error element.

Conventional sequence generation techniques cannot be applied to this interactive process and thus, novel ideas must be considered. It has been proposed that an 'Expert Assembler' containing a selection of appropriate mini-advisors could best provide the assistance that the designer requires. Although several of these advisors will be necessary, two have currently been developed to help with the construction of good assembly sequences. The *Starting Component Advisor* offers suggestions about the most suitable component to start the sequence. The *Next Component Advisor* gives the user a list of possible components that could be added to the sequence next. From this list, the best parts are identified. These advisors offer the suggestions based upon generic rules that have been proven to help to generate a good assembly sequence.

8. VALIDATION OF ASSEMBLY SEQUENCE AND STRUCTURE

The Two-Tier methodology must be able to validate the sequence during development to ensure that the result is both feasible and practical. The approach used for these validation checks is detailed in this chapter. A survey of the relevant literature determines the different sets of constraints that have been applied in the many sequence generation systems. An appropriate set of constraints for sequence validation within a concurrent environment is defined by analysing the results of this review. The final section of the chapter outlines the process for using the validation module within the Two-Tier methodology for the concurrent generation of the design and assembly sequence.

It is proposed that a constraint-based approach will be used to validate the suitability of the sequence and will operate at the liaison level. Thus, relevant and suitable criteria are necessary to verify the sequence as each part is added. These criteria or alternatively, constraints can be defined as requirements, suggestions or preferences for the planner[31] and can be sub-divided into hard and soft constraints. Hard constraints are used to check the geometric feasibility of the assembly. Soft constraints suggest 'best practice' options and determine the practicality of the resultant sequence. A feasible assembly sequence must not violate any hard constraints, but the user must judge the importance of any soft constraint conflicts to define a practical plan. The constraints defined in the Two-Tier methodology are similar to many reported in the literature, but it will be seen that the application is different.

8.1 Validation Criteria Review

As demonstrated in Chapter 2, most approaches to computer-based assembly sequence planning commence with the generation of all possible sequences. This process usually considers the geometric and precedence constraints acquired from either user input or by automatic inference from a geometric model. This method usually results in a large number of potential plans. Many of these are ultimately found impractical because no consideration has been given to technological issues. Thus, it is necessary to prune this set of feasible plans to define a smaller number of practical plans to provide results that are meaningful and useful. Most systems apply a predefined set of constraints to eliminate the undesirable sequences and this process is known as validating the plan.

There are many different validation criteria as most sequence generations systems consider different attributes important. A comprehensive survey of the possible constraints that have recently been applied in sequence generation system has been undertaken by the ARCHIMEDES team[31,32]. This review discusses the relative merits of the different constraints and their implementation considerations. However, the validation process is approached differently within the Two-Tier methodology. Because the interactive construction process allows the user to add each assembly action and component individually, it is possible to validate the changes to the sequence at this time. Although this is an unconventional approach for the definition and application of constraints, the attributes that distinguish a good sequence must be the same. Hence, the literature can be examined to identify the criteria that can be used for the application of both hard and soft constraints in the concurrent sequence generation and design environment. The review will be divided into three areas that will cover the majority of the constraints in common usage:

- *Stability Validation Constraints* – Partially built products must be stable throughout the sequence of build otherwise jigs and fixtures are required for assembly. This set of constraints checks for stability of the assembly.
- *Accessibility Validation Constraints* – To complete an assembly there must be access for the operators hands, any tools needed and for the insertion of the required components. These constraints provide the checks which enable the accessibility needs to be assessed and quantified.
- *Compatibility Validation Constraints* – There must be validation of the liaison attributes to ensure that an appropriate assembly has been defined. This necessitates checks for such things as material and joining process suitability.

8.1.1 Stability Validation Constraints

Stability can be defined as the "resistance to unwanted change due to effects of gravity, motion etc."[32]. Stability is often implemented as a hard constraint that must be satisfied for a feasible sequence, whilst in other situations stability is treated as a soft constraint that should be complied with wherever possible. Whether the validation of stability is considered as mandatory or advisory, it is proposed that the constraint should be satisfied where possible throughout the assembly process. A stable sequence is very important. If stability is not maintained then appropriate jigs and fixtures are required, adding additional unnecessary cost and time into the sequence. Thus, a suitable stability constraint should identify and attempt to eliminate all the unstable states from an assembly sequence. It may be that a totally stable sequence is impossible or impractical and then the instabilities should be firstly minimised and any remaining must have the necessary jigs designed. It has been noted that the stability state is a function of both the current subassembly state and the agility of the assembly system used[81]. A robot with a large number of degrees of freedom may eliminate some reorientations and thus some unstable states.

Many sequence generation systems consider the identification and elimination of instability as a fundamental constraint because of the significant implications. One such assembly-planning environment is $^{\text{High}}$LAP[82,83] which considers the analysis of stability to be important and one of the four included constraints. The Assembly Stability constraint is defined as "Accidental motions of components during the assembly operation caused by gravity, assembly motions, assembly forces are avoided". It is claimed that $^{\mathrm{High}}$LAP is the first sequence generation system which considers the stability of the partial assemblies as well as the final assembly. It includes an algorithm that takes into account static friction. $^{\mathrm{High}}$LAP defines an assembly as *potentially stable* if the net force and net torque on each part is computed to be zero.

The implementation of a stability constraint has proven to be particularly stringent in the GAPP[84] assembly sequence planning system because few feasible sequences remain after criteria has been applied. It is implemented as a hard constraint and can be turned on/off by the user depending upon requirements. The stability of a partial assembly is computed by considering the securing (or stabilising) relationships of the surrounding components and creating a Stability-Directed Subgraph. Once this has been constructed the stability state can be found simple heuristics.

Another assembly planning system has implemented stability as a hard constraint used to narrow down the total number of feasible sequences computed in the first instance78. This approach has considered two different stability states. The static stability calculation considers of gravitational forces and determines if any component will move due to the effects of gravity. The dynamic stability is found by analysing all other arbitrarily oriented forces and can identify any change in component location when reoriented. Currently only translational forces are included in the calculations, but it is planned to add rotational forces into the stability analysis. It is noted that the stability analysis of a component also involves the consideration of all the adjacent parts. Once the forces and adjacencies have been analysed, a set of rules can determine the stability status of any component.

Feasible subassemblies and their operations are identified before the application of the stability and security constraints in another sequence generator[85]. A subassembly is defined as stable if one of the following conditions is satisfied:

- The subassembly has fastening constraints.
- The components have tight or overfit mating.
- The centre of gravity falls within the supporting surface.
- Each component in the subassembly is stable.

A subassembly is said to be secure if one of the following is true:

- The subassembly is fastened.
- The components have no fastener liaisons and zero degrees of freedom.
- The components have direct liaison with fasteners and only have degrees of freedom in the direction of the fastening constraints.

Once the individual subassemblies have been declared stable and secure, the assembly sequence is generated using the AND/OR graph approach.

The systems described so far in this section have considered the stability constraint to be simply a pass or fail state. No quantitative analysis of the instability has been used to determine the potential significance of the unstable state. The ASPEN sequence generation system has proposed a subassembly stability index[79] to quantify the level of stability of an assembly. This is determined by calculating the length of time needed to reposition components and consists of:

- The time required for repositioning the part.
- The extra operating time necessary to support the unstable parts using a hand or suitable jig.

The use of this metric allows the user to make decisions based upon the level of instability in any liaison. The quantification of stability has more similarities to sequence evaluation than to the removal of undesirable planning steps and this will be discussed in Chapter 9.

The literature review has shown that many sequence planning systems consider that assembly stability is extremely important. It is thus felt to be necessary to include checks for instabilities within the Validation module of the Two-Tier methodology. The implementation details will be discussed in section 8.2.1.

8.1.2 Accessibility Validation Constraints

During the actual process of assembly, it must be possible to access both the component and its final location in the assembly. The consideration and checking of this is considered in all assembly planning systems because it is a fundamental characteristic of a feasible sequence. Automatic plan generation invariably involves the calculation of the component precedence relationships and this is where the access issues are considered. Methods developed to find the component precedence in recent sequence generation systems were discussed in detail in section 2.1.

However, of equal importance to validating the component access is the check that the necessary insertion paths for any joining and handling tools have been provided. If any collisions with surrounding parts are identified then that particular assembly action should fail the validation check and a warning should alert the user. Thus for full validation of an assembly sequence, both the required joining and handling tools to complete a liaison should be defined and checked. Sequence generation systems rarely allow the definition of necessary assembly tools, although the selection of machine tools is currently available in many proprietary CAD/CAM packages. Thus, if tools cannot be defined then any collisions cannot be identified increasing the possibility that any sequence may still have production problems despite the applied constraints. This omission is probably because many sequence generation systems are aimed at minimising the user input and thus maximising the automation. Because of the large amounts of data potentially required, most systems do not operate at a sufficient level of detail to allow the consideration of tooling issues. The additional reasoning required to define and validate tools would make a computationally expensive procedure even lengthier. The Two-Tier methodology validates each liaison individually and thus it will be possible to consider and validate the assembly tool actions whenever they are specified.

However, some systems have identified that tools are important to build an assembly and it is necessary to be able to define and analyse their usage within the assembly planning environment. One such system, the GAPP planner[84], considered that analysis of the tool accessibility issues was necessary to find a feasible plan. This constraint has been implemented and eliminates unsuitable state transitions during the initial sequence generation phase.

A more detailed implementation of the attachment of tools and the geometric reasoning for defining the required access for tools has been considered in the ARCHIMEDES assembly planner[29]. The representation of tools in this system is divided into two areas:

1. Tool information independent of assembly
    - the relative time of application of the tool (before, during or after the mating of the liaison)
    - the minimum region of space necessary to apply the tool
    - the location of this space in relation to where the tool acts
2. Information about the tool application in a particular assembly

The necessary tools are either added automatically to the sequence when required, else, if several tools could complete the operation, the user is offered a shortlist from which to choose. The data attached to the tool allows the validation of the tool accessibility checks.

Most reported sequence generation systems do not consider the required tools and thus are unable to reason about accessibility requirements. However, it is felt necessary to include the issue in the validation module of the Two-Tier methodology, see Section 8.2.2. The tools needed to complete the assembly operations must be included to define a totally practical sequence. The component access considerations will require different treatment from most proposed sequence generation systems due to the concurrent approach of this methodology. As it is intended to build the sequence simultaneously with the design, little precedence data will be available. It will thus be necessary to also include constraints to check for component collisions.

8.1.3 Compatibility Validation Constraints

In addition to having no collisions and being stable at all times, the operations specified in an assembly sequence must be compatible. For example, it is of little use to specify a welding process for two components made of a material that is impossible to weld. Thus, constraints should be devised which identify these situations and alert the user to the incompatibility.

To the author's knowledge, the implementation of suitable task compatibility constraints has been given little consideration within the sequence generation literature. This is probably due to most sequence planners having no facility to enter any detailed planning information. The search techniques utilised by many systems mean there is a limit to the data analysed, and thus, any detail is omitted. Therefore, many of the validation checks that could identify a significant assemblability problem are impossible to complete because of a lack of data. The Two-Tier methodology will include compatibility constraints, see Section 8.2.3 to ensure that the sequence developed will be both possible and practical to assemble.

8.2 Constraint Implementation

It is apparent from the review of the literature that many constraints have been used to find suitable assembly sequences. Some of these are still applicable when the sequence is generated concurrently with the design and this section will define those that will be implemented into the Two-Tier methodology. These constraints will be used to validate each part, its liaisons and its attributes on definition into the assembly plan. They will operate on a pass/fail basis; the liaison either conforms to the specified criteria or the constraint is deemed to be violated and the user will be alerted. This discussion will not offer an exhaustive list of constraints necessary to produce a feasible and practical sequence. For example, no representation will be determined to validate the sequence in terms of the factory attributes such as layout, machinery availability and appropriate jigs. The gaps in the currently defined constraints will be addressed in a discussion on further work, see Chapter 12.

8.2.1 Stability Validation Constraints

Section 8.1.1 reviewed the available assembly sequence literature that considered the assembly stability as a means to prune the set of feasible assembly plans. The importance of an assembly that is stable at all times was also discussed. Instabilities in a partial assembly either require jigs, which involves extra cost and additional handling, or increase the difficulty of the assembly operation. Thus, it is believed imperative to check that the assembly remains stable or address the instabilities at an early stage. During the assembly, two separate circumstances must be validated for stability.

- *Current orientation*: When adding a part to the assembly it should remain in the required location given the force of gravity, any forces exerted by surrounding components and any assembly operation forces.
- *Reorientation*: When reorienting a partial assembly, all components must remain in their required location both during the period of reorientation and after the task is completed.

Any stability constraint imposed must consider both of the above states of the partial assembly and calculate the stability accordingly. The Two-Tier methodology provides analyses for these to ensure a feasible and practical assembly sequence. The constraints that are imposed on the liaisons in the generated sequence are:

STABLE: The stability of the partial assembly is checked for its current state and orientation.

STABLE_TURNOVER: The stability of the partial assembly is calculated when the user defines a reorientation operation or a part has been added whose specified insertion vector necessitates a reorientation operation.

8.2.2 Accessibility Validation Constraints

The literature survey of accessibility constraints in Section 8.1.2 has shown that component collisions are generally considered at the time of precedence relationship generation. The Two-Tier methodology proposes that the sequence construction should commence before a full definition of the assembly. This means that it is difficult to determine the precedence relationships. It is impractical to define any component blocking relationships if there is any uncertainty about the completion of the assembly. Consequently, the set of constraints for the Two-Tier methodology must include the validation of component precedence. This can be achieved by determining the access required for the component on insertion and by ensuring that the correct component has been added to a particular location of the partial assembly.

In most systems, it was found that only component collision issues were taken into account. In addition to the space needed to insert parts, handling requirements and supplementary operations, such as welding, must be considered for a practical sequence definition. However, most assembly planning systems fail to provide the facility to define these tools and this means that the accessibility requirements cannot be validated. This is believed to be an unsatisfactory situation because unless the application of tools is considered, the sequence cannot be fully checked for problems. The Two-Tier methodology provides the facility to define the most appropriate tools for the component handling/transfer and those tools needed to complete the necessary joining processes. In this manner the necessary space requirements can be determined and validated at each liaison.

COMP_COLLISION*:* Ensures there is the necessary access for the insertion of the component along its specified insertion vector. This validates the precedence of the components on addition to the sequence.

HANDLING_COLLISION*:* Ensures there is the necessary access to enable the insertion of the component and any necessary handling tools, (including operator anatomy), along the specified insertion vector.

JOINING_COLLISION*:* Ensures there is the necessary access to enable the specified joining tools to be applied to the partial assembly as defined in the joining tool knowledge base.

8.2.3 Compatibility Validation Constraints

Section 8.1.3 stated that compatibility constraints were necessary to ensure that an assembly can actually be built. This section will define the necessary constraints.

For a full definition, every liaison has a number of attached attributes. The *Mating Joint Type* and the *Joining Process* can be defined for the liaison, see Chapter 6, and in addition, the mating components have specified materials. Practical sequences should not have joint types that are incompatible with the detailed joining processes or the component materials. Neither should there be joining process inconsistencies or inappropriate material combinations at the liaison. The specified operations should also be compatible with certain of the factory attributes such as machinery layout, available machines and appropriate jigs and fixtures, however this is outside the scope of the thesis, see Chapter 12. Thus, the compatibility constraints currently included in the Two-Tier methodology are as follows:

MAT_MAT_COMP: Validates the electrolytic corrosion properties of any two materials in contact in the assembly.

JOINING_PROC_MAT_COMP: Checks that the specified materials can be joined using the defined *Joining Process*.

JOINING_PROC_JOINT_COMP: Ensures that the *Joining Process* can be applied to the specified *Mating Joint Type*.

8.2.4 Geometry Validation Constraints

As previously discussed the Two-Tier methodology diverts from the traditional approach to sequence generation. Generally, there is no need to check that the right component has been placed in the sequence as this data forms the basis of the sequence generation process. However, when the designer is building the sequence in parallel with the creation of the product this check becomes crucial. For a valid sequence, the part added to the plan must mate with a component previously inserted. In addition, this component just added to the sequence must physically fit into/onto the specified location. Incorrect tolerance specification or geometric errors could mean that the part does not actually locate into its specified place. This validation is different from just checking for collisions because this constraint also considers the many possible tolerance configurations and assembly topology to check for the fine movement conflict. Therefore, the Two-Tier methodology must include validation checks for both these errors to ensure a feasible and practical sequence:

REQ_FIT: Ensures that the component does not interfere with any adjacent components in its final location. This checks for inaccuracies in the design as well as incorrect component placing.

CORRECT_COMP: Ensures that adjacent faces have been correctly mated with nearby components.

8.3 Interactive Process For Sequence Validation

The application of constraints in many of the assembly planning systems described in the literature is sporadic and incomplete. All of the reported systems utilise some of the constraints but few, if any, seem to check for all the potential issues that must be resolved to fully define a feasible and practical sequence. As previously stated this situation is believed to be mainly due to the computational expense of the sequence generation algorithms. Detailed constraint consideration would prohibitively extend the time taken to define the assembly sequence. The Two-Tier methodology, however, eliminates much of this expensive computation time and offers the potential for the consideration of real assembly issues. At any validation step, only one part has been added and thus the calculations can just relate to this individual action and not the whole set of feasible sequences. This enables the detailed analysis of the constraints described in this chapter. As seen in Chapter 4, the hard and soft constraints are simultaneously applied to mimic the human planning practice.

8.3.1 Strategic and Tactical Constraints

It is believed that it is necessary to have the facility to individually enable and disable the constraints at both the whole assembly level or just for single liaisons. This is required for a number of reasons. The user may want to consider the validation issues at a particular point in the sequence construction and thus wants to remove all constraints until this time. The necessity to remove constraints can also be due to geometry specifications. Consider the example of a bolt with a screw thread, as shown in Figure 8.1. Both the **REQ_FIT** and the **COMP_COLLISION** constraints would be violated every time this bolt was added to the sequence. Specifying the usual linear insertion path would cause interference with the adjacent components and a collision would be detected with the external thread on insertion. Therefore, these constraints can be disabled at this liaison to avoid disguising real problems.

To be able to manage this situation and many others, the Two-Tier methodology allows constraints to be determined at the strategic and the tactical levels of detail, although the constraints themselves are the same. Strategic constraints apply to all the liaisons specified in any sequence. These must be known before the sequence construction. Tactical constraints apply at the individual liaison level and can be enabled or disabled whenever necessary. Initially the applicable strategic and the tactical constraints are equal but the user can control which constraint is applied and when. The strategic and tactical constraints can be changed at any time during or before the sequence construction, to reflect particular circumstances.

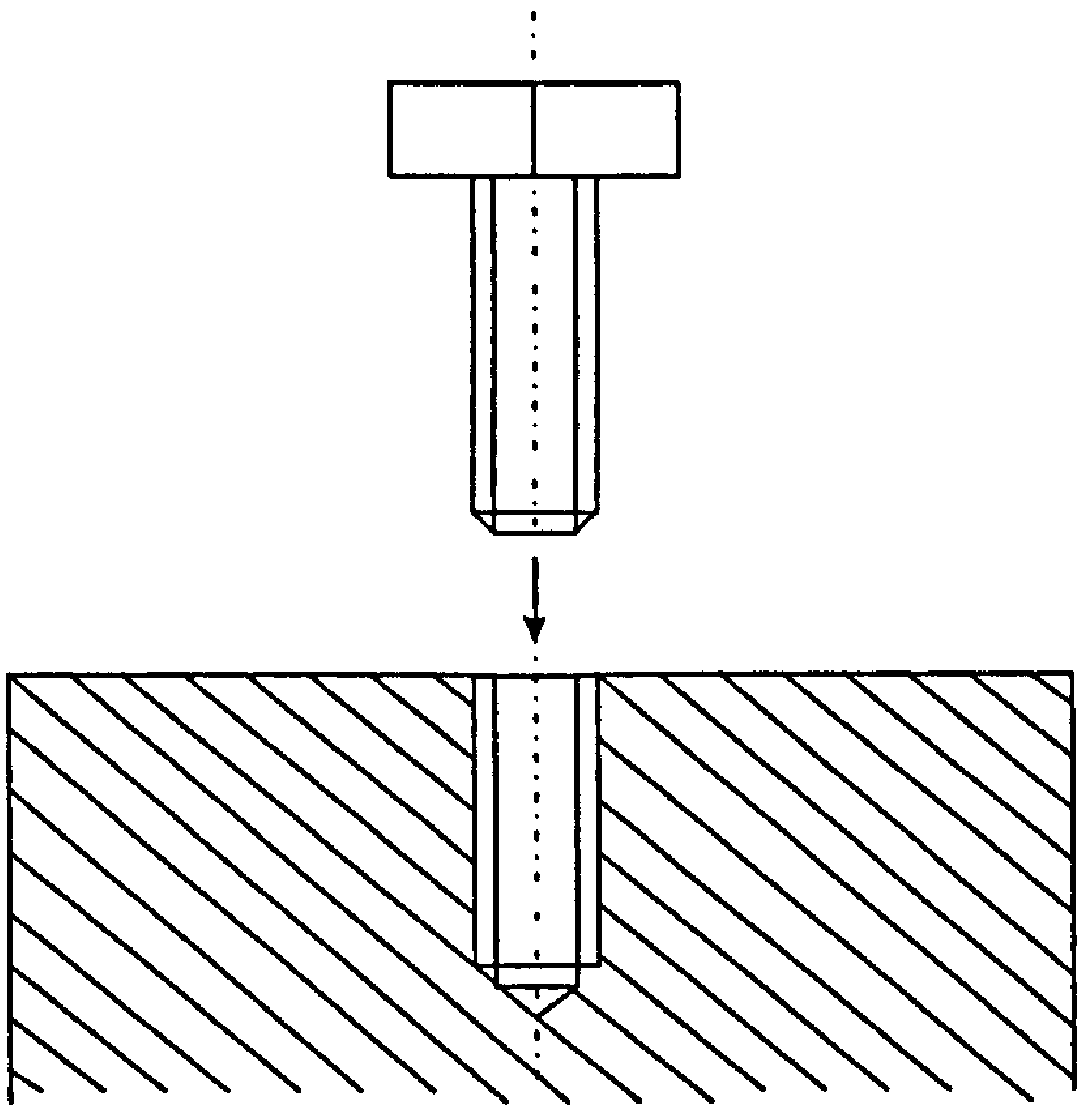

Figure 8.1: *Constraint Violation Example: Bolt In Hole*

8.3.2 Constraint Application

As parts are added to the assembly sequence, the selected validation criteria are invoked for that particular liaison, see Figure 8.2. Any violations are identified and the user should thoroughly investigate the reasons behind the apparent error. Resolution of any violation is left to the discretion of the user because the assembly may be incomplete and further data may explain or solve the problem. This validation process assists in the creation of a feasible and practical sequence as errors are identified at the first occurrence and thus have little chance of propagating through the sequence generation process.

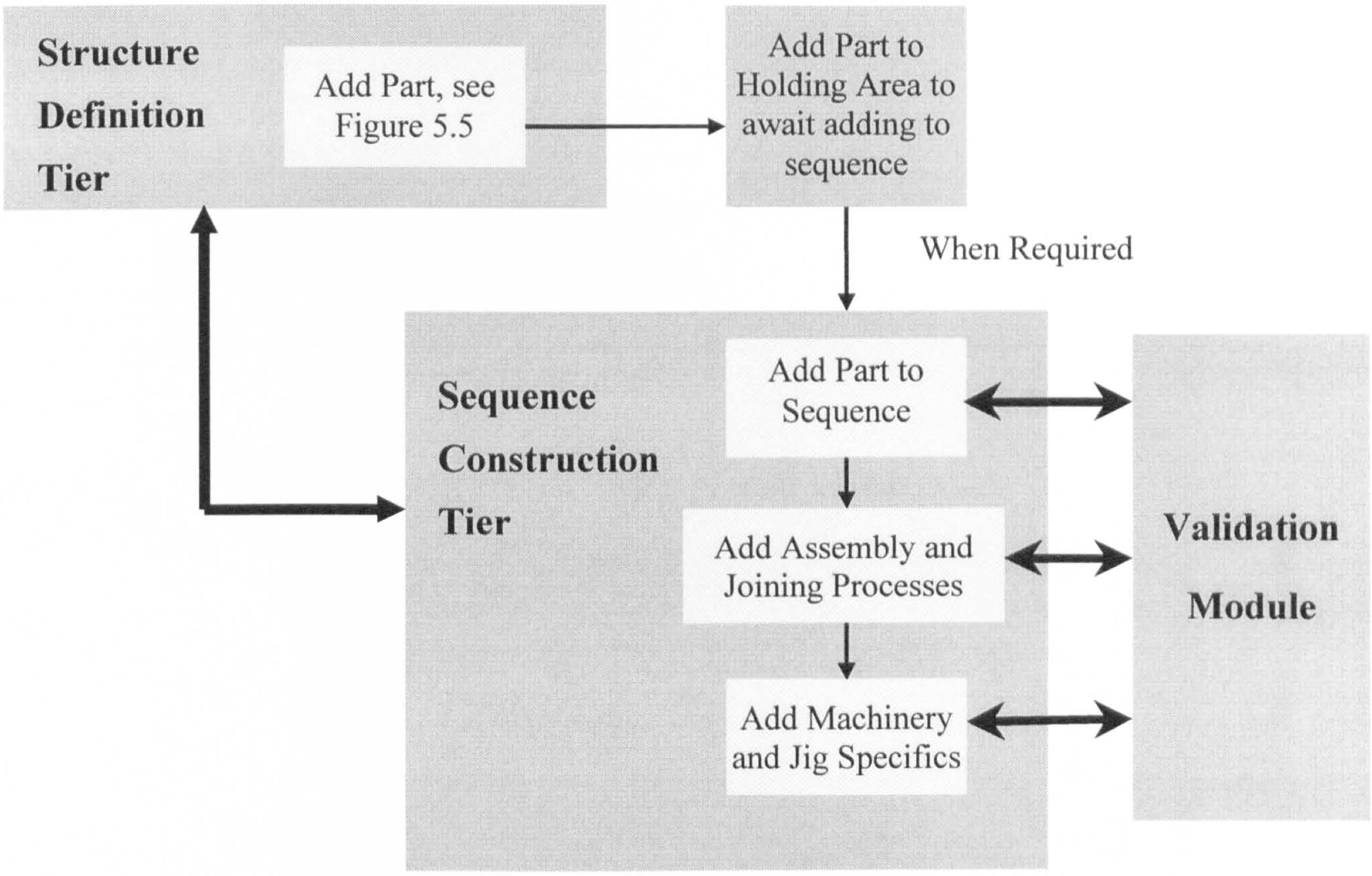

Figure 8.2: ***The Process for Construction and Validation Of the Assembly Sequence***

8.4 Implementation of The Validation Module

This chapter has thus far described the validation process within the Two-Tier methodology and has outlined the included constraints. From the list of constraints detailed, to date only the compatibility constraints have been implemented fully. This section covers the implementation aspects of these three constraints.

8.4.1 Implementation of MAT_MAT_COMP

It has been stated that when two parts are in contact, the electrolytic corrosion properties of the two materials are important. The Two-Tier methodology has access to a knowledge base containing this data. The material attributes of each component are identified and checked against this knowledge base. If it is inadvisable to have these two materials in direct contact then the user will be alerted. For example, the corrosive properties of magnesium are very seriously increased by the presence of steel. Thus, it would be inadvisable to have these two materials in direct contact. An instance of a magnesium component and a steel component with mating face attributes would cause a violation to this constraint and the user would be alerted.

8.4.2 Implementation of JOINING_PROC_MAT_COMP

When a *Joining Process* is specified for a particular liaison, this constraint is invoked to check the suitability of the material / process combination. A knowledge base holds data that details the processes that are compatible for use with different materials. This constraint works at a number of levels. As described in Chapter 6, the *Joining Process* has two levels of definition depending on the detail available at any time. Materials also have number of levels of definition, all of which can be compatibility tested against either level of the specified *Joining Process,* Figure 8.3 shows a sample of this hierarchy.

To illustrate the use of this constraint consider the example of specifying a resistance braze as the process to join a copper part and a nickel part. It is perfectly possible, according to the knowledge base, to define a joining process of resistance brazing with either copper or nickel based components. However, this same data also states that resistance brazing cannot be used to join dissimilar metals. Thus, this constraint is violated in this situation.

8.4.3 Implementation of JOINING_PROC_JOINT_COMP

In Chapter 6 the hierarchy of *Mating Joint Types* and the two different levels that can identify the *Joining Process* were described. It is apparent that these two attributes can have combinations of definition levels. This constraint uses the knowledge base including in the Two-Tier methodology to check for violations and determines the potential compatibility of these two attributes. Table 8.1 shows some examples of the attribute comparison at varying levels of abstraction.

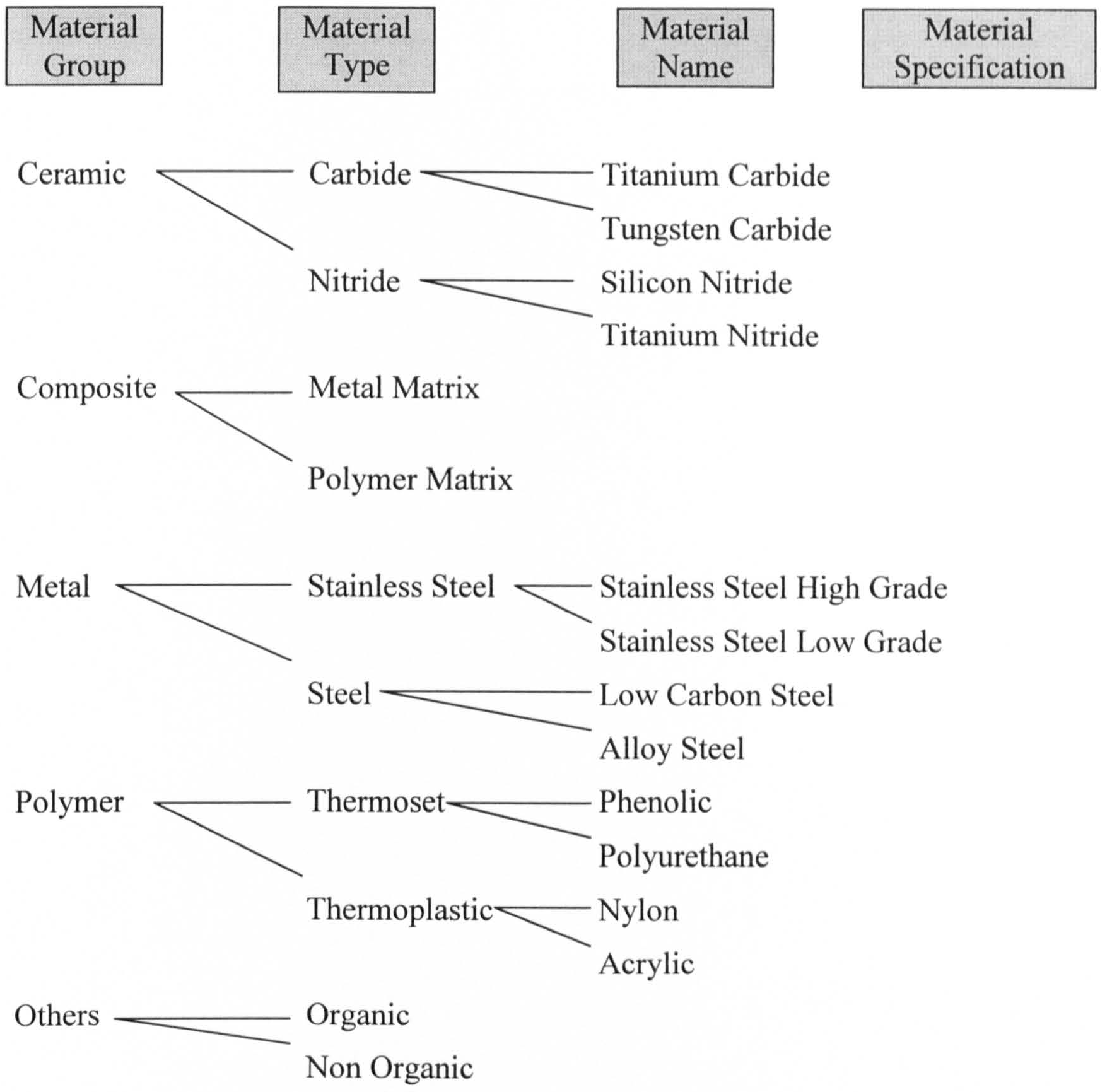

Figure 8.3: ***Sample of Material Hierarchy***

Joining Process	Mating Joint	Compatibility
Welded Joint	Non Permanent	Violation
Welded Joint	Permanent	OK
Resistance Spot Weld	Permanent	OK
Resistance Spot Weld	Permanent Fit	Violation
Resistance Spot Weld	Permanent Contact	OK
Resistance Spot Weld	Butt	Violation
Resistance Spot Weld	Lap	OK

Table 8.1: ***Joining Process Mating Joint Compatibility***

8.5 Concluding Remarks

Relevant literature has been reviewed to identify the set of constraints that should be included in the Validation Module of the Two-Tier methodology. This set of constraints and the process for applying the validation constraints have been described in detail. Only three of the constraints have currently been fully implemented. This has been discussed along with the implementation considerations of the three constraints.

9. EVALUATION OF ASSEMBLY SEQUENCE AND STRUCTURE

There remains only the consideration of the evaluation stage to complete the description of the Two-Tier methodology. This chapter describes the requirements for the evaluation criteria to be used to test the quality of the generated sequences. To maximise the value of these criteria it is believed that they should be able to provide appropriate data about the suitability of the sequence both during the development process and on completion. Firstly, the literature is reviewed to discover if any of the reported evaluation measures can be used in the Two-Tier Methodology. The metrics from the DFA analysis are currently able to provide some sequence evaluation. Thus, these metrics are examined to identify if they are able to evaluate the sequence constructed within the Two-Tier methodology. A discussion on the requirements of the criteria is included to aid the understanding of the need for such evaluation criteria. Finally, suitable qualitative and quantitative metrics are defined which can be used to determine the relative and absolute quality of the developed sequence.

In the Two-Tier methodology, the function of the Evaluation module is to provide a quantification of the assemblability of the sequence. This will enable the generated plan to be compared with other candidate plans or, indeed, against threshold values that can indicate a good sequence. Evaluation of this type is rarely found in sequence generation systems. Those that claim to evaluate sequences are actually only ranking the validation criteria[86,84]. In fact, many sequence generation systems require the user to discern the best sequence from the set of feasible and practical plans presented by the software. The designer, using the Two-Tier methodology, can only generate sequences individually. Thus, it is believed necessary to include the evaluation functionality to provide data about the suitability of the constructed plan. The approach described in this chapter is novel because the defined evaluation criteria can provide useful data *before* the sequence is complete. This provides the user with information about how the sequence is progressing during the development process.

9.1 Evaluation Criteria Review

The industrial survey carried out as part of this research found little evidence of sequence evaluation. In fact, only one of the ten companies visited even considered that the sequence quality is an important factor in production efficiency. This lack of industrial emphasis on plan optimisation has also been noted elsewhere[45]. It is also reflected in some of the sequence generation systems reported in the literature, which do not try to find the most appropriate plan. Those that do attempt to evaluate the sequence quality tend to analyse the plan after the application of both the hard and soft constraints[87,23]. Thus, there can often be a large number of sequences under consideration depending on the number and stringency of the applied constraints. The evaluation process involves the application of metrics to the sequence attributes. It is aimed to provide the user with plan quality and suitability data, but the final interpretation of the results is left to the user in most systems. The conclusion from this is that both industry and academia have little understanding of the requirements of assembly sequence evaluation. Neither has any consensus been reached regarding the qualities that constitute a good or optimum assembly sequence. One classification[45] of sequence evaluation techniques has tried to categorise the many types of criteria currently reported by the assembly planning literature:

- **Risk Reduction Criteria:**
  Those metrics which aim to limit the possibility of component failure or damage. The application of this can force the late addition of fragile or expensive parts and the delayed completion of irreversible processes.
- **Operational Flexibility Criteria:**
  Parallel plans increase the possibility of flexibility in the sequence, which can be advantageous in many production systems. When designing and assembling modules and variants, the late addition of unique components also increases operational flexibility. Thus, this metric can offer data regarding the suitability of the plan to this approach.
- **Efficiency Criteria:**
  This metric analyses the time taken to assemble the product and the resultant cost. More specifically, these criteria can include the consideration of a number of non-assembly operations such as reorientations, the stability of the assembly and the clustering of assembly operations. The minimisation or optimisation of these attributes can help to reduce assembly time and thus the cost.
- **Compatibility Criteria:**
  This metric analyses the suitability of the plan for particular assembly lines and ensures that specific requirements for partial assemblies are satisfied.

With the exception of the Efficiency Criteria, all the measures included in the previous classification have already been covered by the Two-Tier methodology during the validation stage. Each liaison in the sequence is checked against both hard and soft constraints. This ensures that feasible and practical sequences are generated when all constraint violations are addressed. This alternative approach requires a different type of evaluation. It is believed that appropriate metrics are crucial to the successful utilisation of the Two-Tier methodology because the user only constructs one sequence at a time.

Most industries are striving to reduce costs, so the Efficiency Criteria are an important, and indeed, fundamental measure. This is why these are the most frequent evaluation criterion proposed throughout the literature. CIAPS employs DFA software to compute the assembly cost based upon the difficulty of each assembly insertion. The results for each liaison are attached to the arcs of the graph of all possible sequences. The path of least cost is determined and represents the sequence with the minimum assembly cost. This is the plan that is defined as the best choice[23].

Another approach has implemented a simulated annealing search to identify the lowest cost plan from the diamond graph of all feasible sequences, before any pruning has occurred.[88] A random sequence is taken from the diamond graph, and the costs are calculated using the Holmes Cooprider algorithm[89] for solving the ESTA problem[h]. A small change is made to this plan and the cost is recalculated. If this plan is better than the first, another small change is made. If the second plan is not as good as the first then the initial plan is reinstated and another alteration is made to this plan. The process is repeated until a minimum cost is found. However, it is noted that this method will only find the probable lowest cost sequence.

Neural networks have also been implemented to find the optimal sequence, which was defined as "...the condition that its assembly cost is at a minimum"[81]. The cost is calculated by considering the time penalties for assembly instabilities and insertion direction changes for the sequence.

Assembly cost is generally seen as an absolute measure of sequence quality, but the apportioning of non-direct costs varies widely from business to business. This gives the user a problem. If non-direct costs are not included, the results of the assembly cost calculation are not correct from a business perspective. However, if these costs are included, a false indication may be gained of the suitability of a particular sequence.

Just considering the assembly time can overcome the cost allocation problem. One interactive sequence generation system uses Methods-Time-Measurement, (MTM) standard times to determine the overall time needed to complete the plan[42,43]. ASPEN[79], another assembly sequence generation system includes a comprehensive evaluation scheme to determine the increase in operating time due to the difficulty of the tasks involved. The sum of the following three indices is used to find the total evaluation time.

- *Subassembly Stability Index* - the time taken to reposition any components that have moved due to instabilities in the partial assembly.
- *Operation Complexity Index* - the basic insertion times.
- *Operation Continuity Index* - the time needed to make any additional movements such as reorientations, changing tools etc.

The calculation considers all hidden operations in the time analysis and should give a realistic measure upon which to base decisions. However the total time taken to assemble a product and its overall cost are highly dependent upon the complexity of the design. A complicated design, by definition, would have a high cost and would take a long time to assemble. Thus, time and cost are only useful as comparative measures between a number of sequences generated for a given design. In addition, the Two-Tier methodology requires evaluation criteria that can provide data about the suitability of a sequence during development to enable design decisions to be made interactively.

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[h] The ESTA problem is defined as the determination of the assembly line design with the minimum cost for a given sequence.

It may be possible to use the standard DFA metrics to develop a method of evaluating partially complete sequences. This idea has been previously considered and led to the proposal of two criteria[90]. The metrics were developed from analysing the assembly sequence of a number of electro-mechanical components. It was assumed that the sequences analysed were optimal for the given design. The data compared in this analysis was taken from the product before a Lucas DFA analysis was completed and after the subsequent redesign. The evaluation measures developed are shown in Equation 9.1. The work tried to prove the link between the results of the DFA analysis and a good assembly sequence. Despite the statistically small sample used in this work, further investigation could confirm the existence of robust links between DFA analysis and optimal assembly sequences.

$$\frac{\Sigma \text{ Number of assembly processes}}{\Sigma \text{ Number of components}} < 1.55$$

$$\frac{\Sigma \text{ (Number of assembly processes with DFA score} < 1.5)}{\Sigma \text{ Number of assembly processes}} <= 0.25$$

Equation 9.1: ***Evaluation Measures Based Upon DFA Results***

The results of conventional DFA have been shown to be inadequate when analysing complex assemblies due to combinatorial aspects, such as subassembly partitioning. It has been proposed that for complex assemblies, significant improvements are possible from minor redesigns or by reallocating subassemblies and sequence choice. To assist with this, an Assembly Sequence Analysis (ASA)[91] has been defined. Assembly move difficulty, "actions" / move, (A / m) and liaisons completed per move, (L / m) measures have been developed. Genetic algorithms search the various sequences and subassembly combinations and an "Objective Function", RMS (A / m), evenly shares out the assembly move difficulty across all the moves. Assemblability improvements have been achieved from the application of these metrics to case studies, with few design changes necessary. It was found that the A / m criterion offers the most useful results if all geometric issues have been resolved prior to its application.

This brief survey has shown that there have been few useful sequence evaluation criteria developed to date. Assembly time and cost are extremely important measures but any results should be interpreted with caution at the incomplete design stage. It appears that new measures are required that remain applicable through all the stages of the design process and just provide data about the sequence quality and not the assemblability of the design.

9.2 Evaluation Criteria From Design For Assembly

The Lucas DFA methodology[5] has been proven to improve the assemblability of products and thus reduce costs. As described in Chapter 2.2, it includes the construction of an assembly sequence and the analysis of each component and its liaisons for ease of handling and fitting. This results in a Handling Ratio, Equation 9.2 and a Fitting Ratio, Equation 9.3.

$$\text{Handling Ratio} = \frac{\text{Sum of individual handling scores}}{\text{Number of A parts}}$$

Equation 9.2: ***Lucas DFA Handling Ratio***

$$\text{Fitting Ratio} = \frac{\text{Gripping Score + Fitting Score + Non Assembly Score}}{\text{Number of A parts}}$$

Equation 9.3: ***Lucas DFA Fitting Ratio***

The Handling Ratio, Equation 9.2, should be applied to each component to consider the ease of manipulation of each part for either manual or automatic assembly. It does not give any indication of the merits of the sequence because the geometry and topology of the component determines the result.

In contrast, the Fitting Ratio, Equation 9.3 can be considered to be a sequence evaluation metric. This measure is calculated by analysing each step of the sequence using tables that penalise difficult assembly operations. Thus if the sequence is altered the Fitting Ratio changes, hence, an optimal value can be found for a given design. However, the tables used to compute the ratio include consideration of the component geometry. In a situation, where this is a constant the metric can be used as a definitive sequence evaluation. When the sequence is generated concurrently with the evolving design it can be assumed that geometry is not fixed. Hence, the Fitting Ratio can be used as a guide to the sequence quality, but is not suitable as a plan evaluator in this situation.

9.3 Development Of Evaluation Criteria

The previous section has explored the possibility of using the traditional DFA metrics to provide evaluation measures for assembly sequences that are applicable during the construction phase. It was found that current metrics are unsuitable because the results of the DFA analysis offer an insight into the quality of the overall assembly and each component's assemblability. None of the measures are able to determine whether the components are sorted into a good order for assembly.

It has been stated that the constraints currently embedded within the validation module of the Two-Tier methodology actually include many of the evaluation measures used in other planning systems. This is probably because it is quite difficult to isolate the evaluation of a sequence from its validation because both types of criteria consider the geometry, topology and attributes of the components in the assembly. Many of the systems use the evaluation step to prove the suitability of the sequence for a particular application. As detailed in the previous chapter, the Two-Tier methodology achieves this by validating each liaison against a set of constraints. Therefore, the evaluation stage in this methodology must provide additional information about the quality of the generated sequence. Thus, a measure or measures are required which provide this data. Furthermore, any metrics developed should hold true for all the phases of the design and sequence generation process.

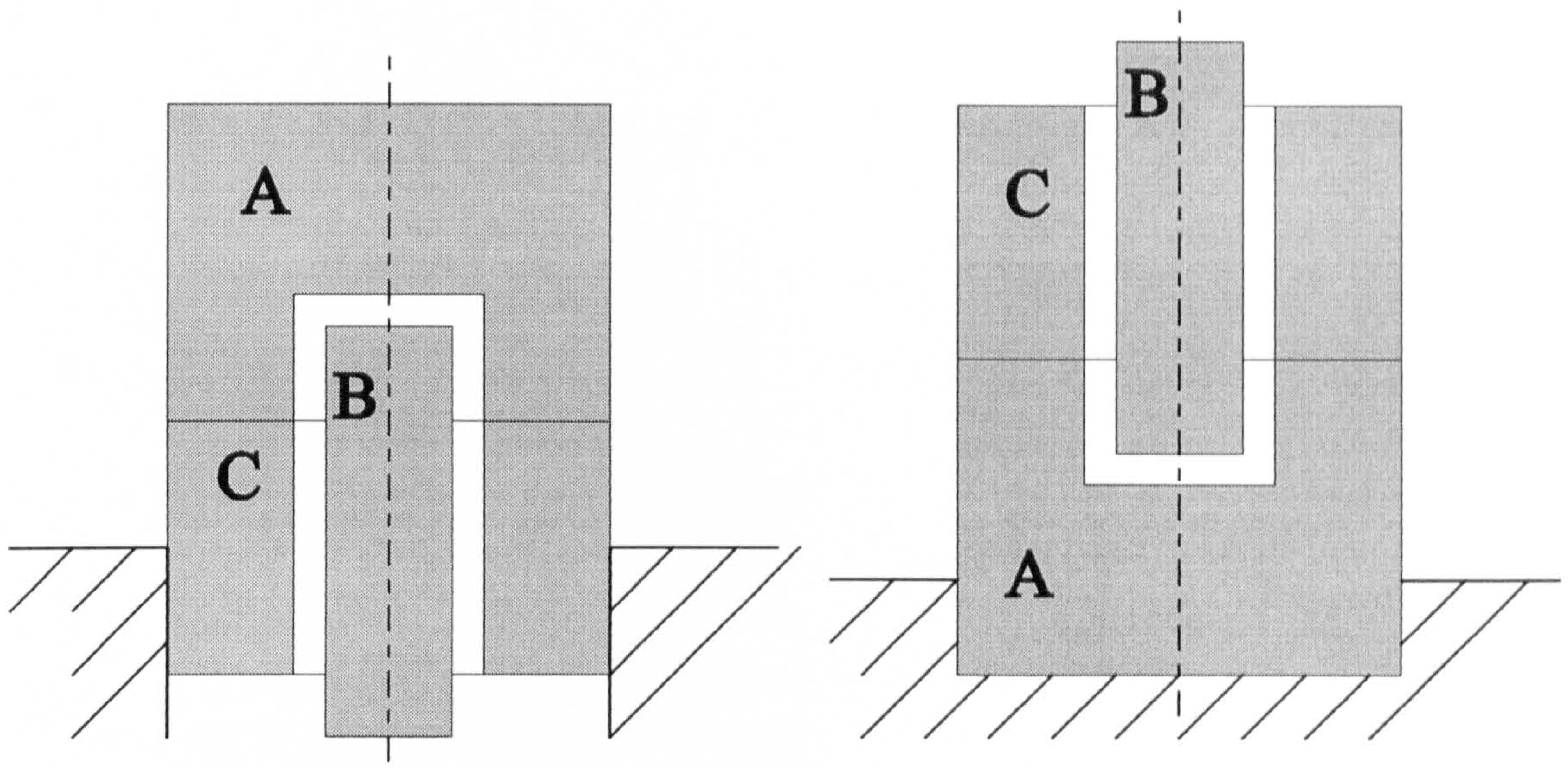
This section explores and develops evaluation criteria that can be used to measure the quality of assembly sequences at any stage in the construction process. Where possible these measures are geometry-independent. The inclusion of geometry in a metric, either implicitly or explicitly, implies some degree of design analysis is considered. It is appreciated that the sequence and the design geometry are inextricably linked, but it is important to include criteria that only measure the suitability of the plan to differentiate between design merit and sequence quality.

9.3.1 Premise 1: An optimum assembly sequence has one assembly action per component

It is proposed that a good assembly plan for any set of components should only contain one insertion process per component or subassembly. It is believed that this premise remains valid throughout the development of the sequence even when incomplete. Figure 9.1 illustrates this principle with a simple example. Sequence (a) has unnecessary turnover and workholder operations. These extra assembly operations could have been eliminated with a little more work, as shown in sequence (b).

Thus, it can be seen that improvements can be made to a sequence by reducing the number of insertion operations. Of course, not only the use of workholders cause extra insertion operations. Disassembly requirements for testing or other needs can also increase the total insertion count. In addition, necessary re-adjustments due to poor assemblability or tolerance stacks add to the overall number of insertions. It is apparent that these extra operations should be avoided wherever possible. It is clear that a significant increase in the number of insertion operations is inadvisable.

It is therefore concluded that the number of insertion operations compared to the part count can give some indication of the quality of an assembly sequence for a given design. Other processes may be necessary to complete the liaison, but the need for these is largely dependent upon the design geometry, as is the difficulty of this insertion operation and other metrics will be required to account for this. It is evident that this measure will not be definitive, but data can be provided concerning the quality of the sequence at stage of construction.



Task 1: Insert C in WorkHolder
Task 2: Insert A
Task 3: Turn Over A and C
Task 4: Insert A and C into WorkHolder
Task 5: Insert B

Number Of Insertion Processes = 5
Number Of Parts = 3

Insertion Processes ≠ Parts

(a) "Poor" Sequence

Task 1: Put A in WorkHolder
Task 2: Insert B
Task 3: Insert C

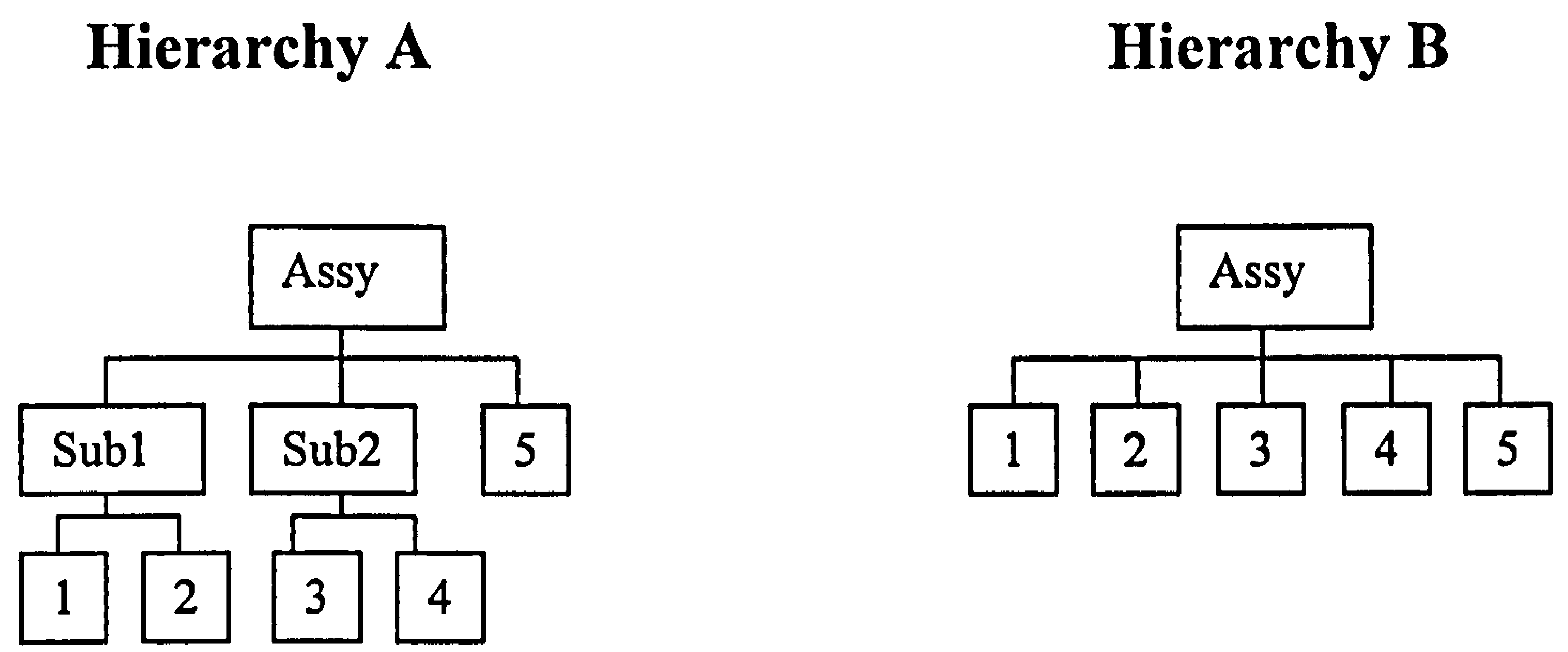
Number Of Insertion Processes = 3
Number Of Parts = 3

Insertion Processes = Parts

(b) "Good" Sequence

Figure 9.1: *A "Good" and a "Poor" Assembly Sequence for the Same Assembly*

To define the metric it must be clear whether subassemblies should be included in the calculation. In addition, two types of insertion operations are involved in any assembly: part–to–partial assembly insertion operations and part-to-workholder insertions and the inclusion of both types should be investigated. To resolve these issues consider Figure 9.2, which shows two assembly hierarchies for the same assembly, consisting of components 1, 2, 3, 4 and 5. Hierarchy A divides the components into two subassemblies Sub1 and Sub2 and will result in a parallel assembly plan whilst Hierarchy B has no subassemblies at all and will have a linear sequence.



Hierarchy A

Assembly Sequence:

Insert 1 into Workholder
Insert 2 into 1 to create Sub 1
Insert 3 into Workholder
Insert 4 into 3 to create Sub 2
Insert Sub1 into Workholder
Insert Sub 2
Insert 5 to create Assy

Workholder insertions = 3
Part to part insertions = 4

Hierarchy B

Assembly Sequence:

Insert 1 into Workholder
Insert 2
Insert 3
Insert 4
Insert 5 to create Assy

Workholder insertions = 1
Part to part insertions = 4

Figure 9.2: ***Effect of Subassemblies on Assembly Sequence***

It can be seen that for Hierarchy A:

$$\frac{\text{Total No. Of Insertions}}{\text{Total No Of Components + Subassemblies}} = 1 \qquad (1)$$

$$\frac{\text{Total No. Of Insertions}}{\text{Total No Of Components}} = 1.2 \qquad (2)$$

$$\frac{\text{Part-to-Part Insertions}}{\text{Total No Of Components}} = 0.6 \qquad (3)$$

And for Hierarchy B:

$$\frac{\text{Total No. Of Insertions}}{\text{Total No Of Components + Subassemblies}} = 1 \qquad (4)$$

$$\frac{\text{Total No. Of Insertions}}{\text{Total No Of Components}} = 1 \qquad (5)$$

$$\frac{\text{Part-to-Part Insertions}}{\text{Total No Of Components}} = 0.8 \qquad (6)$$

It can be seen that the only measure that did not discriminate against either Hierarchy A or Hierarchy B was Equation (1) and (4). Equation (2) and (4) favoured a non-parallel sequence and Equations (3) and (6) give the best result for a hierarchy with the largest number of subassemblies. It is clear that any metric that compares the number of insertions per component must return the same result for any hierarchy combination. This example has proved that subassemblies and both types of insertion must be taken into consideration to ensure that the results of the measure do not favour or discriminate against parallel sequences.

The above example has shown that it is possible to get a result of 1 for this metric for an optimal sequence. However this is a theoretical value and must be tested against some industrial examples to prove validity. Thus 34 electromechanical case studies have been analysed and this metric has been applied. (NB It is assumed that the assembly sequences in the case studies have been optimised for the given design.) A statistical analysis of the results has been completed. The mean has been calculated to define a threshold value for a good sequence. To ensure that the majority of good sequences fall within the defined value, the Upper 95% Confidence Interval of the mean has been found. Thus, the metric becomes:

$$\frac{\text{Total No. Of Insertion Processes}}{\text{Total No Of Components + Subassemblies}} = 1.2$$

This means that for a good sequence:

$$\textbf{\textit{Insertion Index}} = \frac{\textbf{Total No. Of Insertion Processes}}{\textbf{Total No Of Components + Subassemblies}} \leq \textbf{1.2}$$

9.3.2 Premise 2: An optimum assembly sequence is stable at all times and thus a requires a maximum of (1 + subassembly count) workholders

Calculating the stability of the in-progress assembly is another measure that could offer an insight into the quality of the assembly sequence. It is noted that the stability of the partial assemblies has been considered in the Validation Constraints in Chapter 8, **STABLE** and **STABLE_TURNOVER**. These criteria operate a pass/fail state; if an assembly is unstable and a workholder is defined, the constraint is not violated. Adding such extra tasks into a sequence does indeed reduce the number of failed constraints, but adds unnecessary time and cost into the plan. Thus, it is proposed that a metric is needed to measure the use of these jigs and fixtures to ensure that supplementary processes are not added into the sequence just to compensate for poor design and any resultant unstable assemblies. However workholders are integral to the building of any assembly and their use cannot be eliminated. Because extra cost is introduced by their use, the number of workholders should be minimised to an 'acceptable' level. It is suggested that an assembly should require a maximum of one workholder per subassembly and one for the main assembly. This idea was verified against 34 industrial examples to prove if this measure has any value. Again, it is assumed that the case studies have the optimum assembly sequences defined. The metric applied to these examples is shown over:

$$\text{Stability Index} = \frac{\text{Total No. Of Workholders used}}{\text{Total No. Of Subassemblies}+1} <= 1$$

NB The denominator of this measure increments the total number of subassemblies by one to represent the fact that the overall assembly needs a workholder as well as each subassembly.

A statistical analysis has shown that the mean of the sample is not significantly different from 1 and assuming the case studies are representative, it can be concluded that the metric is valid. Further validity testing may be required to ensure that the metric is applicable to all assembly sequences.

$$\textbf{\textit{Stability Index}} = \frac{\textbf{Total No. Of Workholders used}}{\textbf{Total No. Of Subassemblies +1}} \leq \textbf{1.0}$$

Premise 3: An optimum assembly sequence has an average DFA fitting index < some threshold value for each action

It is clear that the difficulty level of the operations involved in a liaison is likely to be an important criteria which significantly affects the time and cost of assembly. The DFA Fitting Ratio (Eqn 9.3) measures the difficulty of building the assembly with relation to the number of essential parts, but Section 9.2 argued the reasons for its unsuitability for an evaluation metric in the Two-Tier methodology. It has been demonstrated that a detailed analysis of the relationship between DFA scores may provide suitable metrics to determine the quality of the assembly sequence[90]. Consideration of the DFA fitting scores for each assembly process may be able to provide data about the difficulty of the defined operations. A good assembly sequence would have a low average score calculated in this manner. A threshold value must be determined, which maps the results of the metric to good and bad sequences for comparison purposes. This threshold value should be such that it can offer data about the sequence as the construction progresses. The same 34 case studies were analysed to define a result for good sequences:

$$\text{Difficulty Index} = \frac{\text{Sum Of DFA Fitting Scores For Processes}}{\text{Total No. Of Processes}}$$

To determine the threshold value for a good sequence, a linear regression analysis was completed on the case studies. A linear relationship was found from the results of these good sequences where the Difficulty Index ≈ 2:

$$\textbf{\textit{Difficulty Index}} = \frac{\textbf{Sum Of DFA Fitting Scores For Processes}}{\textbf{Total No. Of Processes}} \leq \textbf{2}$$

This result can be interpreted as the average DFA Fitting score throughout the sequence should be no higher than 2. This is contrasted against the optimal insertion process that has a DFA score of 1. Thus, it is accepted that a certain amount of insertion difficulty is inevitable.

It initially appears that to calculate a meaningful result, this metric requires a certain level of detail to be defined for each liaison. However, this is not the case. Even if just one process is defined, the numerator will be a low value and the number of processes will be equal to one. Thus, it is believed that the results of this metric will be useful even as the sequence is being constructed.

9.3.4 *Premise 4:An optimum assembly sequence has an average number of assembly processes per component liaison < some threshold value*

So far using the developed evaluation criteria, the deviation from the optimal number of insertions, the stability of the sequence, and the average difficulty of completing the assembly processes can be analysed. However, no consideration has been given so far to the actual complexity of completing each liaison. Thus, another measure that may generate useful data is the Complexity Index, which considers the average number of processes per liaison and represents the overall complexity of building the assembly. This metric is closely related to a measure previously identified[90] which analysed the average number of processes per component and found a threshold value of 1.55. However, this calculation does not acknowledge the existence of subassemblies but does take account of the processes required for their assembly. The Complexity Index must include the number of subassemblies with the number of components to fully represent the number of liaisons.

Thus;

$$\text{Complexity Index} = \frac{\text{Total No. of Processes}}{\text{Total No Of Components + Subassemblies}}$$

To determine the threshold value for the Complexity Index, a linear regression analysis was completed on the 34 industrial case studies. A linear relationship was found from the results of these case studies where the Complexity Index ≈ 1.4:

$$\boxed{\textbf{\textit{Complexity Index}} = \frac{\textbf{Total No. Of Processes}}{\textbf{Total No Of Components + Subassemblies}} \leq \textbf{1.4}}$$

Unlike the other defined indices, the Complexity Index has only limited value during the construction stage of the sequence. During the development of the product, components and subassemblies will generally be detailed before processes are added to the sequence. If the parts are known, but the process data has not been added to the system then the Complexity Index will be artificially good. It is only when the full detail has been added to a liaison in the sequence that any results can be deemed useful. However, as long as the user is aware of the limitations of this metric, the calculation may still provide tentative results.

9.3.5 Time and Cost Criteria

Although earlier in this chapter both time and cost were dismissed as suitable evaluation criteria, they are still important measures. Product cost is an essential piece of data in any business and as such should not be ignored. However, as previously discussed, the determination of both time and cost is open to considerable debate. Many calculations do not take into account the hidden costs of rework and defects and the complex apportioning of non-direct costs. In addition, the results of the time taken and the overall cost have no meaning until the design and sequence are complete. Despite this it was felt necessary to include these measures as part of the evaluation module in the Two-Tier methodology. Whatever process is followed to calculate the time and cost they are simple but crucial measures with which to compare candidate sequences.

A simple method was devised to calculate the time taken which combines Lucas DFA scores with Methods-Time-Measurement (MTM)[92] values. It has been assumed that each part takes a nominal 3 seconds to insert[3]. This corresponds to a Lucas DFA score of 1, an ideal insertion operation. The MTM values were then transposed on to DFA scores to define a time for each penalty point incurred. This analysis showed that each additional point added to the DFA score incurs an additional 1 second of assembly time. This process includes all the non-assembly operations which rate, 1 DFA point = 1 second. Once the time has been calculated by this method, a user defined direct labour rate can be used to determine the overall assembly costs. A detailed DFA analysis must have been completed which in turn requires a fully defined sequence and design for the time and cost values calculated to be of any use.

To illustrate this method, consider the assembly sequence shown in Table 9.1. Step 1 places a part in a workholder and incurs a DFA score of 1. This is classified as a non-assembly operation in DFA and thus there is a direct mapping of DFA score to number of seconds.

Step	Assembly Task	DFA Score	Time
1	Place part 1 in workholder	1	1 secs
2	Place part 2 on to part 1, (Restricted Access)	2.5	4.5 secs
3	Turnover partial assembly	1.5	1.5 secs
4	Place part 3 on to parts 1 and 2 (Alignment required)	1.7	3.7 secs
			10.7 secs

Table 9.1: ***Sample Sequence Demonstrating Mapping Between DFA Scores And Time***

Moving on, Step 2 is an insertion process with restricted access problems. A DFA penalty of 2.5 is gained for this operation. The translation into seconds for an insertion process is as detailed above. The first point is equal to 3 seconds and additional points are 1 second each. Thus because Step 2 has a DFA score of 2.5. The first point adds 3 seconds to the total time and the remaining 1.5 points become 1.5 seconds giving a total of 4.5 seconds. Steps 3 and 4 are calculated in the same way resulting in a total assembly time of 10.7 seconds.

9.3.6 Qualitative Criteria

The previous section has outlined the criteria developed for quantitative evaluation in the Two-Tier methodology. Qualitative criteria are also useful because they enable the easy comparison of candidate sequences. They can also highlight any unacceptably high levels of a particular type of operation or circumstance. This type of criteria is only useful after the sequence has been completed. It is impossible, for example, to compare the number of reorientations in two sequences if one or both are incomplete. The data that is useful to include in the evaluation depends upon the perspective of the user. Thus the data calculated in this module reflect the need to understand and interpret the quality of the assembly sequence. Thus, the Evaluation module in the Two-Tier methodology contains the following qualitative measures:

- Number of different joining processes
- Number of workholders required
- Number of reorientations specified
- Number of non-value added operations
- Number of constraint violations

The inclusion of this data provides assistance to enable the user to understand the sequence parameters and their reflection of the sequence quality.

9.4 Concluding Remarks

This chapter considers how to quantify the quality of the generated sequence, by the use of geometry-independent measures where possible. The DFA metrics and a survey of relevant literature failed to provide any existing measures that were suitable for this analysis. Thus, new criteria were developed which could provide quality data about both a developing sequence and a complete sequence. Four metrics were defined which enabled quantitative values to be calculated. It is evident that a sequence may only meet some of these criteria and it is left to the discretion of the user to decide which metrics are most important at any given time. The need to provide an overall result for the sequence quality has been recognised in some recent work. Methods have been developed which use a simulated annealing search to find the sequence with an optimal combination of some pre-defined evaluation criteria[93,94]. The provision of a definitive measure for the sequence quality was considered outside the scope of the research into the Evaluation module at the current time.

The threshold values calculated for each of the metrics is based upon a statistical analysis of the same set of 34 electro-mechanical case studies. To increase confidence in the applicability of the values for all products, further analyses must be completed on assemblies that are more diverse.

Despite the lack of a universal definition it was decided to include both time and cost as evaluation criteria. Although these can give results that can be misinterpreted, overall product assembly cost is too important not to be calculated. Thus, simple analyses have been developed to provide rough time and cost measures from data already in the model. In addition to the calculation of quantitative criteria, some relative measures are provided to give extra data about the sequence quality. This offers the user the as much data as is available to make an informed decision about the assemblability of the designed product.

10. SPADE IMPLEMENTATION

A Two-Tier methodology to construct an assembly sequence parallel with a developing design has been described so far in this thesis. To enable the testing of the concepts within the process it has been implemented into a software environment called **SPADE** (Sequence Planning And Design Environment). This chapter describes the application, which is illustrated in Figure 10.1 and the functionality that facilitates the Two-Tier methodology. The realisation of the **SPADE** system is achieved through the integration of the ACIS solid modelling kernel embedded within Visual C++. Data storage and retrieval is accomplished through utilisation of an Access database. The Expert Assembler with its integral *Starting Component Advisor* and *Next Component Advisor* is implemented within the CLIPS expert system environment.

The author has developed the majority of **SPADE,** comprising the Structure Builder, the Sequence Builder and the validation and evaluation module implementation. However, the assistance of the following colleagues is gratefully acknowledged:

- Ms H. Mei for the CLIPS implementation of the Expert Assembler;
- Ms S. Tate for the development and integration of the Four Layer Model and any geometric reasoning techniques required;
- Mr G.F. Dalgleish for the DFA analysis implementation and the links to the ACIS modeller.

To develop a system such as **SPADE** it is necessary to represent and store all the relevant product data. Product models are generally used for this purpose and **SPADE** is no exception. A product model holds information about every conceivable aspect of a design. Some form of geometry and topology representation is required to define each component along with the location and orientation of those parts within the overall assembly. Other data is probably also required about how to manufacture each part and other such part-level attributes. It may also be necessary to hold data about the adjacencies between the components and details of how the product is assembled. The information that can be added to a product model is dependent upon the perspective of the user of the data. Thus for the application all the data outlined above will be needed.

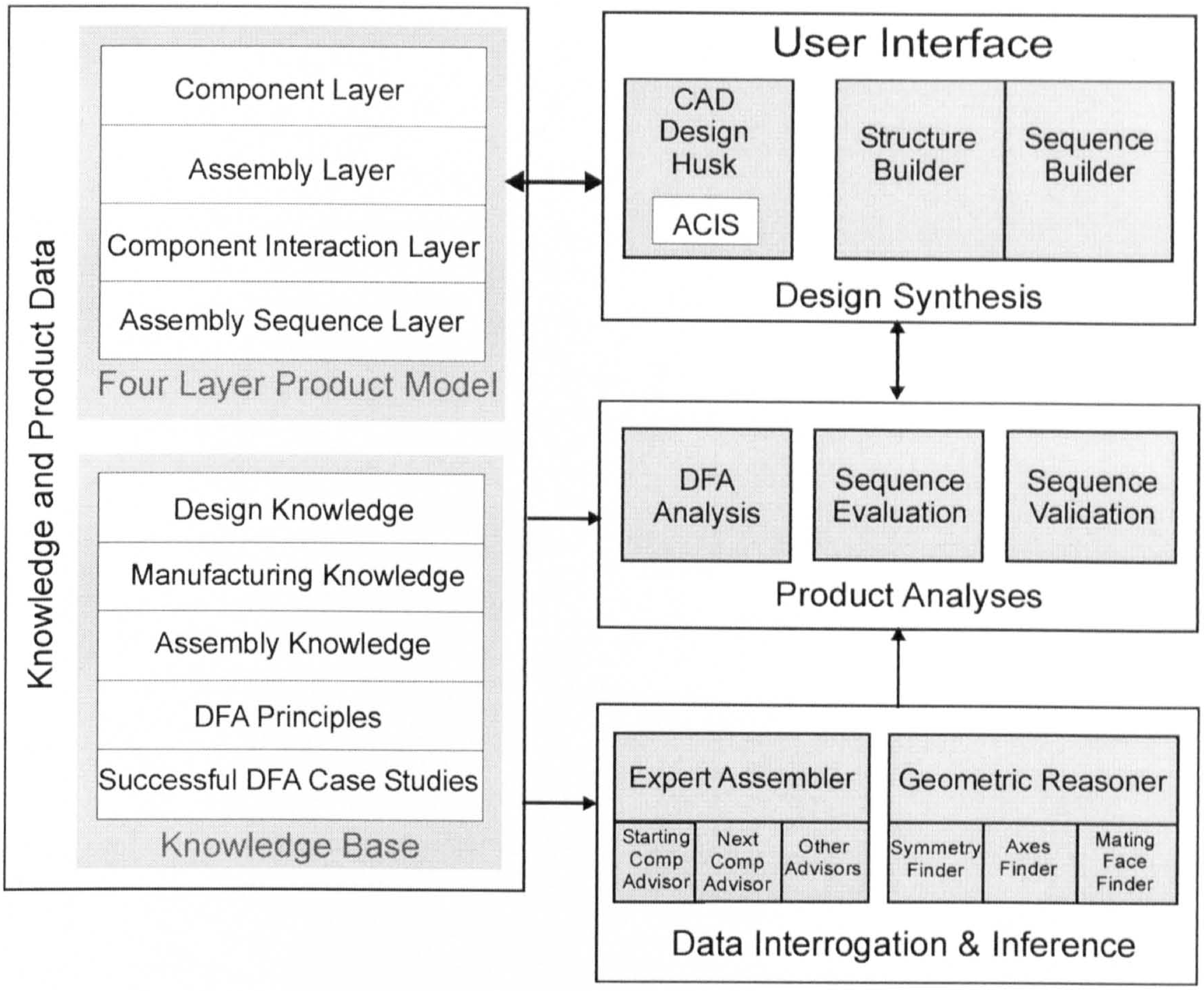


Figure 10.1: SPADE ***Assembly Oriented CAD Environment***

A Four-Layer Product Model is provided by **SPADE** as the underlying data structure. This was developed from work that previously identified that over 70% of the data required by the DFA analysis could be inferred from this model[48]. Each of the four layers of this product model depends on, has access to or includes all data in the lower layers. These layers are labelled as follows:

- *Component Model* - solid model (ACIS 'sat' file), enhanced with component attribute information such as surface finish, material etc.
- *Final Assembly Model*- position and orientation information for each instantiated component within the assembled product.
- *Component Interaction Model* – details of the component mating faces, their method of assembly and other liaison attributes.
- *Assembly Plan Model* – temporal data including sequence of component assembly operations including non-assembly processes.

An object-oriented approach is used to implement the Four-Layer Product Model. Each of the included models are implemented as a child of a parent 'Layer' class. The *Component Model Layer* is instantiated as many times as there are components in the assembly. In Chapter 5, it was found that the Two-Tier methodology required four disparate types of components:

- New Component
- New Subassembly
- Existing Component
- Existing Subassembly

Thus, four derived Component Model class types hold data and methods for each of these types of components. For instance, a data member of the New Subassembly class describes which other *Component Models* are members of this particular subassembly. The *Final Assembly Model* and *Component Interaction Model* are only ever instantiated once for a particular assembly. Although there should only ever be one *Assembly Plan Model* for each assembly, the ability to explore a number of candidate sequences means this model can be instantiated for comparison purposes. However, the final design in **SPADE** only has one instance of *Assembly Plan Model.* Data persistence is achieved by exporting the data stored in the four layers of the model to an Access database to facilitate data searches and ease of retrieval.

10.1 SPADE Described

SPADE is designed to enhance the working practices of the user and enables the easy consideration of assembly issues as early as possible in the design process. A simple way to interactively develop assembly sequences is provided to achieve this. The sequence generation process is closely aligned to that detailed in Chapters 4 to 9, following the breadth first, depth second approach and allowing for the integration of the chosen hard and soft constraints.

The implementation of the Two-Tier methodology within **SPADE** comprises two workspaces and the additional CAD facilities and are visually shown in Figure 10.2:

- *Structure-Builder* - a window which allows the development of assembly structures and contains the methods described in the Structure Definition tier
- *Sequence-Builder* - a window for the building of assembly sequences, the processes detailed in the Sequence Construction tier are included. In addition, a holding bay area is provided which contains those parts waiting to be inserted into the assembly sequence.
- *CAD Solid Modeller* - a set of CAD windows to facilitate the designing of each component, subassembly and overall product assembly.

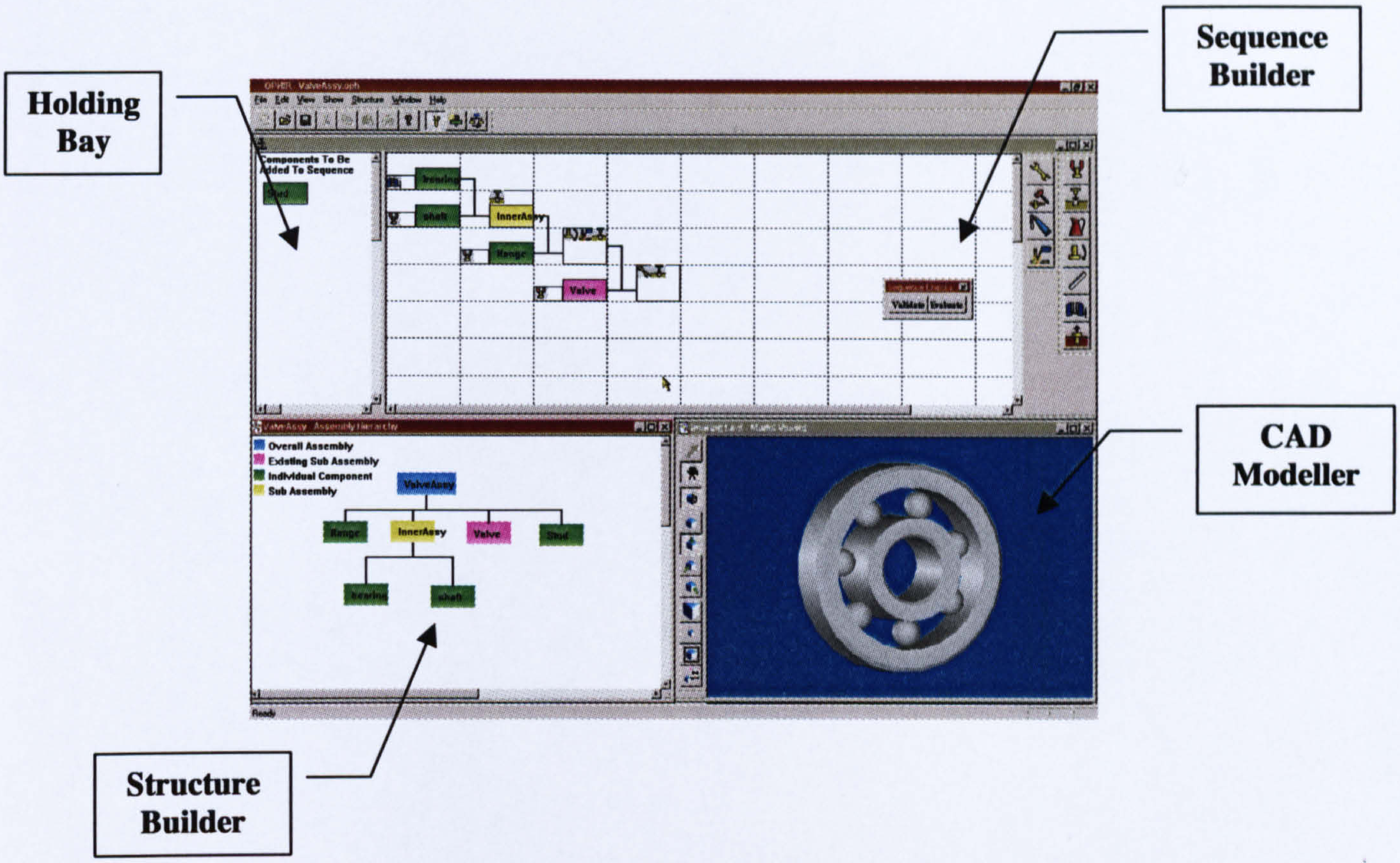


Figure 10.2: *A Screenshot of the SPADE System*

SPADE is fully interactive and allows the user unlimited access to all workspaces at all times. This enables the design of a component to be completed simultaneously with the consideration of subassembly partitioning and sequence construction as described in the Two-Tier methodology. It is in this way that any new assemblability issues are highlighted during the design process.

10.1.1 Structure Builder Module

The requirements of the Structure Definition tier within **SPADE** are realised in the *Structure Builder* Module as shown in Figure 10.3. This workspace provides the functions that enable experimentation with the different possible product structures as developed from the function structure defined in the concept design stages. This task offers the opportunity to consider and document proposed subassembly partitions.

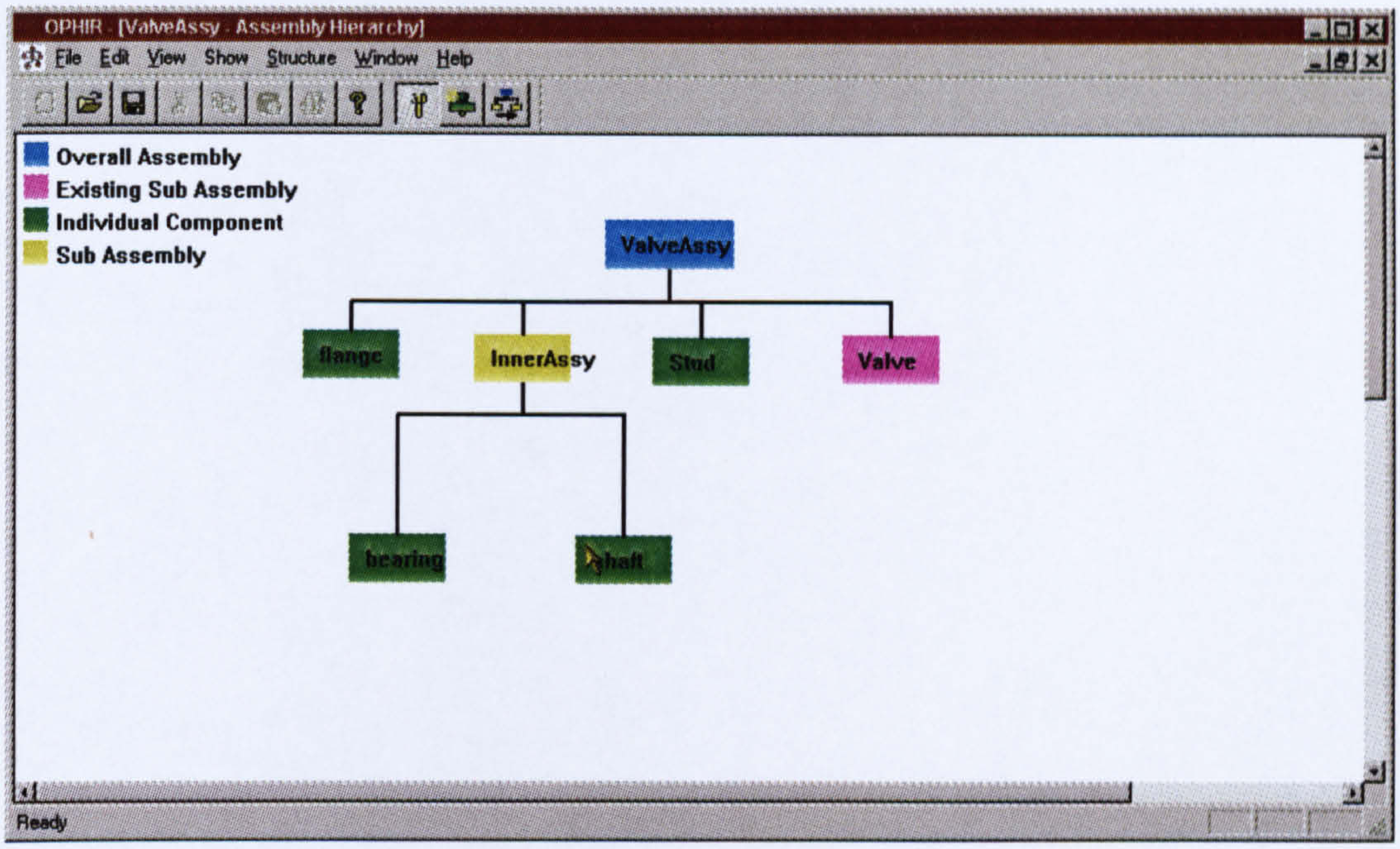


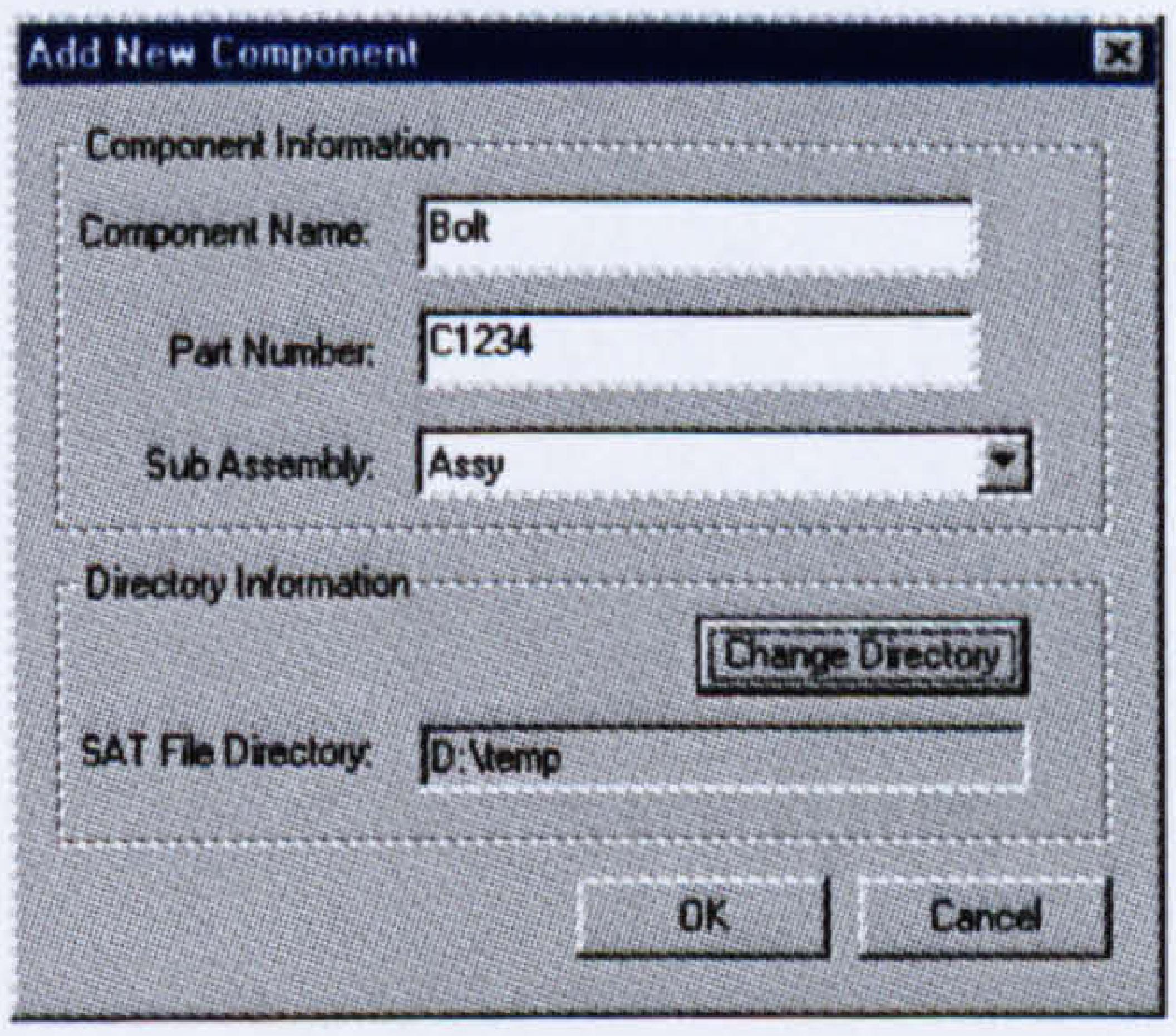
Figure 10.3: ***Structure Builder Module***

Revisions are also possible to enable the exploration of differing levels of parallelism in the assembly sequence. By working with this module, the designer can examine the assembly structure and is able to apply heuristics to ensure that a near-optimal configuration is achieved. The output of this workspace may be of use to other business functions - for example, it is believed that output of this module could be used by purchasing as a product Bill of Materials.

The *Structure Builder* workspace is the first to be used when work commences in **SPADE**. This is because parts and subassemblies are initially created and placed in the hierarchy in this module, no other functions are possible until this is defined. The following paragraphs describe the procedure completed when adding the different types of component or subassembly to the structure, and thus, to the product model.

New Component – colour code 🟩

1. Choose the Add Component icon
2. Fill in part details as shown in the dialog box in Figure 10.4
3. The new component is:
   - Visually added to the structure.
   - Visually added to the "Holding Area".
   - Defined in an empty CAD screen
   - Defined by a New Component object
   - Added to the Four Layer Model



Component Information

Component Name: Bolt

Part Number: C1234

Sub Assembly: Assy

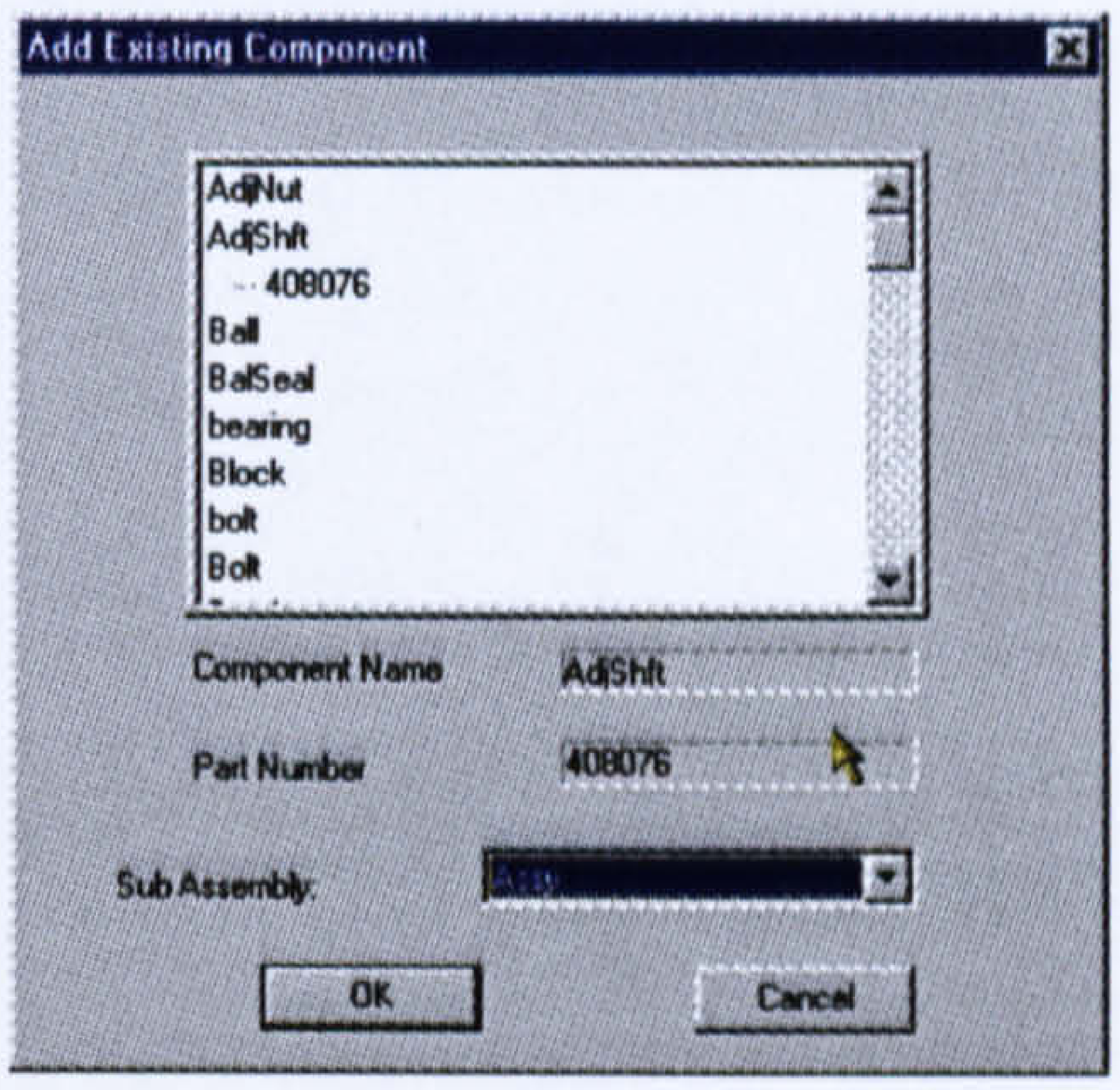
Directory Information

SAT File Directory: D:\temp

Figure 10.4: ***Add New Component Dialog Box***

Existing Component – colour code 🟩

1. Choose the Add Component icon
2. Choose the required part from the choice given as shown in Figure 10.5
3. Existing component is:
    - Visually added to the structure.
    - Visually added to the "Holding Area".
    - Model is opened in a CAD screen
    - Defined by an Existing Component object
    - Added to the Four Layer Model



Component Name AdjShft

Part Number 408076

Sub Assembly: Assy

Figure 10.5: ***Add Existing Component Dialog Box***

New Subassembly – colour code 🟨

1. Choose the Add Subassembly icon
2. Choose the parts for the subassembly, as shown in the dialog box in Figure 10.6
3. New subassembly is:
    - Visually added to the structure, member components are removed from their current position and re-added as members of New Subassembly
    - Visually added to "Holding Area", if the member components have been added to sequence these are removed and also added to "Holding Area"
    - Model is opened in the CAD screen, showing member components in position.
    - Defined by an New Subassembly object
    - Added to the Four Layer Model

Component Name: AdjShft

Component Name: Housing

Sub Assembly Name: SubAssy

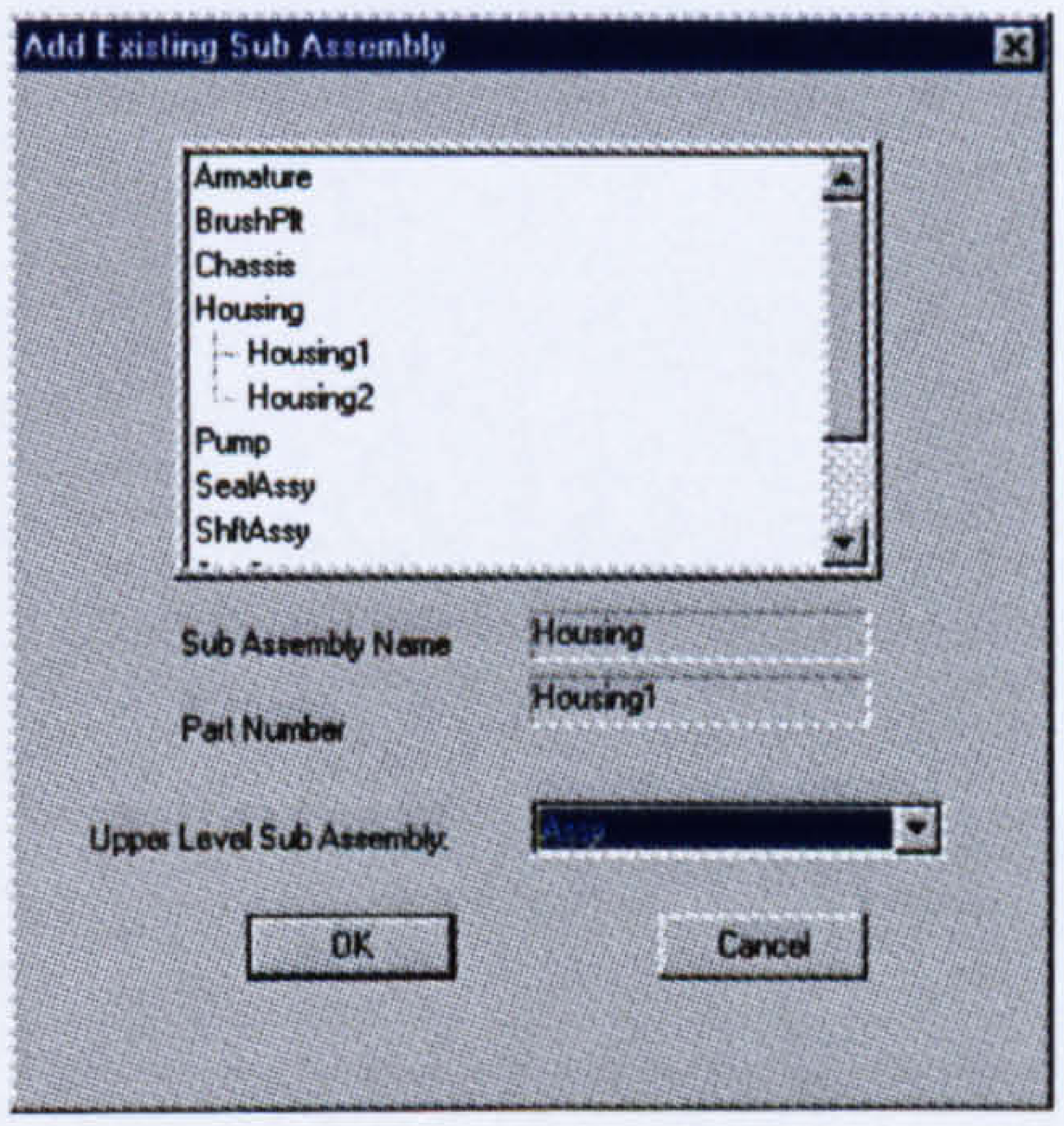
Sub Assembly Part Number: SubAssy1

☑ Add To Master Component Database

Figure 10.6: ***Add New Subassembly Dialog Bo***

Existing Subassembly – colour code 🟪

1. Choose the Add Component icon
2. Choose the required subassembly as shown in Figure 10.7
3. Existing subassembly is:
    - Visually added to the structure
    - Visually added to the "Holding Area"
    - Model is opened in a CAD screen
    - Defined by an Existing Subassembly object
    - Added to the Four Layer Model



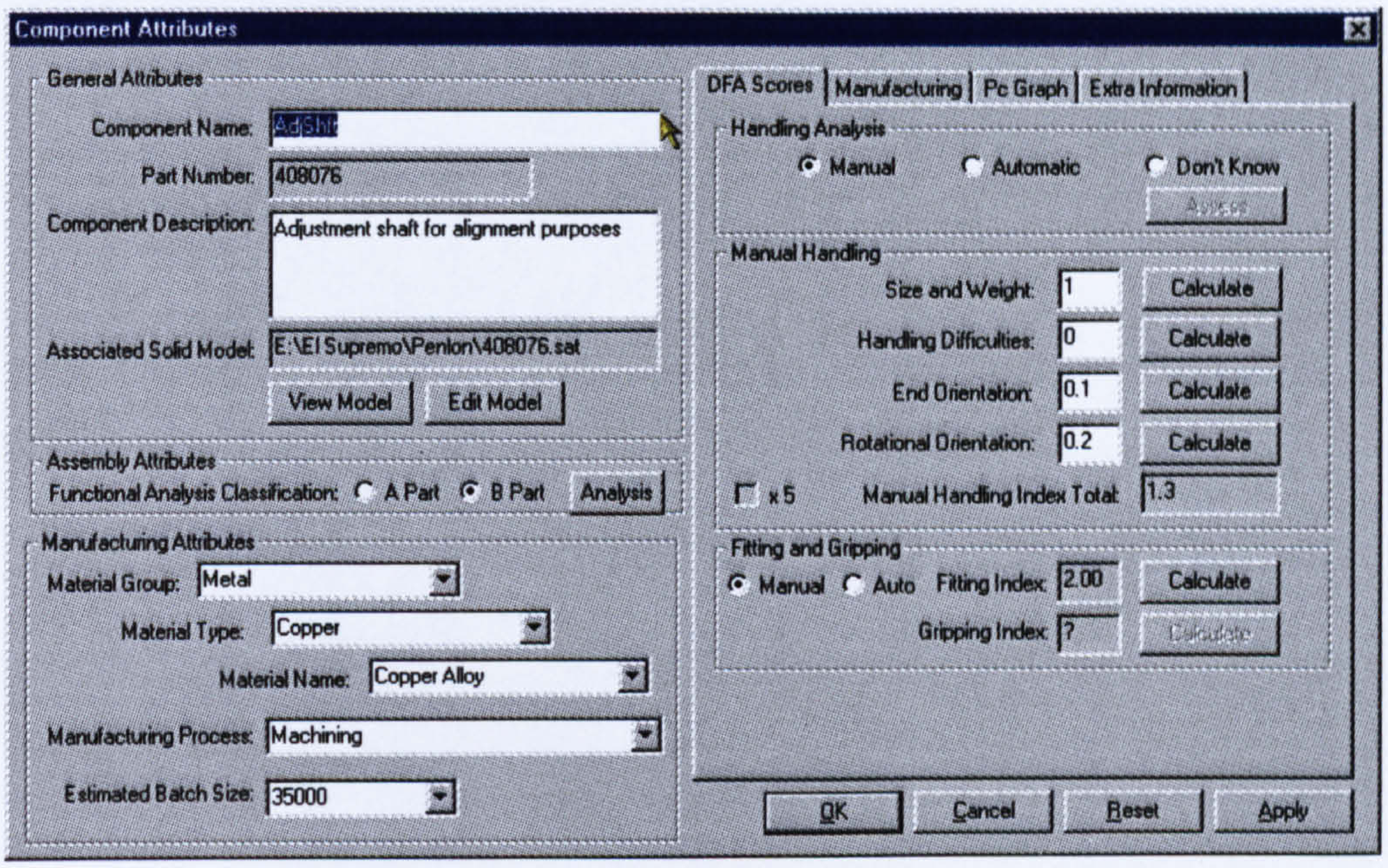
Sub Assembly Name Housing

Part Number Housing1

Upper Level Sub Assembly: Assy

Figure 10.7: ***Add Existing Subassembly Dialog Box***

Figure 10.8 shows the dialog box, which can be used to attach the attributes to all components and subassemblies. Accessing the appropriate screens through this box can be used to complete a traditional DFA analysis. However, this can also be done through the sequence screen as shown later.


Component Attributes

General Attributes
Component Name: AdjShft
Part Number: 408076
Component Description: Adjustment shaft for alignment purposes
Associated Solid Model: E:\El Supremo\Penlon\408076.sat

Assembly Attributes
Functional Analysis Classification: ○ A Part ● B Part

Manufacturing Attributes
Material Group: Metal
Material Type: Copper
Material Name: Copper Alloy
Manufacturing Process: Machining
Estimated Batch Size: 35000

DFA Scores
Handling Analysis
● Manual ○ Automatic ○ Don't Know

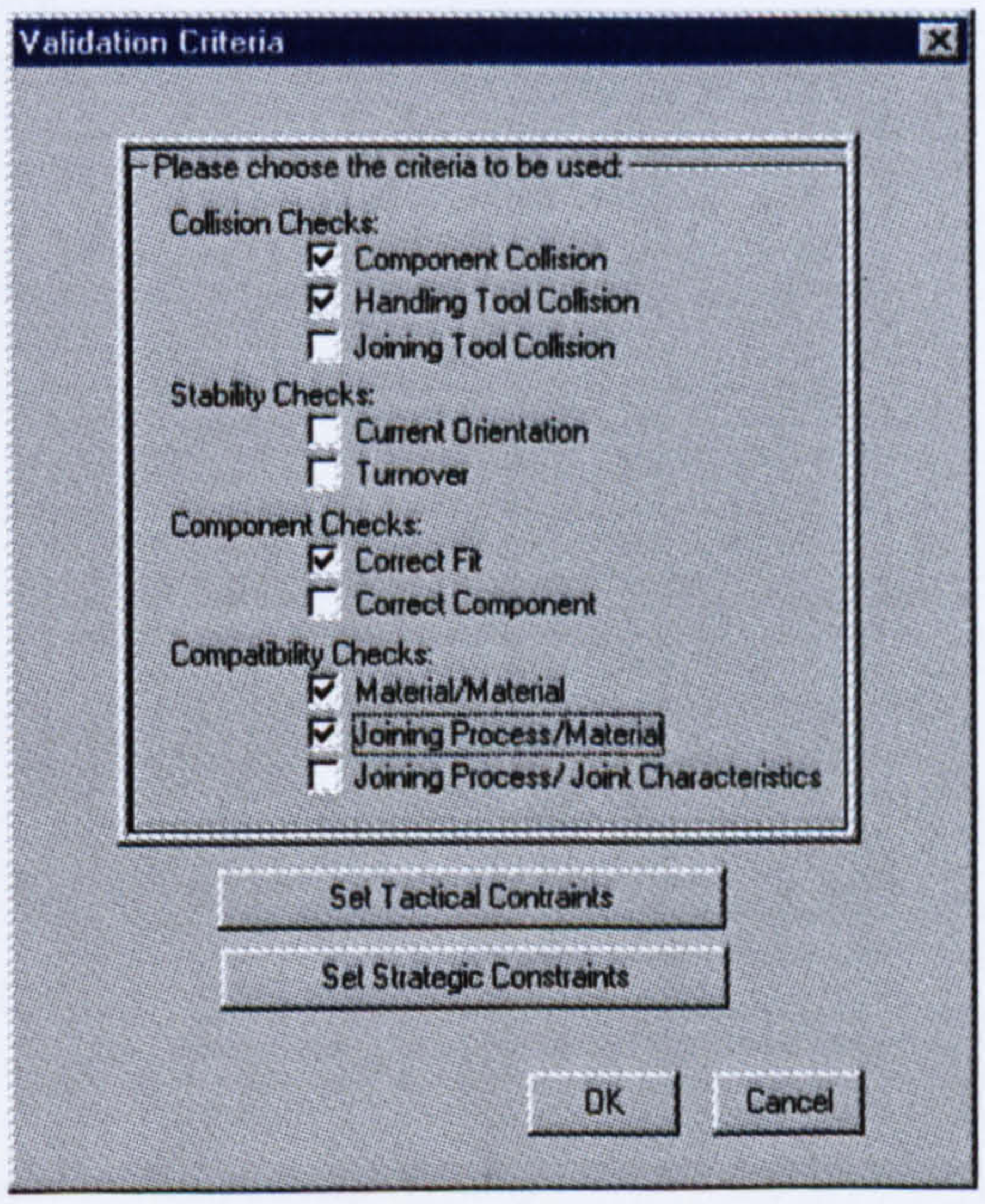
Manual Handling
Size and Weight: 1
Handling Difficulties: 0
End Orientation: 0.1
Rotational Orientation: 0.2
☐ x 5
Manual Handling Index Total: 1.3

Fitting and Gripping
● Manual ○ Auto
Fitting Index: 2.00
Gripping Index: ?

Figure 10.8: ***Dialog Box for Component Attribute Data***

10.1.2 Sequence Builder

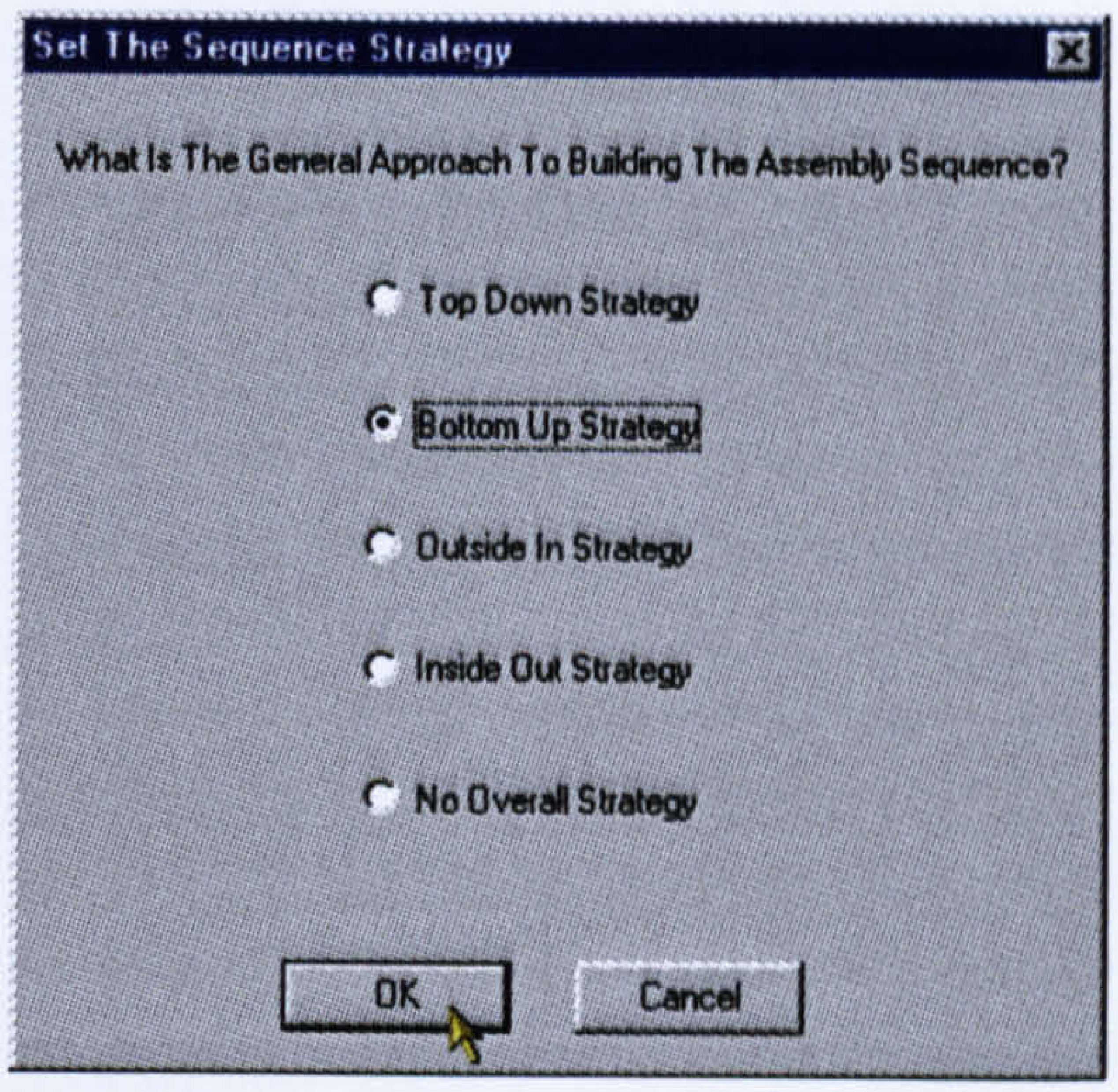
Once the process of adding components to the structure has been started, the interactive construction of the sequence can begin at any time. However, certain information must be available to **SPADE** before the sequence building can commence. Firstly, the set of strategic constraints for the sequence validation must be defined. This is completed using a dialog box as shown in Figure 10.9 and involves ticking the required options. This sets the constraints at each sequence step. A similar process can be used to override this for exceptional circumstances, which changes the tactical constraints that are only applied at the defined liaison.


Validation Criteria

Please choose the criteria to be used:
Collision Checks:
☑ Component Collision
☑ Handling Tool Collision
☐ Joining Tool Collision
Stability Checks:
☐ Current Orientation
☐ Turnover
Component Checks:
☑ Correct Fit
☐ Correct Component
Compatibility Checks:
☑ Material/Material
☑ Joining Process/Material
☐ Joining Process/ Joint Characteristics

Figure 10.9: ***Constraint Definition Dialog Box***

In addition to defining the constraint set, the sequence strategy must be defined. This is the overall build direction and assists with the reasoning process about suitable next parts. A dialog box, shown in Figure 10.10, automatically appears and the user simply clicks the required option.


Set The Sequence Strategy

What Is The General Approach To Building The Assembly Sequence?

○ Top Down Strategy
● Bottom Up Strategy
○ Outside In Strategy
○ Inside Out Strategy
○ No Overall Strategy

Figure 10.10: *Definition of The Sequence Strategy*

Once both the constraints and the sequence strategy are defined, the construction of the sequence can commence. The visual representation of assembly sequence embodies much relevant data. The temporal data is conventionally determined by the order in which the components are shown on the screen from left to right as detailed in Figure 10.11. Assembling two components has been shown to involve three distinct stages, pre processes, insertion processes and post processes. Figure 10.11 also shows the representation for this data. Boxes have been allocated to the assigned actions for these three areas, the *Pre Process Box,* the *Insertion Box,* and the *Post Process Box.* Components or subassemblies are

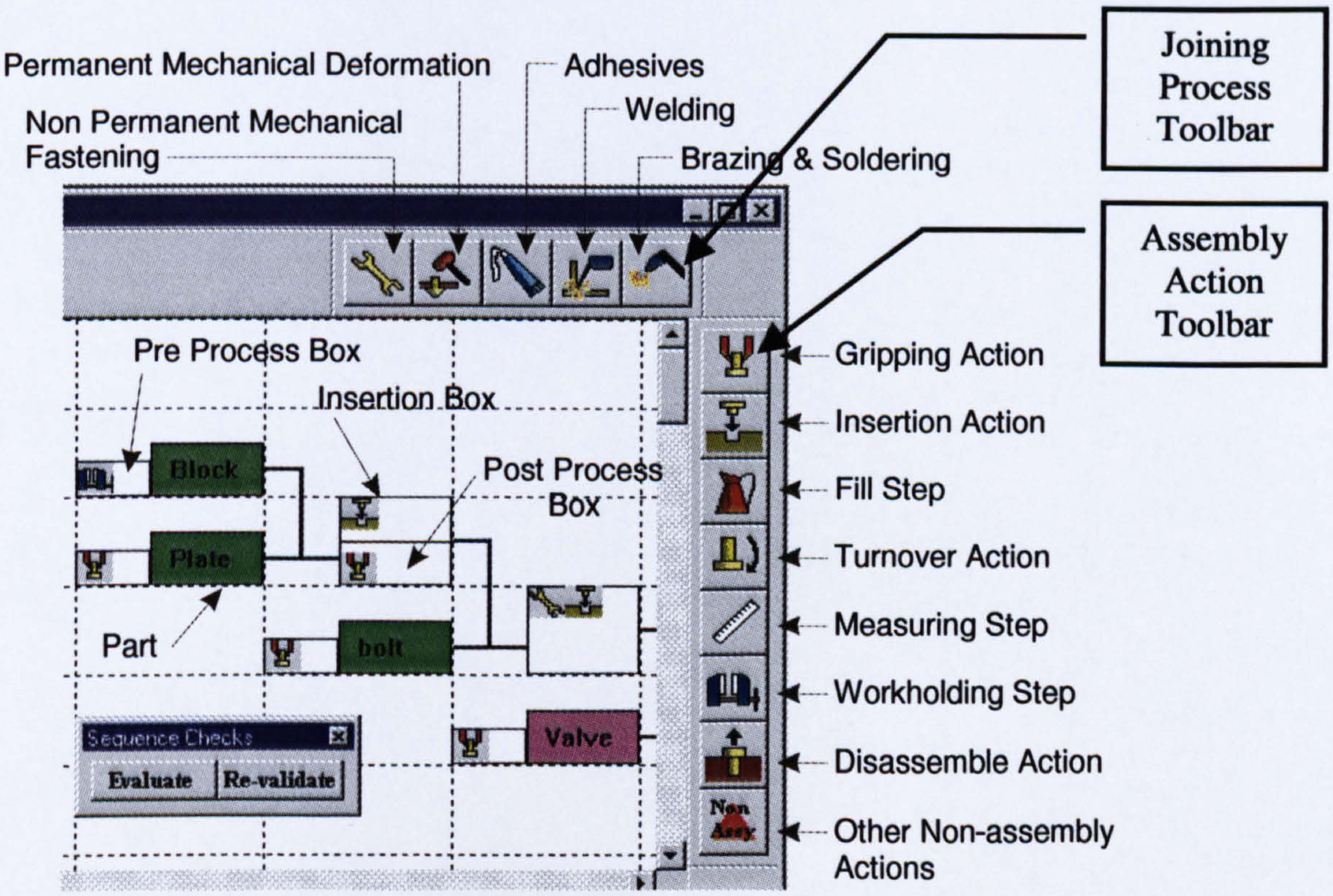
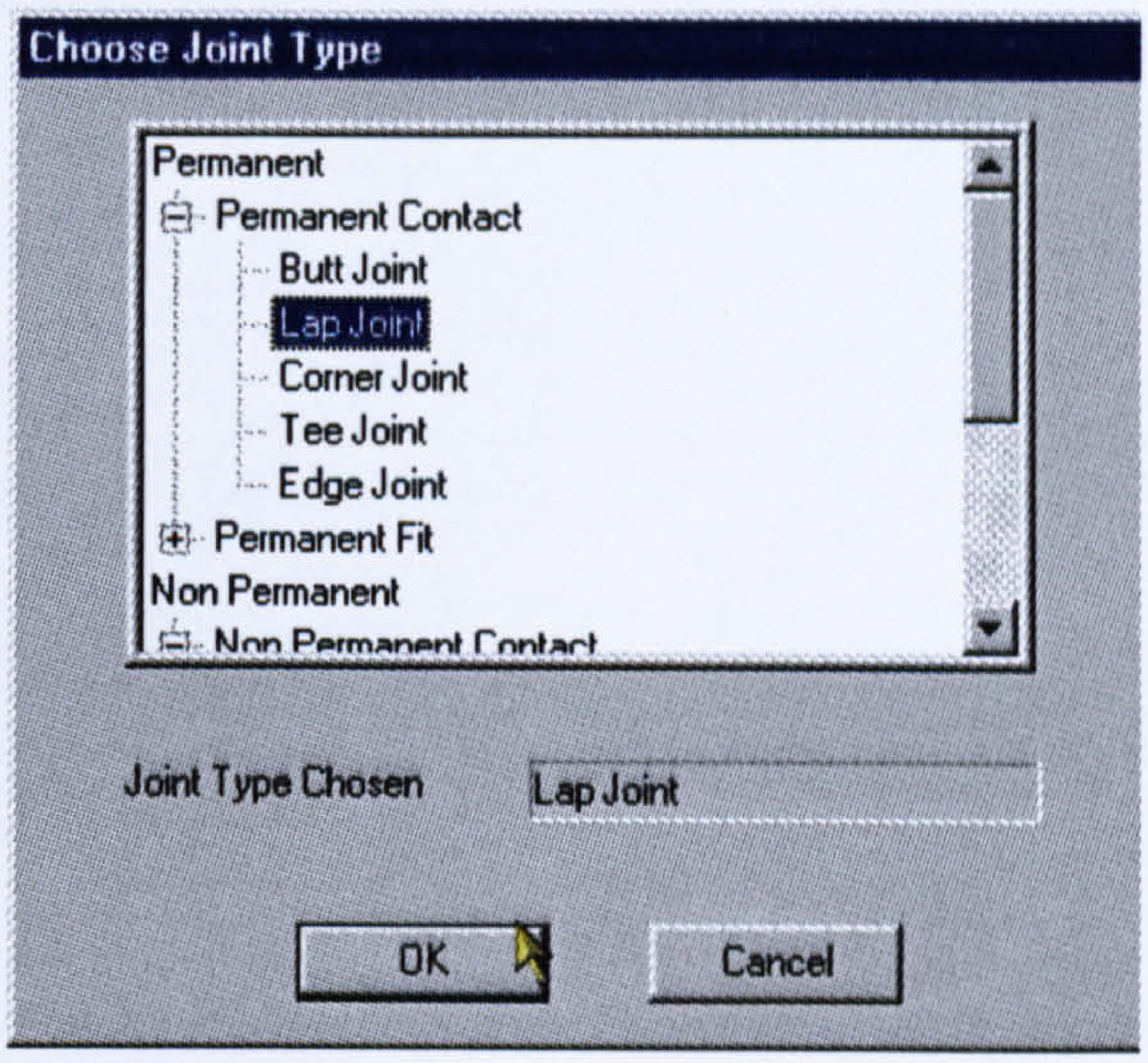


Figure 10.11: *Assembly Sequence Representation In SPADE*

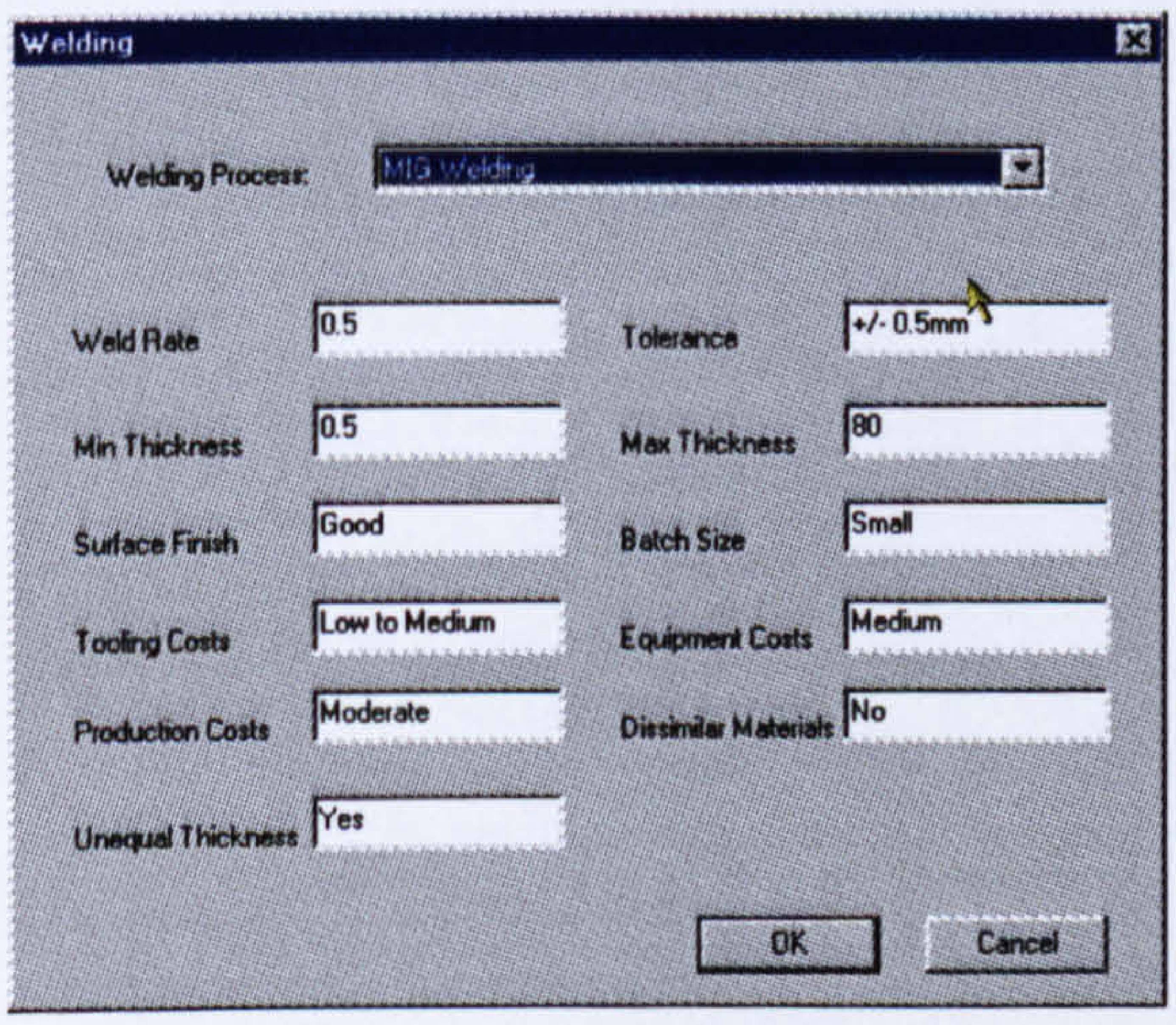
picked from the "Holding Area" and placed in the required position in the sequence. Some components may not have been defined at a particular stage so the sequence can be constructed in a non-sequential manner. It is even possible to add a component to the sequence when there are few or even no attributes or geometric model detailed. To help the user build a practical and feasible sequence, warnings are given if a particular action cannot be completed until a certain piece of data is added.



Joint Type Chosen: Lap Joint

Figure 10.12: ***Setting the Joint Type of a Liaison***

In addition to component data, there are also liaison attributes to consider. The three types of liaison data necessary were defined in Chapter 6. These are ***Mating Joint Type***, *Assembly Action* and *Joining Process*. The dialog box shown in Figure 10.12 can be used to specify the *Mating Joint Type* of the liaison. The different levels of definition can be seen in the dialog box that can be used to input the data currently available. Right mouse clicking on the Insertion Box, see Figure 10.11 enters this data. The input of this liaison attribute is not compulsory but can facilitate further validation of the assembly.



Welding Process: MIG Welding
Weld Rate: 0.5
Tolerance: +/- 0.5mm
Min Thickness: 0.5
Max Thickness: 80
Surface Finish: Good
Batch Size: Small
Tooling Costs: Low to Medium
Equipment Costs: Medium
Production Costs: Moderate
Dissimilar Materials: No
Unequal Thickness: Yes

Figure 10.13: ***Example of Joining Process Attribute Box***

Figure 10.11 also shows the toolbars that provide the facility to further define the assembly sequence in terms of relevant *Assembly Actions* and *Joining Processes*. Additional attributes can be added to these processes to provide even more detail to the sequence and increase the accuracy of any future validation and evaluation. Figure 10.13 shows the dialog box that allows further definition of overall *Joining Processes*. An integral knowledge base provides the user with detailed process data to aid decision-making.

Double clicking upon any *Assembly Action* can invoke a detailed DFA analysis of that process. This is the same analysis that can also be completed through the Component Attribute box (Figure 10.8)

The facility to save a number of candidate assembly sequences is also available. This is to enable comparisons to be made between sequences, which allows the user to explore all the options and deliver the assembly plan most suited for the circumstances involved.

10.1.3 Expert Assembler

In Chapter 7, the importance of the correct choice of base component when starting to create an assembly sequence was highlighted. The user is helped with this fundamental decision by a series of suggestions generated by the *Starting Component Advisor.* This module of the Expert Assembler is invoked before the sequence construction commences. The Advisor works in the "Holding Area" of **SPADE** as shown in Figure 10.14. Coloured borders are used to identify those parts which are unsuitable as base components, which is the most suitable contender and also which parts could be potential starting components, but are not necessarily the best choice.

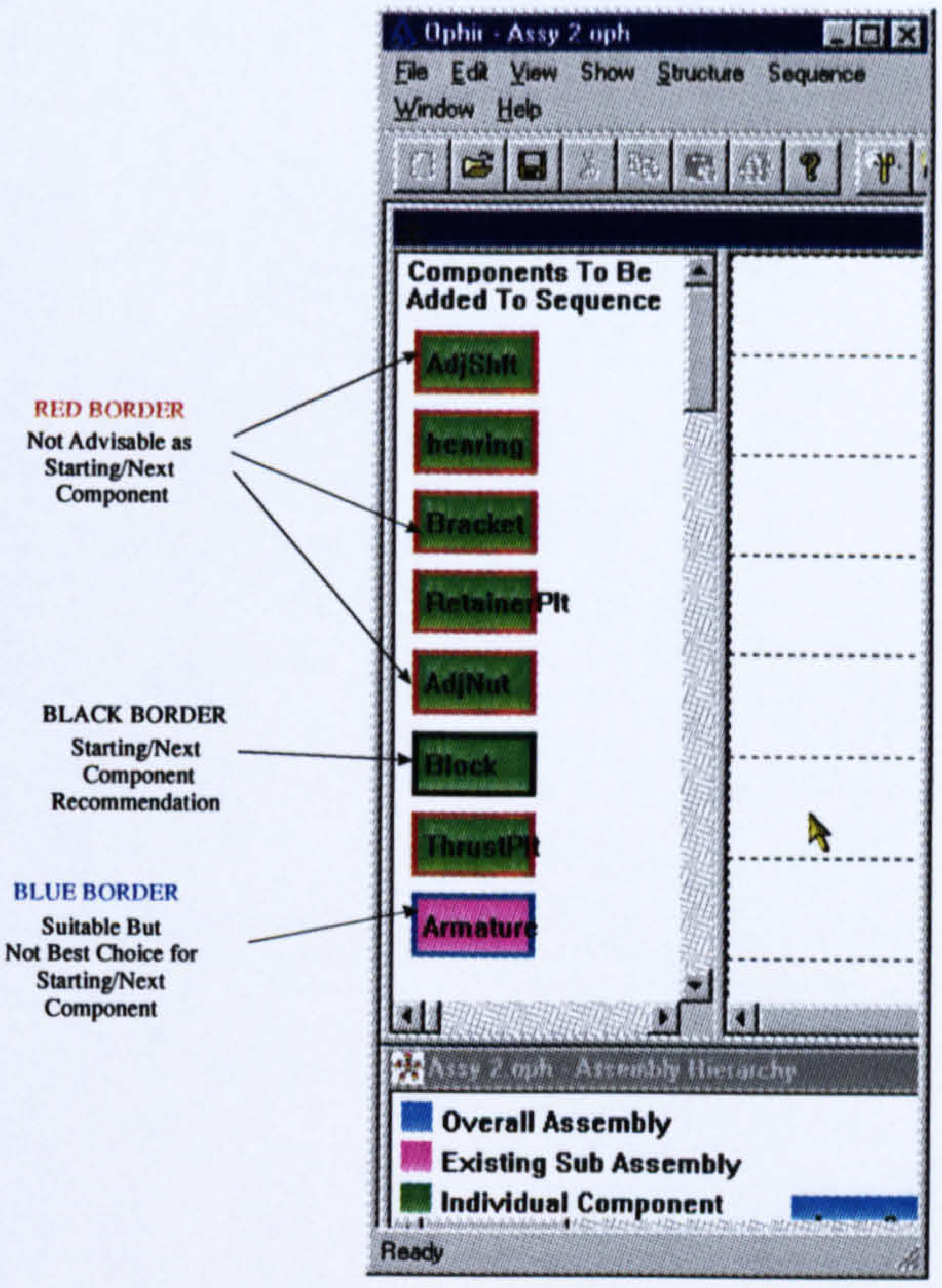
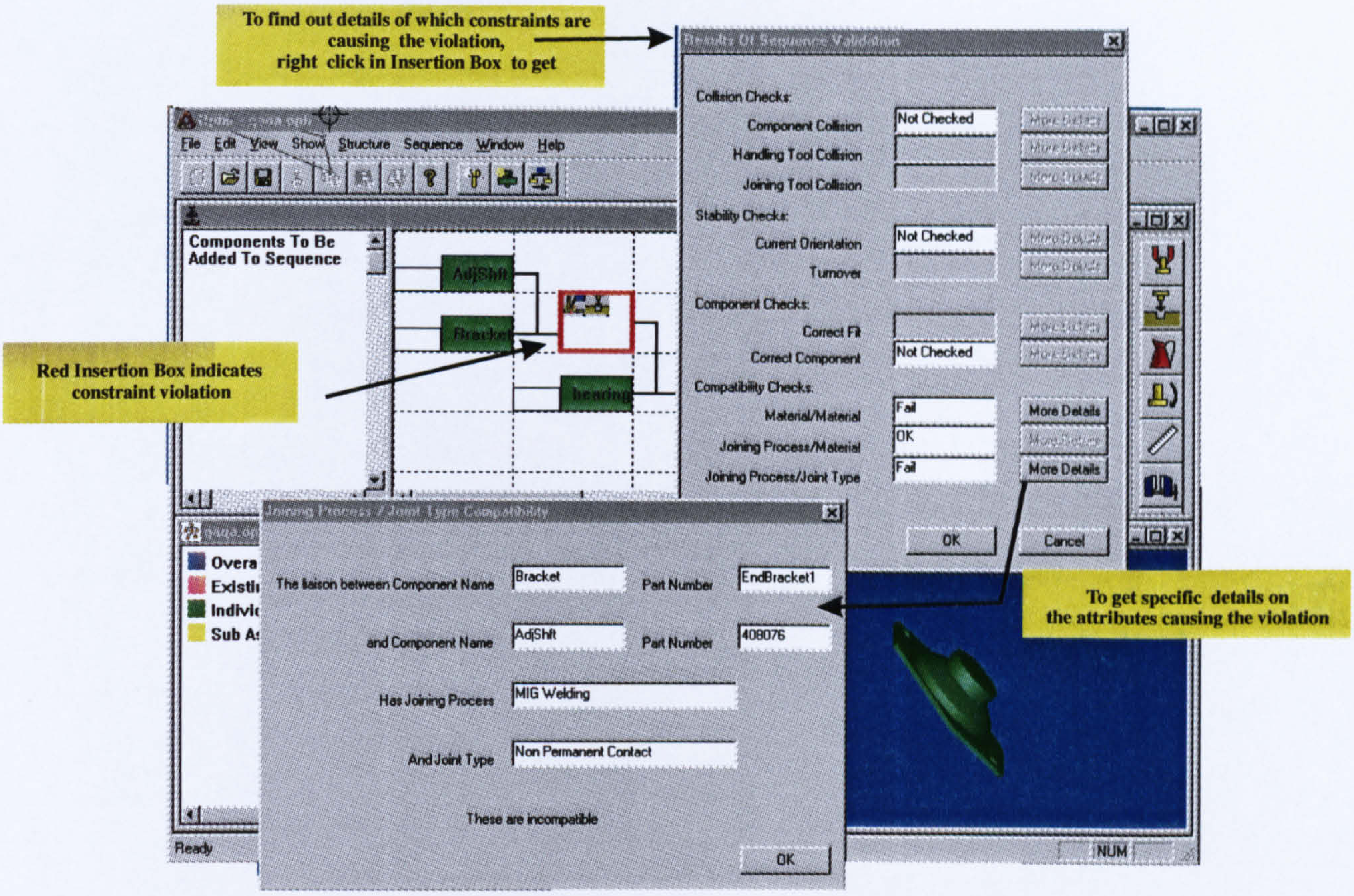


Figure 10.14: *Key For Starting/Next Component Selection*

Once the sequence generation has commenced, it is also important to choose the most suitable component to follow. Again, the user has assistance with this decision from the *Next Component Advisor.* Similar colour coding is used to represent the component status as shown in Figure 10.14. Thus, the actual advisor that has inferred the data is transparent to the user to reduce confusion and data overload. More information can be determined about the suitability status of any part via a dialog box that gives reasons behind the advice from the two advisors.

10.1.4 Validation Module

The Validation Module is automatically invoked in **SPADE** every time a component is added to the assembly sequence. Re-validation can also be requested when changes are made at any time during the sequence generation. The system uses a constraint approach for validation as described in Chapter 8. The constraints set is defined before the sequence construction but can be amended at any time. The user is visually alerted of constraint violations as they occur by a red box around the component or liaison that has created the problem, as shown in Figure 10.15. This enables the correction of any mistakes as the design progresses. More information about a particular violation can be requested to facilitate the resolution of the issue and to assist with any future design decisions, this is also shown in Figure 10.15. The validation algorithms are always invoked when a part is added to the sequence. However, if little data is available some analyses may be incomplete. The dialog box shown in Figure 10.15 keeps the user updated with which validation constraints have not been fully checked. It is evident that as more attributes and geometry become available, the more accurate the results from **SPADE** will become.



To find out details of which constraints are causing the violation, right click in Insertion Box to get

Red Insertion Box indicates constraint violation

To get specific details on the attributes causing the violation

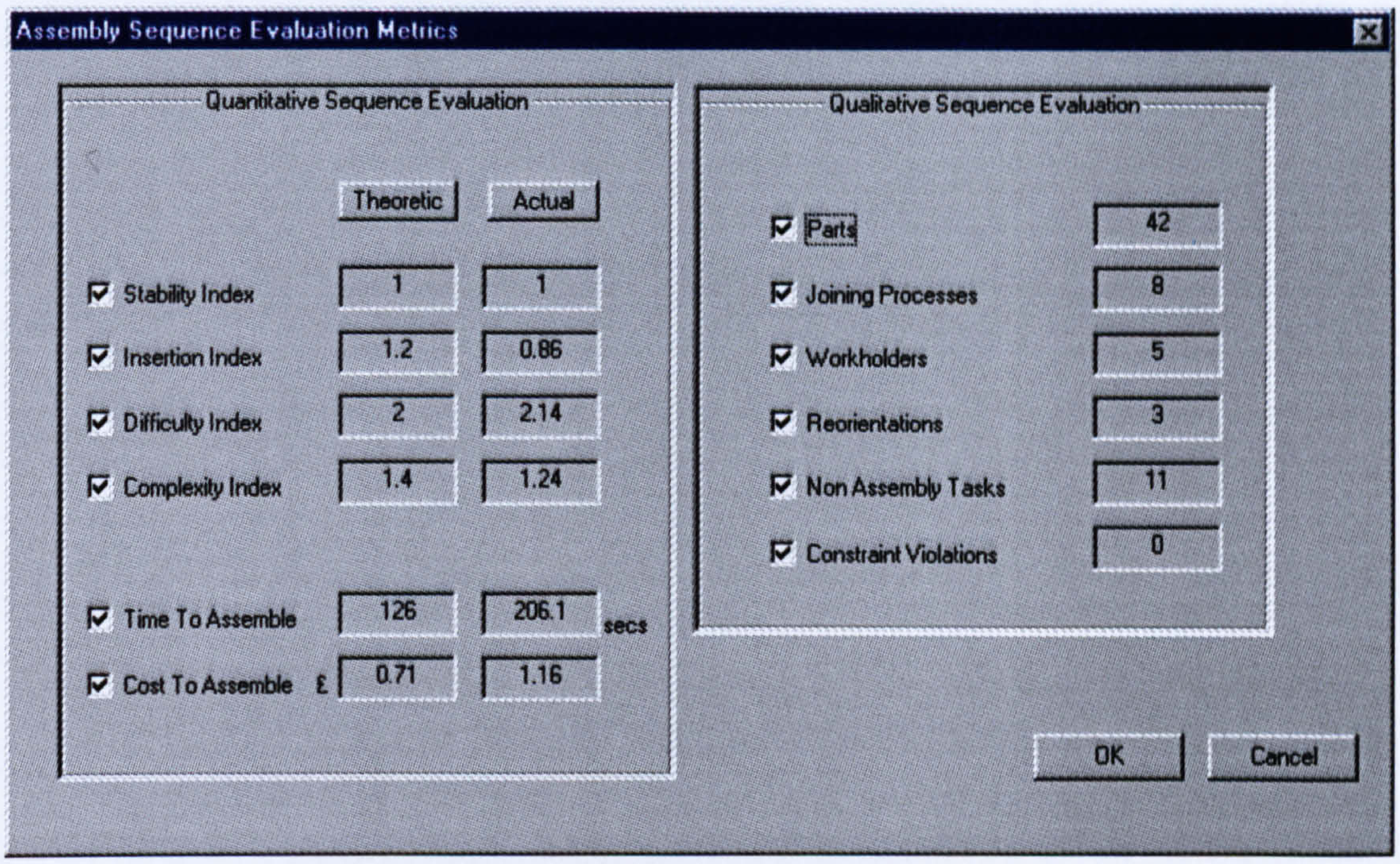
Collision Checks:
Component Collision: Not Checked
Handling Tool Collision:
Joining Tool Collision:
Stability Checks:
Current Orientation: Not Checked
Turnover:
Component Checks:
Correct Fit:
Correct Component: Not Checked
Compatibility Checks:
Material/Material: Fail
Joining Process/Material: OK
Joining Process/Joint Type: Fail

The liaison between Component Name: Bracket Part Number: EndBracket1
and Component Name: AdjShft Part Number: 408076
Has Joining Process: MIG Welding
And Joint Type: Non Permanent Contact
These are incompatible

Figure 10.15: *Validation Of A Liaison*

10.1.5 Evaluation Module

It was proposed in Chapter 9 that evaluation is necessary for the assessment of the assembly sequences and the overall design. The results of this evaluation can then be used to select the most appropriate design and sequence or to measure improvements of incremental redesigns and sequence generation. As with the validation functionality, the Evaluation Module can be used at any time during the design process and sequence generation to provide interactive feedback on the progress of the sequence generation. Figure 10.16 shows the dialog box that provides the user with the evaluation data. To speed up the analysis, only those calculations requested by the user are performed. It can be seen that the four evaluation indices that were proposed in Chapter 9 are included along with time, cost, and a selection of qualitative data. During the early stages of the design, the accuracy of the evaluation results is dependent upon the data available, as with all the processes within **SPADE**. No warnings are given about the data integrity, the user must be aware that the calculations can only be completed with available data. However, as seen in Chapter 9, most of the evaluation measures can provide useful information at the early stages of design with correct interpretation.



Assembly Sequence Evaluation Metrics

Quantitative Sequence Evaluation

	Theoretic	Actual	
☑ Stability Index	1	1	
☑ Insertion Index	1.2	0.86	
☑ Difficulty Index	2	2.14	
☑ Complexity Index	1.4	1.24	
☑ Time To Assemble	126	206.1	secs
☑ Cost To Assemble £	0.71	1.16	

Qualitative Sequence Evaluation

☑ Parts	42
☑ Joining Processes	8
☑ Workholders	5
☑ Reorientations	3
☑ Non Assembly Tasks	11
☑ Constraint Violations	0

Figure 10.16: ***Evaluation Of The Assembly Sequence***

10.2 Concluding Remarks

This chapter has outlined the **SPADE** system, the computer-based implementation of the Two-Tier methodology for concurrent generation of designs and sequences as described in the previous chapters. The representation of the assembly structure, assembly sequence and the product geometry has been described and also how data is input and interrogated. To further appreciate and understand **SPADE** the reader is referred to the next chapter where three case studies are developed and analysed using this system.

11. CASE STUDY RESULTS

The preceding chapters have presented a Two-Tier methodology for the concurrent development of the design and assembly sequence and its computer-based implementation, **SPADE**. This new approach contains novel methods and calculations that must be shown to work for industrially relevant products. The aim of this chapter is to illustrate the use of this methodology and to show that it can be successfully applied to a set of case studies. Three different products taken from industry are used to demonstrate the use of the approach. Also illustrated are the methods used to construct the assembly sequence and identify assemblability problems. However, it is impractical to demonstrate the use of **SPADE** during the creation of a product from first principles. Outside of an industrial design situation, it is almost impossible to replicate the processes involved and ensure the result is a viable product. Thus, the examples will demonstrate the methodology encapsulated within **SPADE** using a combination of components with no geometry and with completely defined geometry. It is believed that this is a satisfactory approach to establish validity, as the proposed methodology has not attempted to redefine the creative processes involved in design.

Three industrial products will form the basis of case studies that will demonstrate the use of the methodology. The overall aim of this chapter is to develop and analyse these three examples within the **SPADE** environment. This is in order to prove that the Two-Tier methodology offers a practical way to concurrently consider the generation of the design and the assembly sequence. Each case study will illustrate a different aspect of the methodology and **SPADE.** The examples will be developed using the actual implementation of **SPADE** and screenshots of salient stages will be included to aid the readers understanding of the system operation. The three case studies and their individual objectives are briefly described below:

Case Study 1 - Flanged Valve

This is a basic assembly consisting of 7 parts. It is suitable for illustrating the process of concurrently developing the design and the assembly plan because of the simplicity of the product.

Case Study 2 - Valve Block

This example is a more complex 29 part subassembly which forms the top half of an anaesthetic vaporiser. This is a real product currently in production, but it has some inherent assemblability issues. The development of the assembly design will be employed to demonstrate how these problems could have been highlighted and resolved before reaching manufacture if the Two-Tier methodology had been used during the design stages.

Case Study 3 - Discriminator

This assembly of 42 parts is an example taken from the web pages of the ARCHIMEDES Project[95]. A documented 'optimal' assembly sequence is available which the ARCHIMEDES software has generated. This case study will show that using the Two-Tier methodology enables assembly plans to be found which are comparable to or better than the "expert" constructed plans in terms of the defined evaluation metrics.

11.1 Case Study 1 - Flanged Valve

This case study uses a standard pipework flanged valve and aims to demonstrate the use of the methodology and **SPADE**. The model of this assembly is shown below in Figure 11.1. It comprises 7 components and will be manually assembled at an appropriate assembly workstation. It is assumed that the designer has completed a concept design outline. The necessary components and their geometric features now need to be identified and thus **SPADE** can be invoked. At this stage in the process the designer is aware that certain components are needed so these can be immediately added to **SPADE**.

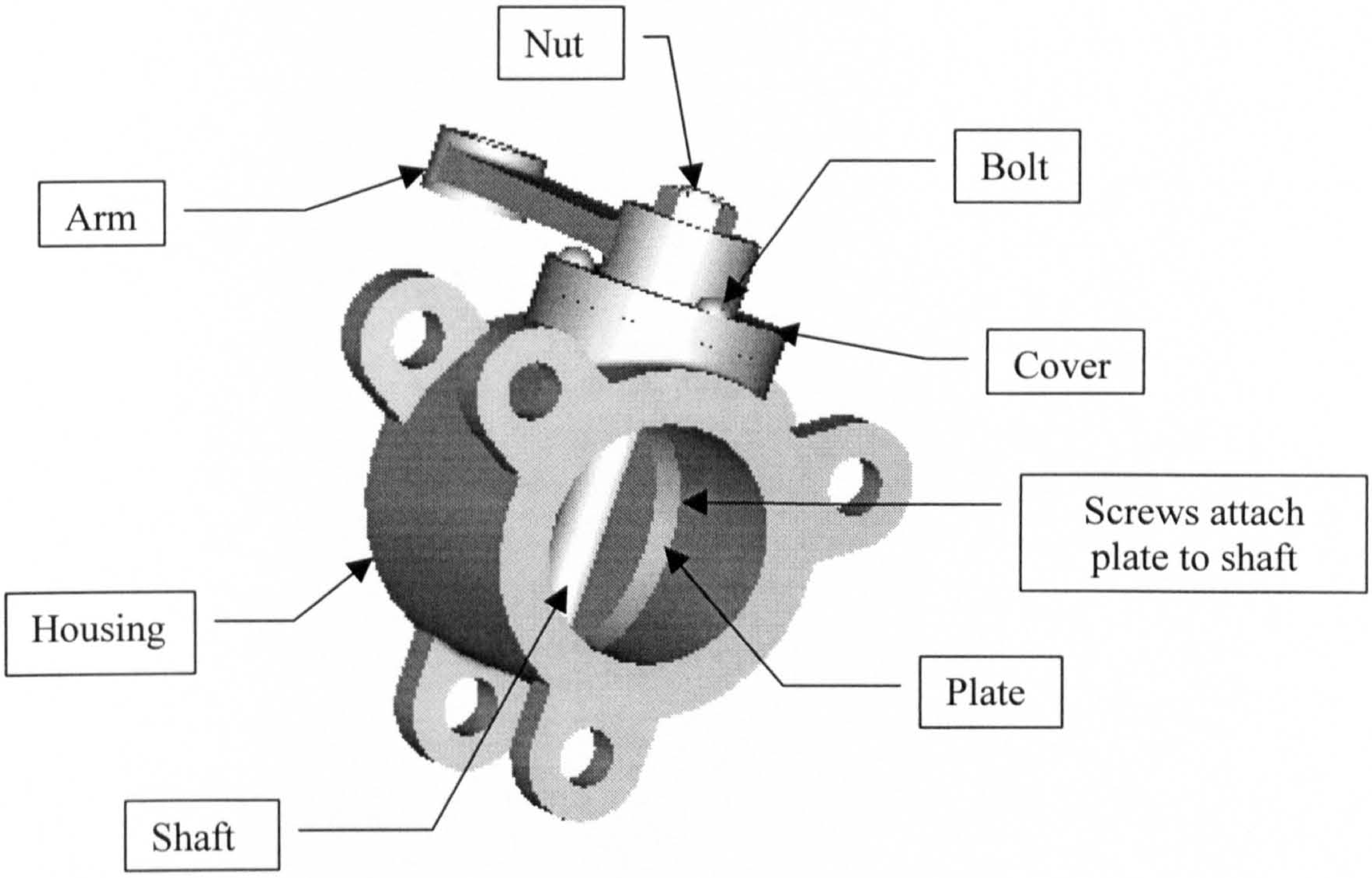
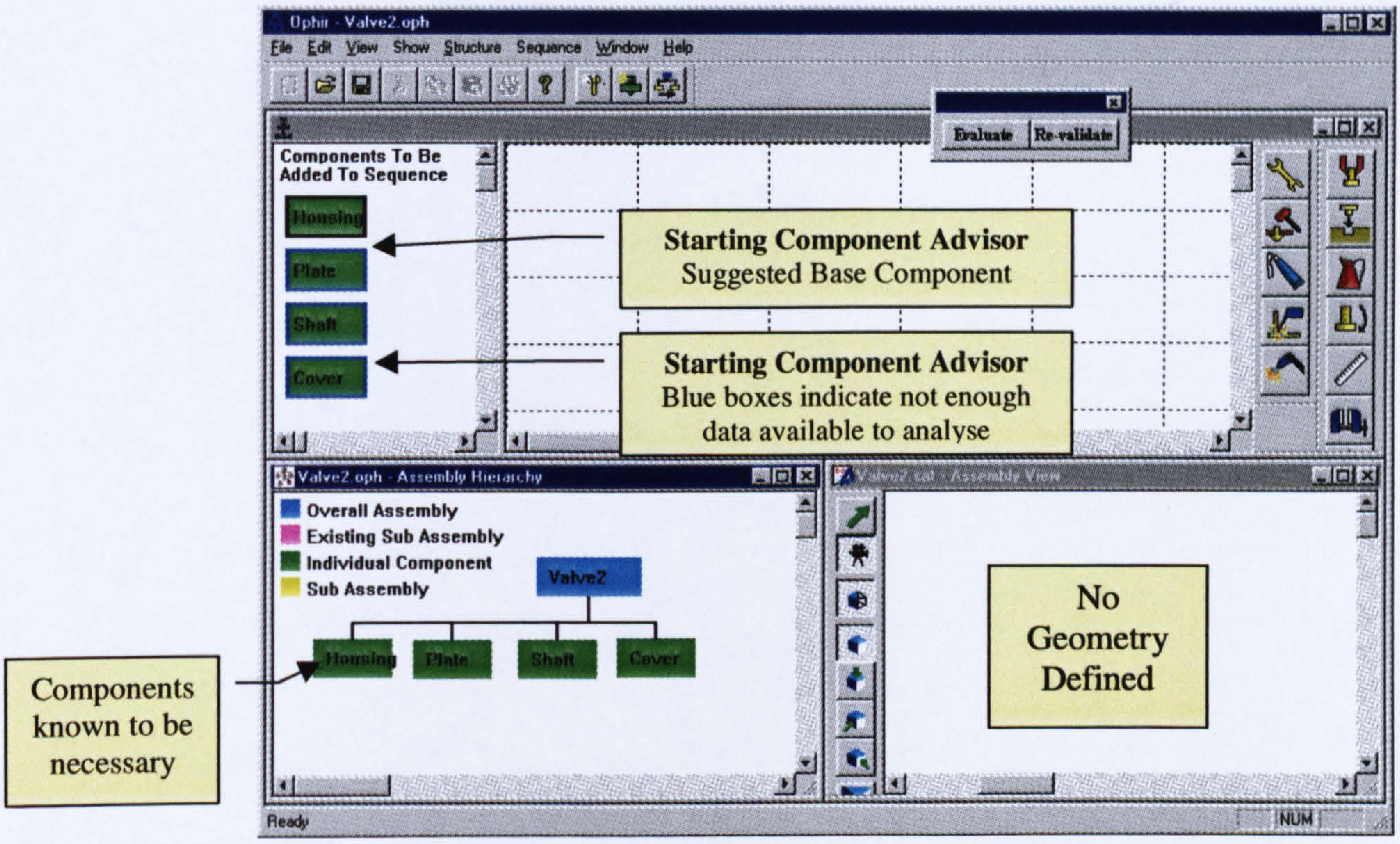


Figure 11.1: ***Flanged Valve***

If it is assumed that the model does not exist, it is apparent that some form of valve housing and a plate attached to a shaft will be required to perform the necessary functions. In addition, the assembly will also almost certainly require a cover to locate the shaft. This data can be entered into the system and the resultant **SPADE** screen shot functions. In addition, the assembly will also almost certainly require a cover to locate the shaft. This data can be entered into the system and the resultant **SPADE** screen shot is shown in Figure 11.2. The required pipework bore for the valve design has been defined in the specification so some approximate overall dimensions and material can be entered for the housing. This information indicates that the housing is probably the largest and the heaviest of all the currently defined components. Thus, this part is recommended as the most suitable choice by the *Starting Component Advisor* for the base component of the assembly sequence, see the representation shown in Figure 11.2. The presence of a blue box around the other components indicates that any suggestions are vulnerable to change because not enough data has been input to complete an analysis. Thus, any advice offered should be cautiously received at this stage. It is interesting to note that no specific geometry has been entered into **SPADE** and already tentative assembly sequence details are emerging.



Starting Component Advisor
Suggested Base Component

Starting Component Advisor
Blue boxes indicate not enough data available to analyse

Components known to be necessary

No Geometry Defined

Figure 11.2: ***Step 1 Of Designing the Flanged Valve and its Assembly Sequence in SPADE***

The sequence construction could commence at this point in the analysis. However little data has been entered into **SPADE** to allow any useful corroborating validation or evaluation checks to be completed. Thus, any available information should be input when known. Some component attributes are apparent very early in the design process. Material, batch size and manufacturing process are all pieces of data that may be decided and entered at this stage, although any type of product data can be added at the time of determination.

One advantage of the Two-Tier methodology embedded within **SPADE** is that the subsequent step is totally left to the discretion of the designer at all times. The options for the next stage include:

1. Enter the *Sequence-Builder* to commence/recommence the assembly plan construction.
2. Using conventional CAD functionality to detail geometry for one or more of the currently defined components.
3. Input some non-geometric attributes for one or more of the available components.
4. Enter the *Structure-Builder* to make changes to the assembly hierarchy.
5. Add one or more additional components or subassemblies.

Quantitative analysis of the design and sequence can be completed in addition to these construction type options given above. For the purposes of this example, it is assumed that the designer has decided to follow option 2 and create some solid models for each of the inputted components. Once this has been completed, the assembly sequence can be built. Before this task starts, the user is prompted by **SPADE** to choose the applicable constraints and the assembly strategy. It is decided to apply all the hard and soft constraints to the sequence and the assembly strategy was defined as inside out. The sequence generation can now commence. The housing remains the *Starting Component Advisor's* suggestion for the most suitable base part after the full geometric definition of each component. Thus it was added first to the *Sequence-Builder,* as shown in the partial screenshot in Figure 11.3. When the geometry of this housing is analysed, it is found to require a workholder, which is represented in Figure 11.3.

As shown in Chapter 10, the *Next Component Advisor* within **SPADE** also makes use of these coloured boxes to indicate part suitability. Figure 11.3 illustrates this advisor in action. It shows that the Shaft and Cover are indicated as appropriate choices for adding to the sequence next. For some reason it is has advised against the addition of the Plate. On interrogation, it is found that this is because the plate does not mate with any parts already in the sequence, resulting in an unstable assembly if the Plate was assembled at this point.

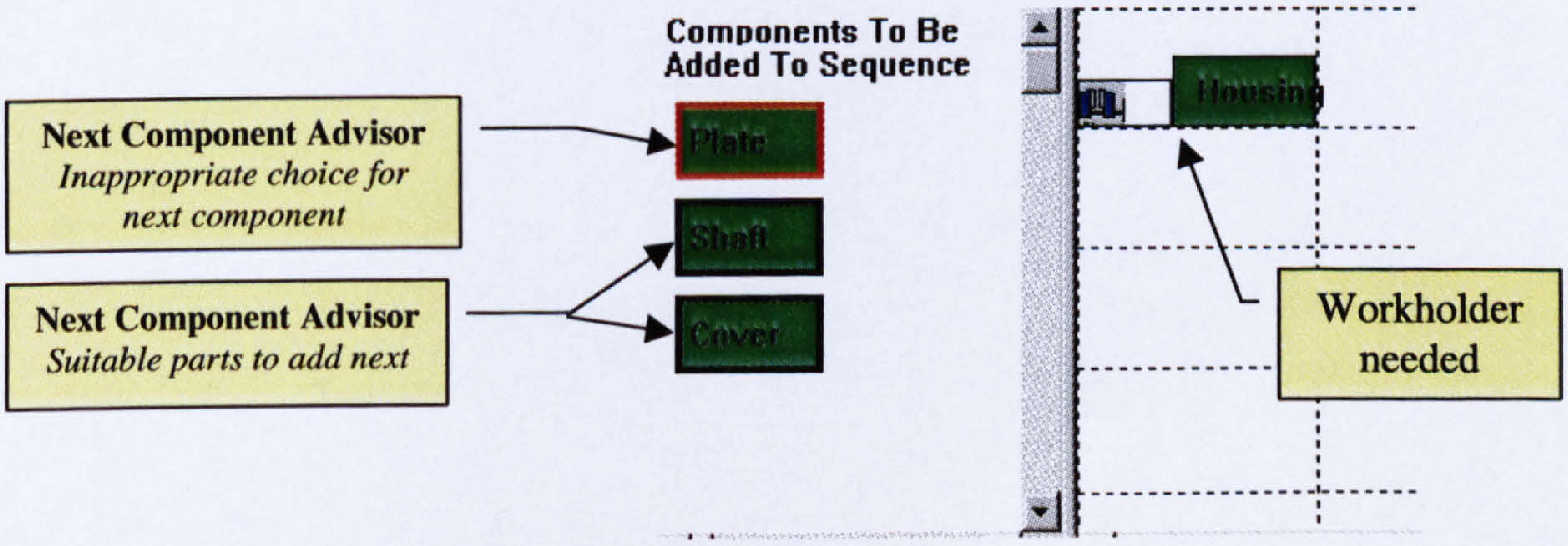
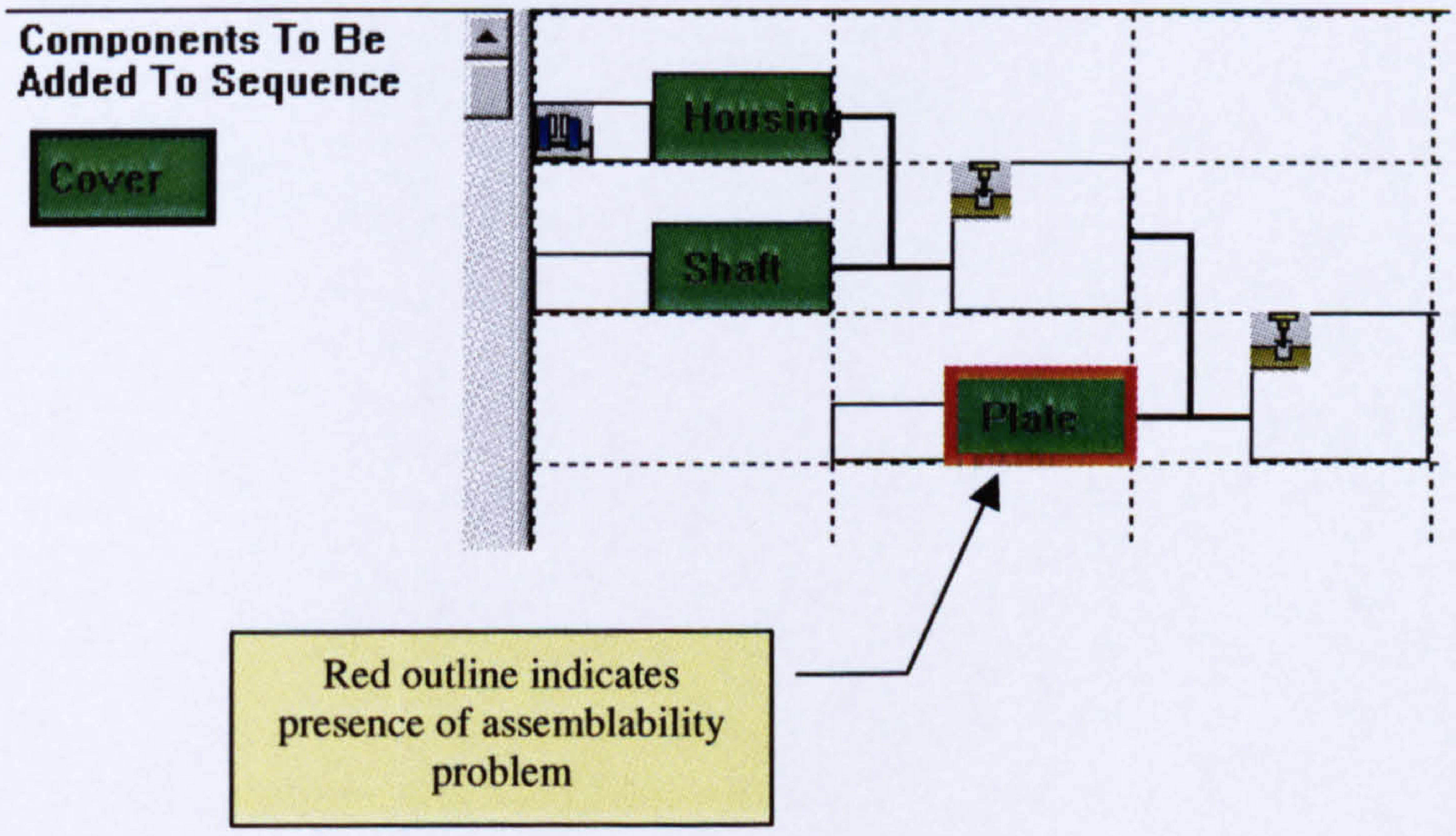


Figure 11.3: ***Base Part Added To Assembly Sequence***

A current limitation of **SPADE** is the inability to define the component precedence for use in the *Next Component Advisor*. If this data was available it would be found that the shaft must be inserted before the cover. As it is the designer is not explicitly informed of this fact, the system currently relies upon the engineering expertise of the user to identify the issue. If however, a sequence was developed which had the cover added before the shaft, the *Component Collision* constraint would be violated and an assemblability problem would be identified.

Now that the Shaft and the Plate have been added to the assembly sequence as shown in Figure 11.4, the designer may decide that it is time to do an analysis that may identify any current assembly issues. This is where the earlier application of the traditional DFA techniques can offer some constructive advice. When the insertion of the Plate on to the Shaft is analysed, it is found to be problematic as indicated by a red outline around the Plate in Figure 11.4. Because of the position of the Shaft in the Housing, it is difficult to get sufficient access for the Plate insertion. There is also a stability problem because there is no fixed attachment between the Plate and the Shaft before the addition of the securing screws. The designer is now aware of these potential problems and, because the analysis was completed early in design process, is still in a position to make any necessary changes to the design. The Two-Tier methodology cannot force the designer to make assemblability improvements. No computer-based system can yet take account of all the variables that constrain designers so to make amendments mandatory may be counterproductive. Rather **SPADE** serves to provide tools and techniques that can facilitate the identification of assemblability issues early enough in the design process to make alterations possible at minimum cost.

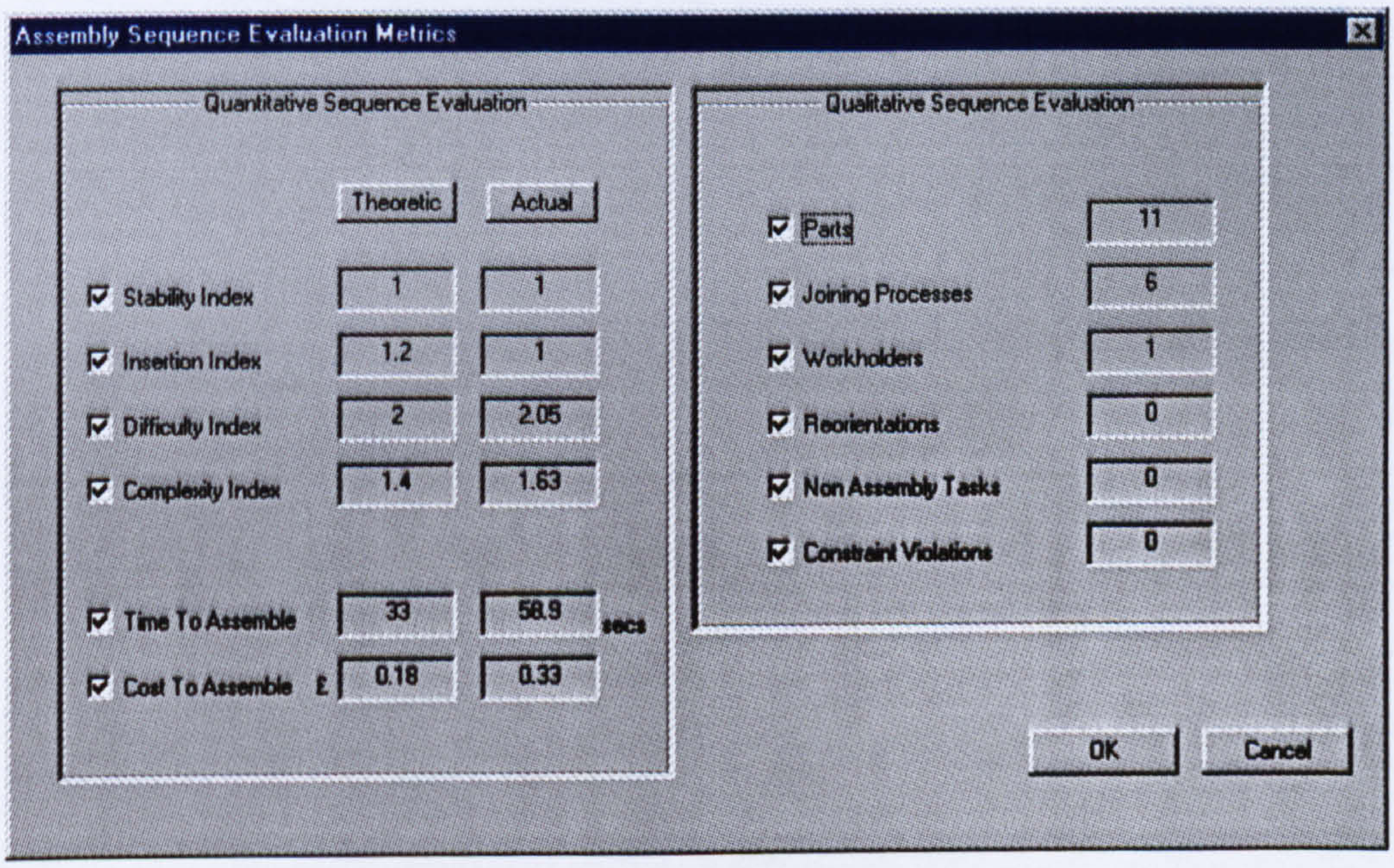


Red outline indicates presence of assemblability problem

Figure 11.4: ***Identification of an Assemblability Problem with the Plate***

At this stage in the development process, other attributes can be attached to the liaisons such as joint type, joining process and other assembly operations. The more information that has been inputted into the system, the more accurate the analyses and suggestions become. This does not reduce the value of the advice given early in the process, it just means that the designer needs to be aware of the changing nature of the design. It is true that if no geometry had been available for analysis, the above issue would probably not have been identified until the relevant components had been modelled.

This iterative procedure detailed in the preceding paragraphs should be followed until the design and assembly sequence are completed. At this stage, the designer may decide to evaluate the design and the sequence. It would perhaps have been more useful had the designer considered the value of the evaluation metric results throughout the design process as this would have highlighted areas for concern as the design progressed. Nevertheless, it is still a useful exercise to look at the scores at this stage. There is still time to make changes if necessary. Figure 11.5 shows the evaluation results from **SPADE** for this assembly, which shows that overall, the design of the valve is good. The Stability Index and the Insertion Index are found to be close to the optimal values. The Difficulty Index is only marginally above the threshold, but the assemblability problems associated with the Plate mean that the Complexity Index is quite high. Thus, the design will cost almost twice as much to assemble as an optimum design. These figures mean that the designer may have to provide justification for this potentially unnecessary cost to management and may have to revisit the design to improve the Plate to Shaft liaison.



Assembly Sequence Evaluation Metrics

Quantitative Sequence Evaluation

	Theoretic	Actual	
☑ Stability Index	1	1	
☑ Insertion Index	1.2	1	
☑ Difficulty Index	2	2.05	
☑ Complexity Index	1.4	1.63	
☑ Time To Assemble	33	58.9	secs
☑ Cost To Assemble £	0.18	0.33	

Qualitative Sequence Evaluation

☑ Parts	11
☑ Joining Processes	6
☑ Workholders	1
☑ Reorientations	0
☑ Non Assembly Tasks	0
☑ Constraint Violations	0

Figure 11.5: ***Evaluation Results For the Flanged Valve***

11.2 Case Study 2 - Vaporisor Valve Block

The second case study involves the analysis of a Valve Block, which is a large subassembly of a vaporiser. A vaporiser mixes anaesthesia gases for operating theatre usage. Figure 11.6 shows the Valve Block in its final position in the overall product.

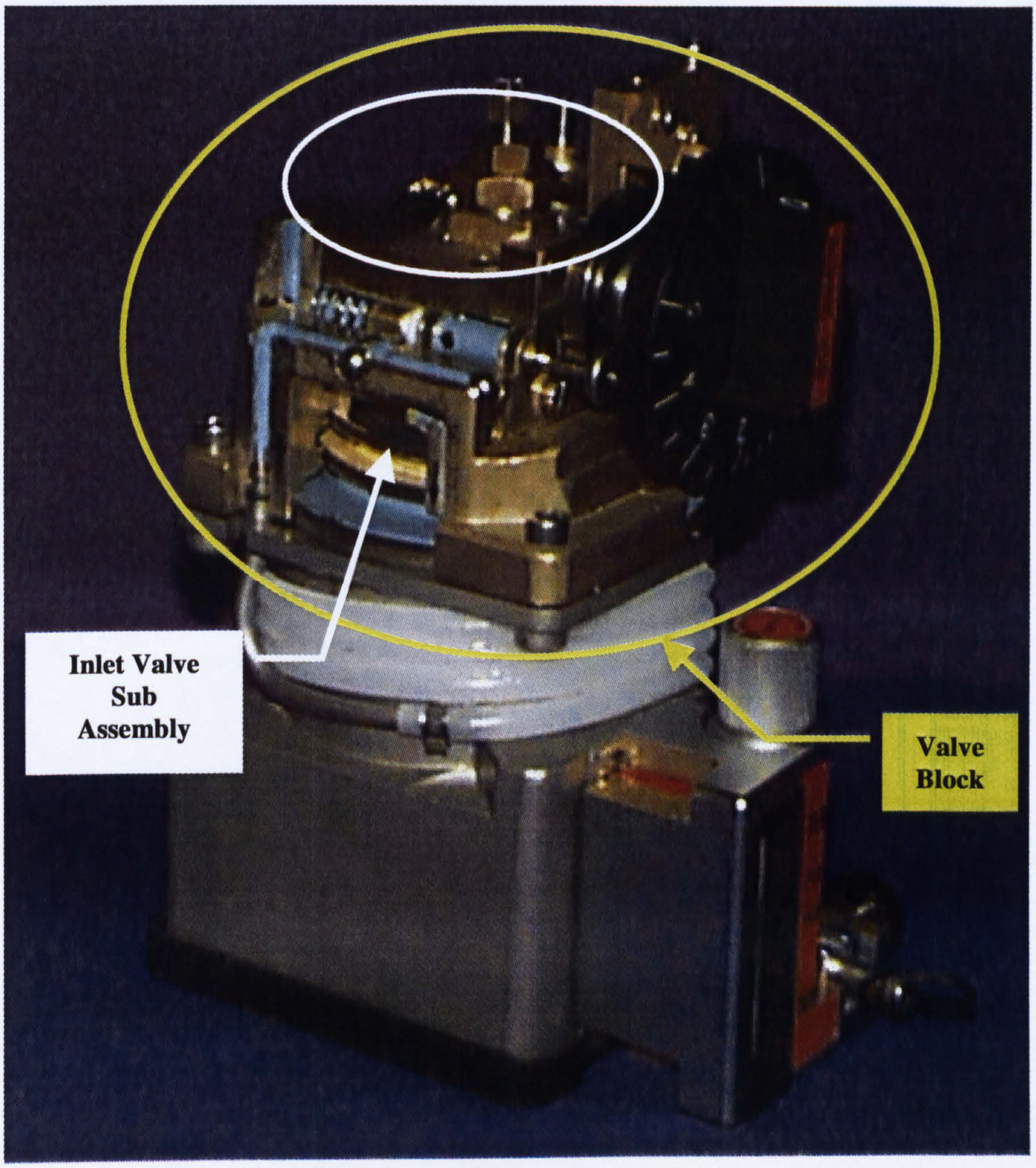


Figure 11.6: ***Valve Block of Vaporiser Showing Inlet Valve Subassembly***

Also identified in the figure is the Inlet Assembly that will be seen to have some assemblability problems identified by **SPADE**. Because the vaporiser is a product currently in production, the case study will reconstruct a plausible design and analysis scenario that aims to highlight the assemblability issues. The Valve Block consists of 29 parts and is to be designed appropriately for manual assembly along a suitable assembly line. Because Case Study 1 was developed to show the process of using **SPADE**, the design creation and planning generation approach will not be followed as closely in this example. Instead, this example will focus on the identification of assemblability issues and the iterative nature of the methodology.

The Inlet Valve Subassembly, modelled in Figure 11.7, is an important part of this product. Thus, it was decided to start the design of the Valve Block with this set of parts. The functional requirements of this subassembly have dictated that an end seal, a shaft and a spool are required to regulate the gas flow. These parts and their material requirements, as defined in the specification, were entered into **SPADE**. The gas flow rate and working pressure are also given in the specification so some geometry can be detailed immediately. Additionally it is clear that the Valve Block requires a housing and so this is added to **SPADE**. The status of the system is shown in the screen shot, Figure 11.8. Other areas of the valve block assembly can now be considered once this subassembly has been defined to the current satisfaction of the designer.

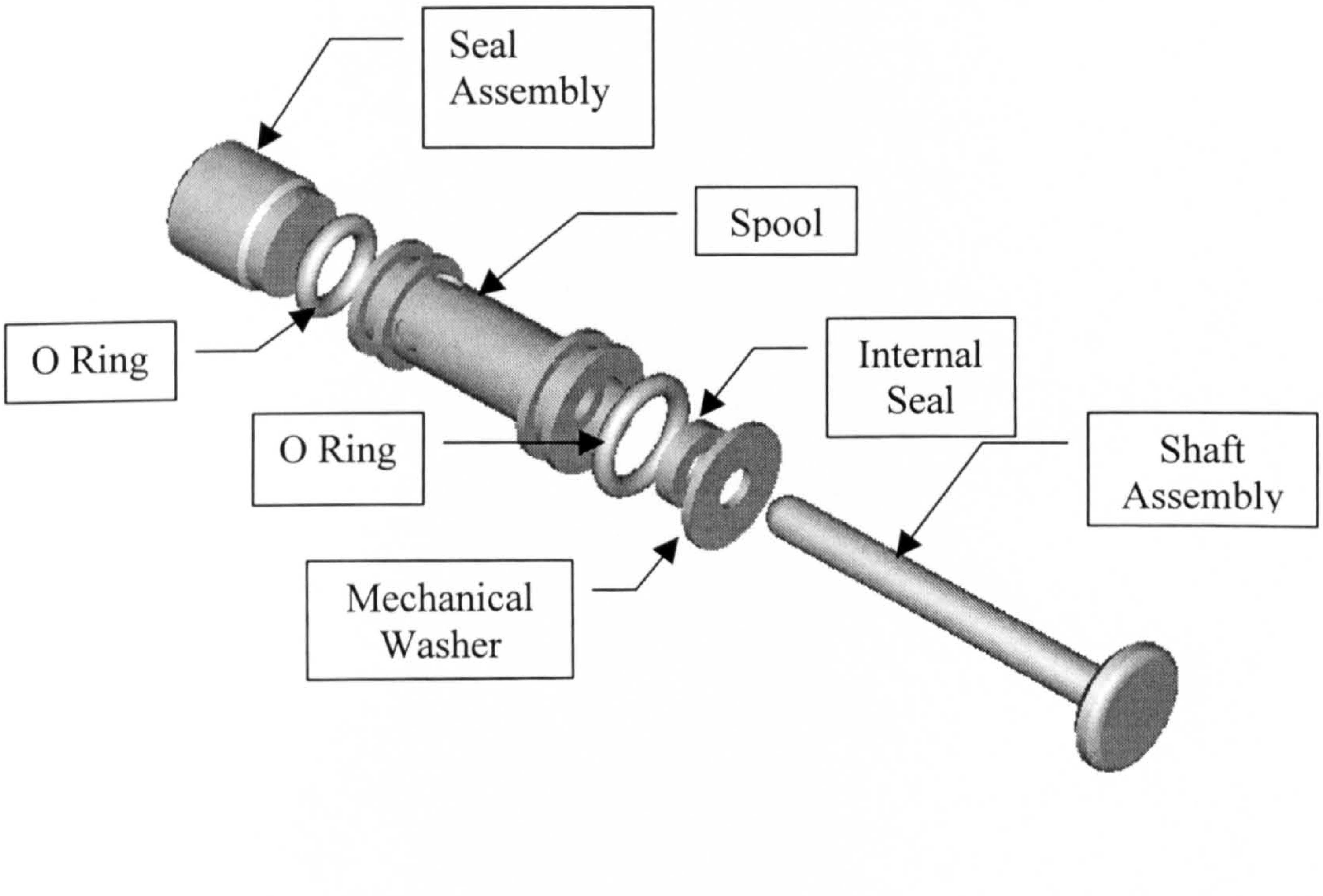


Figure 11.7:*Exploded Model Of Inlet Valve Sub Assembly*

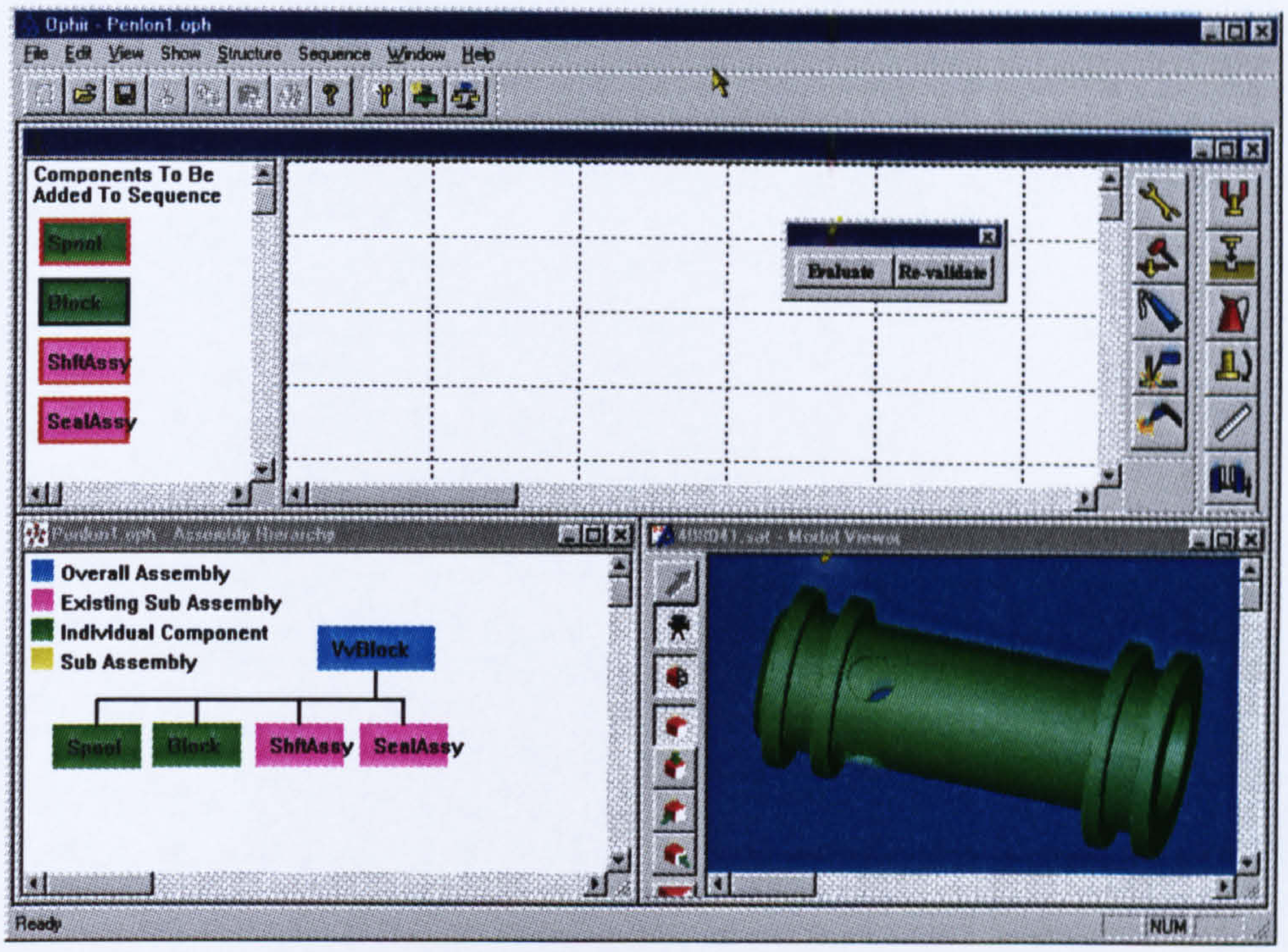


Figure 11.8: ***Starting To Design The Valve Block Of The Vaporiser***

The result of the designer's work so far in SPADE is shown in Figure 11.9. It can be seen that it is at the stage when most of the components have been determined and some work has been directed towards the assembly sequence definition. Even now, before the sequence has been fully defined, some assemblability issues are apparent. Three problems can be seen indicated in the screenshot. Further investigation by the designer shows that the violation labelled Problem 1 is created from a stability issue during the reorientation of the subassembly. The components are not secure and require careful handling to maintain the correct position. The violation indicated by Problem 2 highlights the high DFA Fitting Analysis score of the Control Plate (ContPlt) insertion. This assemblability issue is caused by an awkward screwing operation. The final issue identified here, Problem 3, is a component precedence issue. Locknut2 must be inserted before Locknut1 to eliminate a component collision constraint violation. Because the designer is now aware of these problems, they can be addressed. Had the design progressed following traditional methods there is no guarantee that these problems would have been noticed and dealt with at this stage in the process. Conventional application of the DFA analysis would have only found the awkward screwing operation on the Control Plate. The other two problems may have been identified during the analysis, but the issues are outside of the scope of DFA.

At this point it may be interesting to look at the Valve Block evaluation scores calculated by **SPADE**, for the current stage of development and on completion. It aims to identify if the evaluation metrics can offer any hints about the final quality of the product. Figure 11.10 shows the calculated evaluation metrics for the same stage of the vaporiser design as shown in Figure 11.9. It can be seen that the Complexity Index and the Insertion Index are low, but the Stability Index and the Difficulty Index are showing high figures which may provide a clue that the design requires some more work.

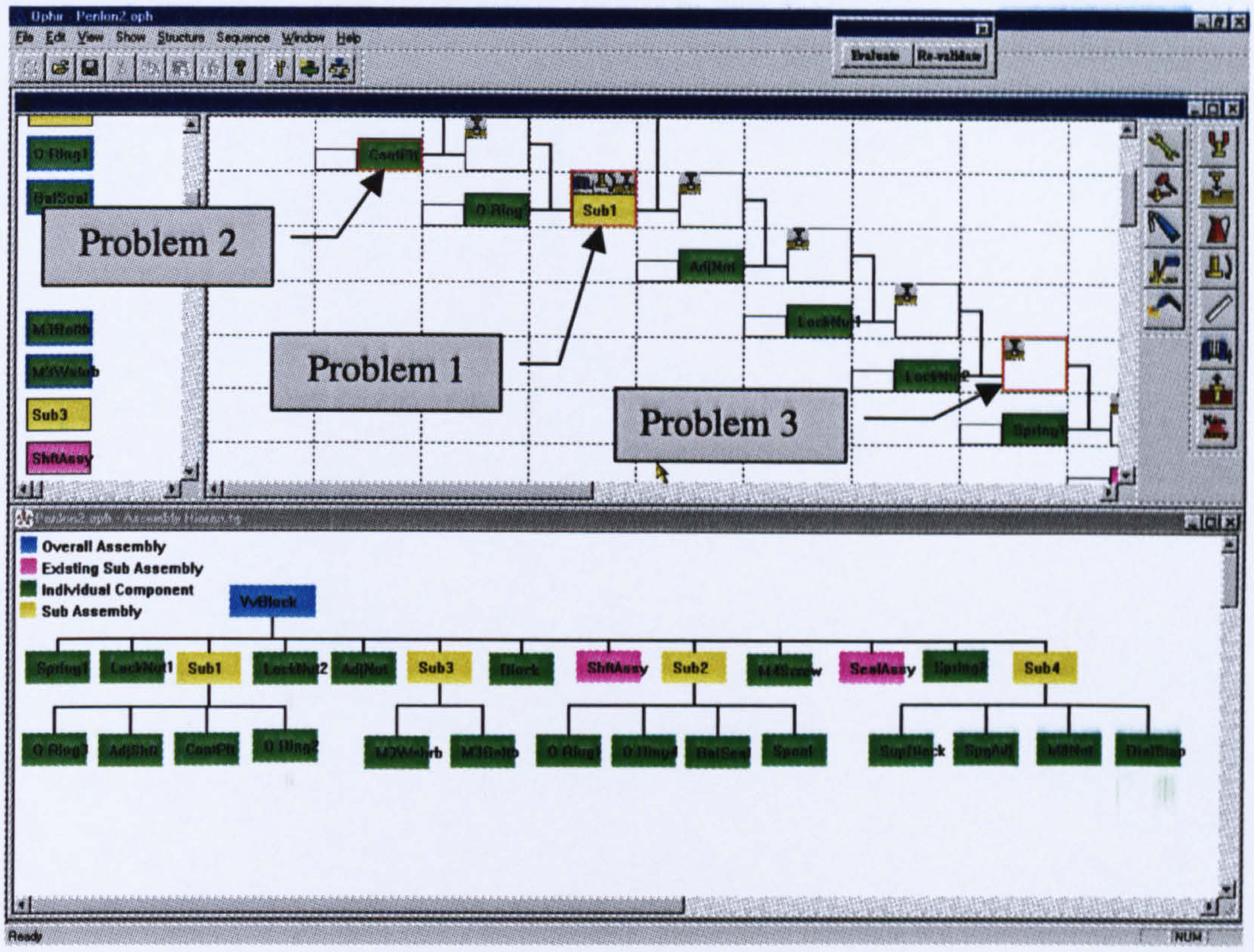
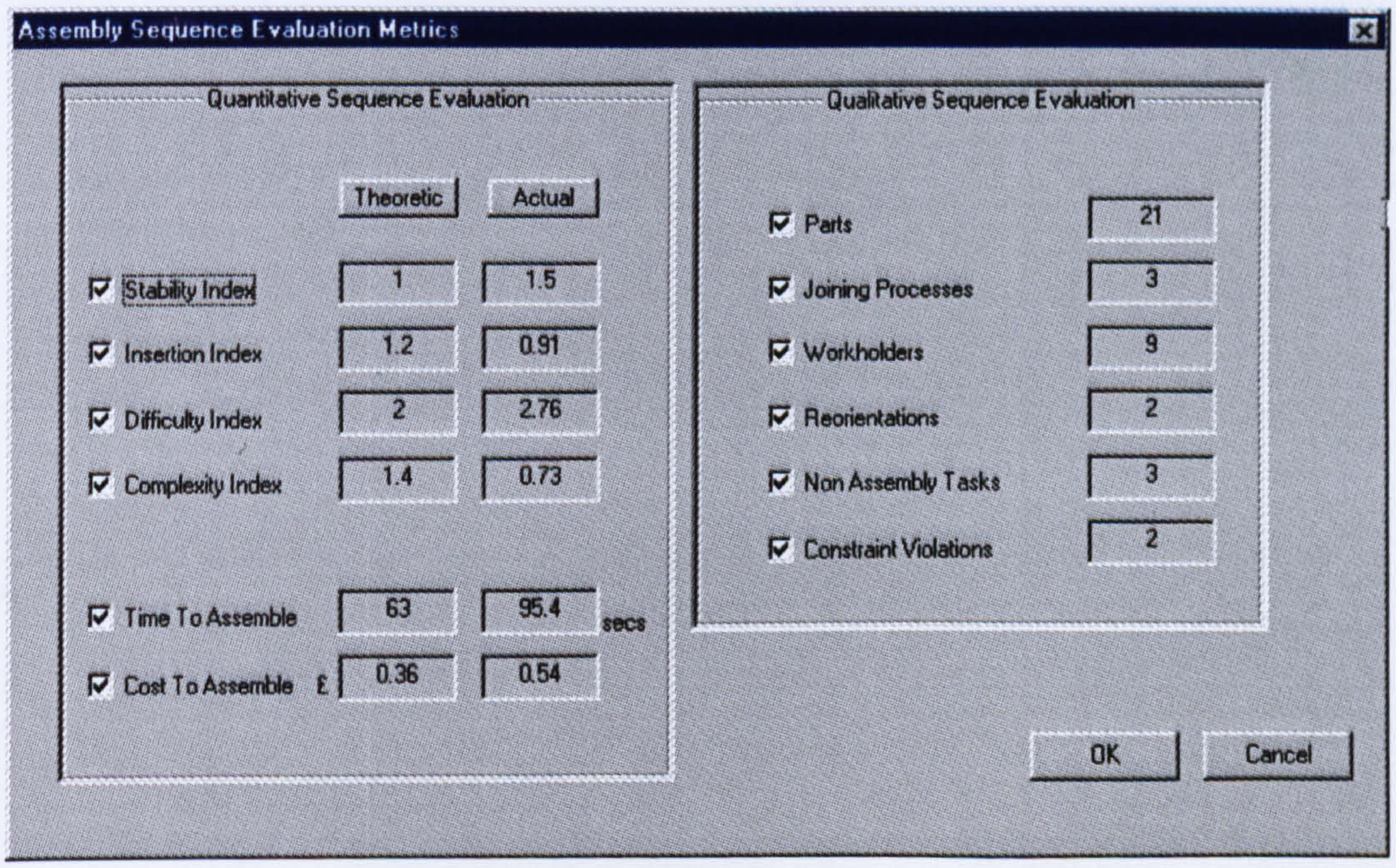


Figure 11.9: ***Partially Complete Design Of Vaporiser Valve Block***


Assembly Sequence Evaluation Metrics

Quantitative Sequence Evaluation

	Theoretic	Actual	
☑ Stability Index	1	1.5	
☑ Insertion Index	1.2	0.91	
☑ Difficulty Index	2	2.76	
☑ Complexity Index	1.4	0.73	
☑ Time To Assemble	63	95.4	secs
☑ Cost To Assemble £	0.36	0.54	

Qualitative Sequence Evaluation

☑ Parts	21
☑ Joining Processes	3
☑ Workholders	9
☑ Reorientations	2
☑ Non Assembly Tasks	3
☑ Constraint Violations	2

Figure 11.10: ***Vaporiser Evaluation at the Same Stage of Design as Figure 11.9***

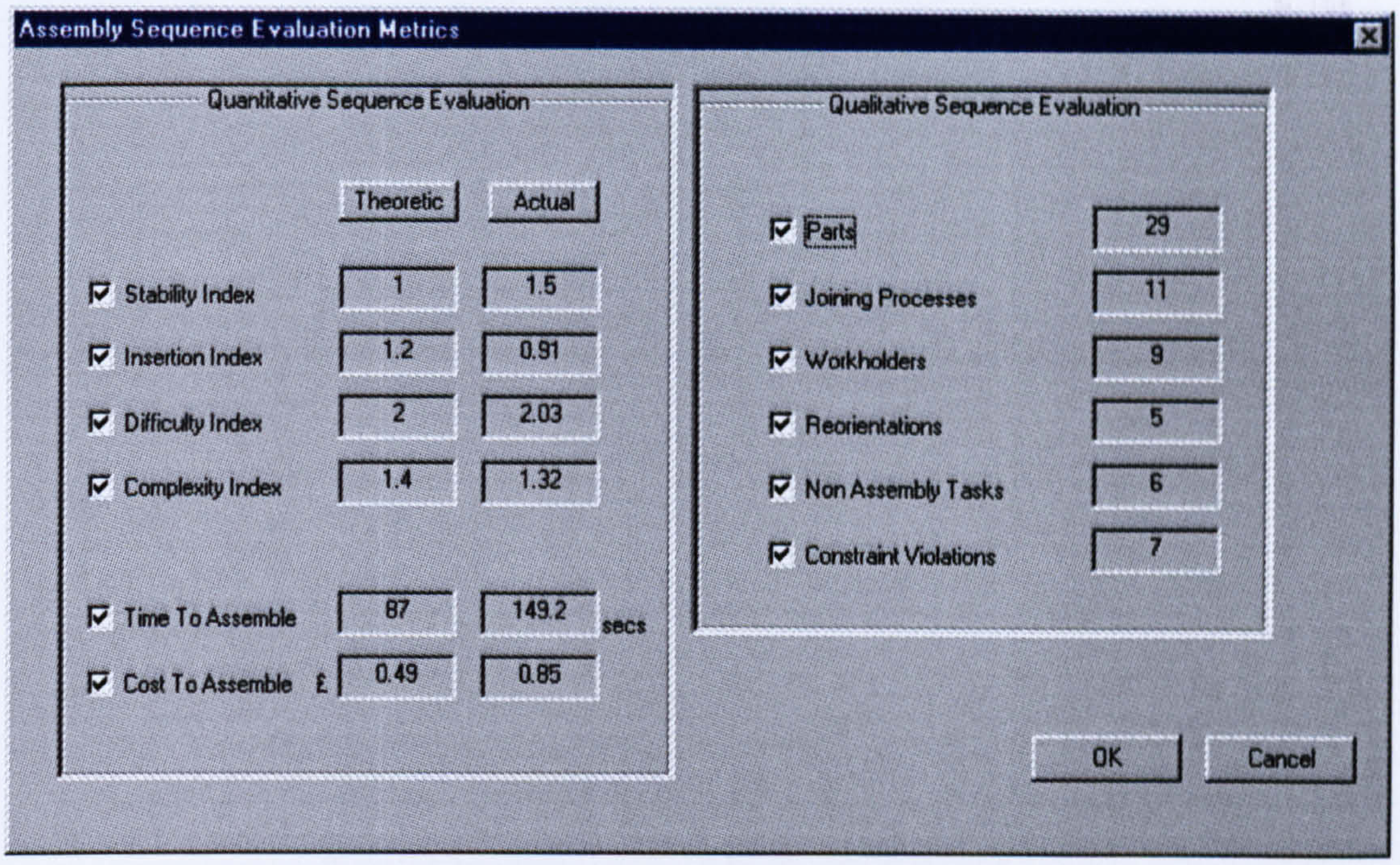
The high figure in the Stability Index has arisen because of the large number of workholders required to stabilise the Valve Block during the assembly process. These are required for a number of reasons. Several axes are used for insertions and thus separate fixtures are necessary to accommodate the reorientations. In addition, three of the five subassemblies require a workholder to complete the assembly. Thus, the Valve Block is an assembly that is inherently unstable and thus has a high Stability Index. The design geometry could be changed to improve this situation. The solutions could be, either reduce the number of axes of insertion, (which would also help with reorientation penalties in other metrics) or provide some planar faces to make the design stable without the need for fixtures.

The Difficulty Index is also found to be sub-optimal in the current design. Although the sequence has not yet been fully defined, the fitting index average is still very high for the operations added so far. This situation can have a few explanations. It could be that the defined tasks are the most awkward and thus the Index will reduce as other easier operations are added. Conversely it could be that the value is representative of the final Difficulty Index and action needs to be taken to improve the assemblability of the product. Thus, the designer needs to monitor the results of this metric to follow the trend of the values. If the Index does not start to reduce, as the sequence is further defined then work is required to reduce the assembly difficulty of the product.

The low values of the Complexity Index and the Insertion Index show that the current design and sequence do not have too many operations per liaison completed. However, this situation can occur when the sequence is not fully defined. It is possible that the scores can increase as more detail is added to the sequence. Again, the trend of the metrics requires careful monitoring to identify if further design work is necessary.

The implication of the evaluation analysis of the scenario, as presented by this case study, is that the design currently takes 50% longer to assemble and thus will cost 50% more than an optimal design and sequence configuration.

The evaluation metrics for the completed design, given in Figure 11.11, are calculated assuming the designer has not made any changes based upon the information given in Figure 11.10. When the results are examined, it can be seen that the Stability Index and the Insertion Index have remained constant and so the early indications have predicted the final results correctly. The Complexity Index has risen slightly, but it is still low enough not to need any attention. Thus, the early indicator again had some value. The Difficulty Index however has reduced to an acceptable level, which means that the prior alert was unfounded. This shows that there is merit in regular examination of the evaluation results providing the designer is aware that the values should be only treated as a guide to the final sequence quality. It is the trends of the results during the development process that is important not the absolute value. If a metric starts to veer from the threshold value at any time, the designer should take remedial action.



	Theoretic	Actual	
☑ Stability Index	1	1.5	
☑ Insertion Index	1.2	0.91	
☑ Difficulty Index	2	2.03	
☑ Complexity Index	1.4	1.32	
☑ Time To Assemble	87	149.2	secs
☑ Cost To Assemble £	0.49	0.85	

☑ Parts	29
☑ Joining Processes	11
☑ Workholders	9
☑ Reorientations	5
☑ Non Assembly Tasks	6
☑ Constraint Violations	7

Figure 11.11 : ***Completed Vaporiser Evaluation***

11.3 Case Study 3 - Discriminator

The data for this case study has been taken from the ARCHIMEDES repository[95]. Figure 11.12 shows the model of the Discriminator, a safety device that prevents accidental operation of a system.

The ARCHIMEDES Assembly Planner generated the animated assembly sequence including the tool constraints presented on their Web Site. The example in this section compares this published sequence with one developed using **SPADE.** It aims to illustrate that the application of the Two-Tier methodology can produce plans that have the same or less, overall assembly time. It is noted, however, that this case study will not be a true balanced comparison because of the intrinsic differences of the approaches. The ARCHIMEDES system plans from a completed description of the design utilising as much automation as practical. **SPADE** provides tools to help a designer build the assembly sequence concurrently with the design. The implemented automation only validates the existing choices of the designer. However the evaluation measures, times and costs that have been calculated by **SPADE** can be used as valid comparisons between the resultant plans from the two systems. It is not intended to go through the planning stages systematically but rather the results of the process will be presented and compared to the ARCHIMEDES sequence.

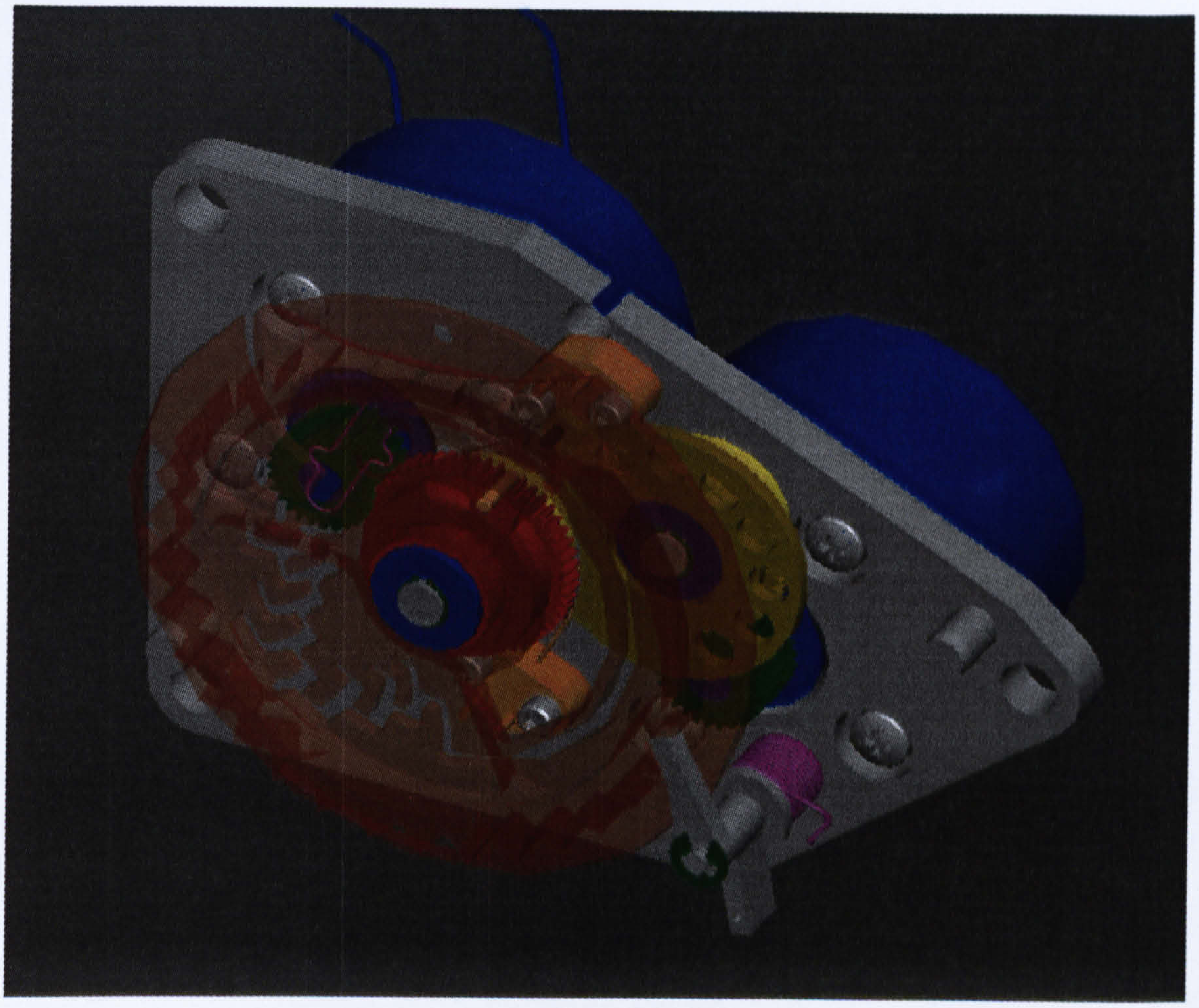


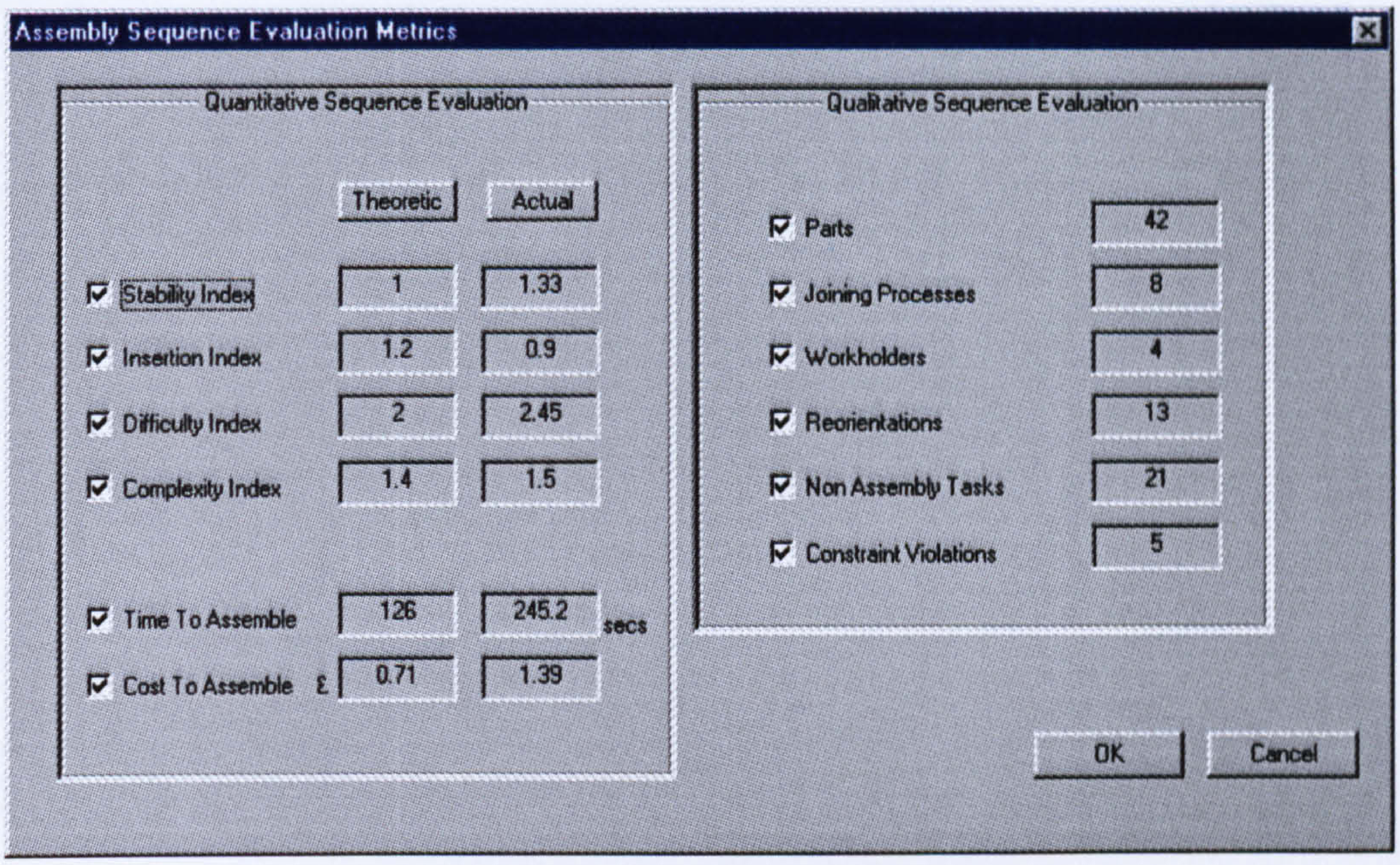
Figure 11.12: ***Discriminator As Presented By*** **ARCHIMEDES**

Firstly, the ARCHIMEDES' sequence was entered unaltered into **SPADE** to enable the calculation of the evaluation metrics for the plan. The results of this exercise are shown in Figure 11.13 The Complexity Index and Insertion Index are both within limits, but the Stability Index and the Difficulty Index are well above accepted parameters. On closer investigation, 5 constraint violations were found that relate to stability problems during reorientations of the assembly. This situation is not surprising, as ARCHIMEDES does not consider stability as a necessary criterion for assessment. To rectify the problems the assembled parts would require additional retainers and/or workholders, to prevent movement during the reorienting operation. The large number of welding operations are required, which are heavily penalised in the DFA Fitting Analysis, explain the high Difficulty Index. Had the designer been creating the assembly in the **SPADE** system, this issue would have been highlighted during the design stage, and alternatives could have been considered. The sequence generated by ARCHIMEDES for this design takes around twice as long to assemble as one optimised for assemblability. However, no metrics have been exceeded and thus, it could be considered an acceptable solution.

To enable a comparison to take place, an assembly sequence was generated using the tools and techniques included in **SPADE** to create as near an optimal sequence as possible. Design changes could not be considered because the resulting sequence had to be judged against the ARCHIMEDES plan. This limited the improvement potential of the Two-Tier methodology. For example, the high number of welding operations mean an unacceptably high Difficulty Index, but this issue cannot be addressed for the purposes of this case study. Figure 11.14 shows the evaluation measures calculated from the **SPADE** sequence. This plan was constructed following the suggestions given by the *Starting Component Advisor* and *the Next Component Advisor* and resolving as many constraint violations as possible without altering the design. It is immediately apparent that this plan offers a major advance over the ARCHIMEDES sequence. All the evaluation metrics are close to the threshold value which indicates a near optimal sequence. This means that building the assembly takes 16% less time and cost, a significant improvement.

The main contributors to the substantial decrease in assembly time were the use of the rules "Cluster similar joining processes" and "Cluster similar insertion paths". These heuristics are included as an integral part of the *Next Component Advisor* and aim to influence the component choice of the user towards better sequence plans. In this case study, their application has guided the user into considering different alternatives to the ARCHIMEDES sequence. **SPADE** has also assisted with the generation of a plan that has no stability constraint violations. Again, this has been achieved by the appropriate application of heuristics in the Expert Assembler.

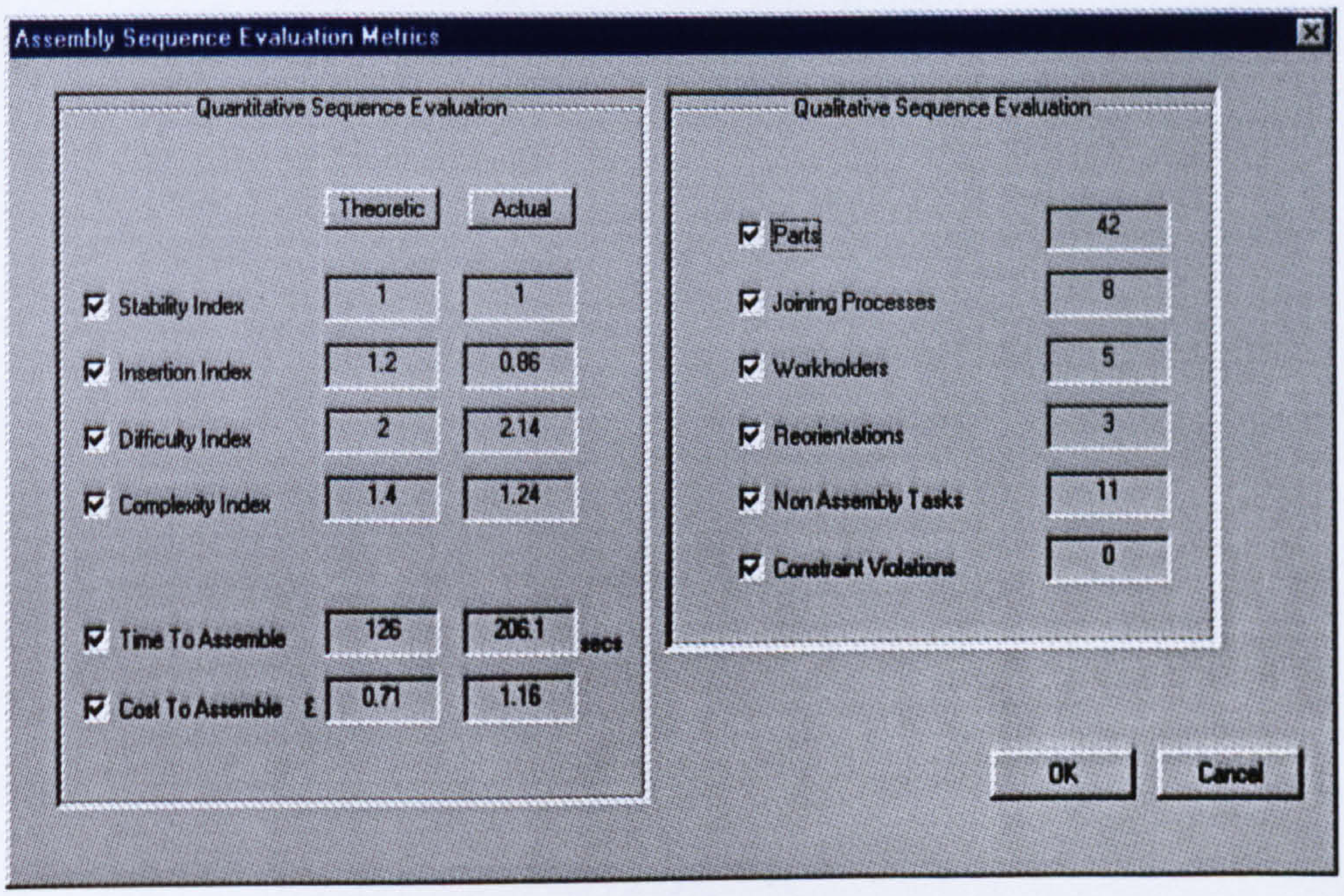
The improved sequence does utilise some base components that were not necessarily the most obvious options, but were proposed as second choice by the *Starting Component Advisor*. This situation is possible as the actual component selection is at all times left to the discretion of the designer. It is felt justified to include this in the case study because the iterative nature of the Two-Tier methodology means that the best option will often become apparent as the development progresses. However this process does have some negative aspects; poor choices are not prohibited so there are no guarantees that the improved sequence would be found by all users. Although the integral "Expert Assembler" assists the user, suitable training and the full appreciation of assembly issues are still required to use **SPADE** successfully and to fully realise its potential for improvements.



	Theoretic	Actual	
☑ Stability Index	1	1.33	
☑ Insertion Index	1.2	0.9	
☑ Difficulty Index	2	2.45	
☑ Complexity Index	1.4	1.5	
☑ Time To Assemble	126	245.2	secs
☑ Cost To Assemble £	0.71	1.39	

☑ Parts	42
☑ Joining Processes	8
☑ Workholders	4
☑ Reorientations	13
☑ Non Assembly Tasks	21
☑ Constraint Violations	5

Figure 11.13: ***Evaluation Of Discriminator Sequence Generated by*** **ARCHIMEDES**



	Theoretic	Actual	
☑ Stability Index	1	1	
☑ Insertion Index	1.2	0.86	
☑ Difficulty Index	2	2.14	
☑ Complexity Index	1.4	1.24	
☑ Time To Assemble	126	206.1	secs
☑ Cost To Assemble £	0.71	1.16	

☑ Parts	42
☑ Joining Processes	8
☑ Workholders	5
☑ Reorientations	3
☑ Non Assembly Tasks	11
☑ Constraint Violations	0

Figure 11.14: ***Evaluation Of Discriminator Sequence As Generated by*** **SPADE**

11.4 Concluding Remarks

The aim of this chapter was to demonstrate the use of the **SPADE** system to generate assembly sequences in parallel with the design process. It was decided that it was impractical, in this instance, to test the methodology on a case where the design was incomplete. Thus three complete product designs, a pipework valve, the valve block of a vaporiser and a discriminator were used, but some of the components were left undefined for demonstration purposes. The case studies were used to try to demonstrate the power and functionality of the **SPADE** system and the underlying Two-Tier sequence generation methodology.

By working through the sequence generation process for Case Study 1 - Flanged Valve, it was shown that it was both possible and useful to commence building the assembly sequence before the design was complete. Case Study 2 - Valve Block demonstrated how **SPADE** identifies assemblability issues. It was also shown that, although DFA can detect many issues, there are some that fall outside the scope of the methodology and are often missed. It also proved that by monitoring the evaluation results throughout the generation process a useful overall impression of the final sequence quality could be gained.

Case Study 3 - Discriminator had a different objective to the other case studies. The development of this example demonstrated that SPADE is able to develop sequences that take less time to assemble than another assembly planning system, ARCHIMEDES. To achieve this the Expert Assembler's suggestions must be followed, the trends indicated by the evaluation metrics must be observed and no hard or soft constraints are to be violated. In fact, this example realised a significant time saving of 16% over the sequence developed by the ARCHIMEDES system. This plan was already a good sequence but **SPADE** was able to find additional improvements by ensuring there are no constraint violations and by following the suggestions offered by the integral advisors.

It is believed that the case studies developed in this chapter have proven the effectiveness of the Two-Tier methodology and its computer-based implementation, **SPADE**. It is believed that the use of this tool can successfully generate both good designs and near optimal sequences simultaneously.

12. CONCLUSIONS

For many years, researchers have attempted to automate the sequence generation process. However, the industrial investigations reported in this thesis have shown that there is a disparity between many of these proposed approaches and the manual methods used by human assembly planners. It was found that the latter applied a breadth-first, depth-second approach to the task. This meant that the subassembly partitioning was completed before the planners considered detailed component planning. It was also observed as part of this industrial survey, that the application of the hard and soft constraints was interwoven throughout the generation process.

This thesis has proposed a Two-Tier methodology that is significantly different from previously reported approaches because the industrial findings have been used as the inspiration for a designer-led sequence generation process. Tools and techniques have been developed that use the process of generating an assembly sequence to improve the assemblability of the products. The Two-Tier methodology offers support for the construction, validation and evaluation of a suitable assembly sequence in parallel with the design development. Embedded knowledge is used to help with the plan generation because designers are rarely assembly experts.

The top tier of the proposed methodology provides facilities for the definition of the assembly structure and realises the breadth-first approach. Tools to allow the construction of the sequence are included in the lower tier to support the depth-second approach. A constraint-based method validates the sequence as it progresses and highlights any violations. This allows the user to investigate problems and implement solutions interactively. Novel evaluation techniques and early application of DFA analyses are able to provide data about the quality of the sequence, both during the development process, and after completion of the assembly sequence and design detail.

SPADE, the computer-based implementation of the Two-Tier methodology, includes the tools to allow the designer to build the sequence alongside the use of a traditional CAD system. The *Structure Builder* and *Sequence Builder* modules realise the two tiers of the methodology and provide the necessary support for the sequence generation process. An appropriate windows-based graphical interface allows for user-friendly operation. A Four-Layer Model underpins **SPADE** to provide data storage and retrieval capabilities. **SPADE** has the potential to form the basis of a much more comprehensive system that allows the designer to consider and document any number of issues during the design process. In addition, the system could also be used by other business functions to enable decision-making based upon an explicitly defined assembly structure early in the PIP.

The Two-Tier sequence generation methodology and **SPADE** have been tested on a number of industrially relevant case studies. It has been proven possible to construct the assembly sequence before the design is completed and that this process can highlight assemblability issues. **SPADE** has also shown that the use of the Two-Tier methodology can improve upon assembly sequences generated by other assembly planning systems.

12.1 Limitations Of The Two-Tier Methodology and SPADE

Whilst many advantages can be claimed when using the Two-Tier methodology, there are still inherent limitations and areas of incompleteness. Some of these points are the result of a lack of implementation time. However, some issues constitute limitations of the approach. All of these problems will be covered in this section.

A number of areas of implementation within **SPADE** have not been completed due to time constraints. One such function is the provision of editing facilities. Once a part has been added to either the structure or the sequence there is no facility provided to either move or remove the part. This makes initial accuracy imperative and is indeed an unsatisfactory situation in practice. Not all the geometric or 'hard' constraints have been fully implemented in **SPADE**. This means that whilst the methodology includes provision for all the detailed constraint types, some of these have not been added into **SPADE**. The other area that has not been fully integrated into the implementation is the factory specific knowledge. Thus, Level 3, Planning Level (see Section 6.3) of the sequence representation is not included in **SPADE**. The DFA analysis has only been partially implemented. Currently, manual overrides must be applied to the evaluation metrics to find the Fitting Indices. For a full Two-Tier methodology implementation, **SPADE** must include all the DFA analyses. Speed is also an issue within **SPADE** although little geometric analysis has been implemented. It is believed to be due to the superfluous updating of the screen after every calculation. In addition, it is not possible to adjust the justification and size of the sequence representation to account for all types of plan. These are simple coding issues and can be resolved easily.

It is possible to add attributes to the explicit liaisons in the sequence representation. However, there is no facility to add data to implicitly completed liaisons. To illustrate this point, consider an assembly of three parts with an assembly sequence of Part 1, Part 2, Part 3. **SPADE** allows attributes to be attached to the two liaisons between Part 1 and Part 2 and Part 2 and Part 3. However if Part 1 also mates with Part 3, there is no facility to add additional attributes to this adjacency. It is assumed that this link has the same attributes as the Part 2 to Part 3 liaison and calculates all results on this premise. It does not necessarily follow that all the faces joined in a liaison have the same attributes. The validation constraint analysis has a similar problem. Each explicit liaison is checked using the chosen constraints, but implicit liaisons are not considered for the reasons discussed above. It is assumed that the validation of the explicit liaison will also be correct for any implicit adjacencies. However, each mating face and its attributes must be included to fully validate the sequence. Thus, the existence of different attributes for each mating face should be considered in the analysis and implemented into **SPADE**.

The Expert Assembler, with its two integral advisors, is available to assist with sequence construction. This is based upon some general rules that have been proven useful, but somewhat limited. A set of more detailed rules with a more powerful inference mechanism would further enhance the quality of the suggestions, thus improving the resultant sequence. In addition, the consideration of part precedence in the *Next Component Advisor* would reduce the number of errors in the sequence construction. The knowledge embedded in the system is extensive but far from exhaustive. More materials, joining processes, manufacturing processes and relevant attributes should be added to ensure that the suggestions given by the *Expert Assembler* are correct for all situations.

As seen in Chapter 9, the evaluation criteria have been based upon a study of 34 electromechanical case studies. Whilst this is a statistically significant sample, the examples are all taken from a similar industry. A more comprehensive survey of different types of assemblies should be completed to confirm the wider applicability of the metrics and thus increase the certainty of the accuracy of the threshold levels.

The Two-Tier methodology represents a totally new process of working for designers and has ramifications throughout the whole business. As with all new methodologies its successful implementation will rely, not upon the sophistication of the computer system, but upon fundamental changes to the design process and the PIP. Unless the designer is required to take responsibility for assemblability issues, no amount of new methodologies will improve the general state of assembly apathy in industry today.

12.2 Recommendations For Future Work

The previous section has outlined areas in both the Two-Tier methodology and its implementation, **SPADE** that require more work to ensure that the system can be used in practice. There are many improvements to further develop the methodology and **SPADE** that could form the basis of a new piece of work. Some of these have been briefly discussed in the body of this thesis but dismissed as outside the scope of the research.

It may be possible to use the assembly strategy to provide another means of validating the sequence. If the user has defined that a bottom-up build is required and then the sequence has started to follow an inside-out strategy, the designer could be alerted and asked to rethink the situation. This will require complex geometric reasoning algorithms and other rules that can assist with the determination of the assembly strategy and compare to the chosen build direction.

Certain assembly actions and attributes implicitly infer other actions or attributes. This area has not yet been exploited in the methodology. For example, if a partial assembly has been defined as unstable then it could be assumed that a workholder is required. Since the system has details of the partial assembly geometry and the instability data, it should be possible to either automatically select a workholder from a pre-defined list or alternatively start the design of a new jig. A similar process could identify the need for the application of tools, either handling or joining. Again, these can be selected from a set of possible tools. If a suitable tool cannot be found, because for example, the volume required for use is not available, then the user could be alerted

Another area that has not been considered in the original methodology is the link between the assembly structure and the assembly sequence. These views are two different representations of the same data and as such, there must be some rules that could be used to validate the structure. Currently the Two-Tier methodology does not include any facility to check and optimise the assembly structure. By considering the sequence and structure simultaneously, it should be possible to identify rules that can validate the subassembly partitioning and thus further improve the assemblability of the product. The Two-Tier methodology also does not provide support for the transfer from a function structure to an assembly structure. Building upon the idea in the previous paragraph the method could be extended to support the determination of the assembly structure from function structure. This will require even more functionality to deal with undefined geometry.

The Expert Assembler currently includes two mini-advisors that suggest candidates for the base component and the next component. These two advisors can provide the user with the majority of the information needed to construct a feasible and practical sequence. Many other advisory modules could be developed to help to further improve the sequence quality. A Joining Process Selector could suggest suitable processes to secure the components; a Jig Designer could determine whether a jig should be used and, perhaps even, design one for the user.

Currently the support offered by the Two-Tier methodology ends when the design is complete and a good assembly sequence has been defined. However, this sequence may not be suitable for use in reality because specific factory considerations are not included. Knowledge about factory layout, tooling, line balancing and assembly line design should be included. Consideration of these issues can then be incorporated into the validation methodology to improve the practicality of the resulting sequence.

The defined evaluation metrics give the designer an understanding of the quality of the sequence being constructed. This decision should be based upon an amalgamation of the four measures. Numerical methods can be employed that combine the results of the individual calculations. An overall metric can then be defined that offers an absolute view of the sequence quality.

One final area that could be researched is the value of the assembly structure to other business functions. The similarity of the assembly structure to the Bill Of Materials cannot be ignored and the relevance of this data at an early stage in the design could be explored. This could lead on to an investigation of the possibilities to integrate the Two-Tier methodology into an appropriate PDM, (Product Data Management) system.

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APPENDIX A

Questionnaire For Knowledge Engineering Interview

Company:____________________ Date:____________________

Name:____________________ Position:____________________

General Business:

Market Sector:______________________________

No Of Variants: ______________________________

Yearly Production:______________________________

Breakdown of Cost:

Material Cost ______%

Labour Cost ______%

Overheads ______%

Batch Size: ______________________________

Approx Size and Weight Of Finished Product: ______ Kg

___mm x ___mm x ___mm

PDP Process:

Are any DFA tools used?______________________________

____

When is the assembly sequence first considered?______________________________

____

How do Designers and Assembly Planners communicate?____________________

____

____

____

Assembly Planning Process:

Are any formalised construction methods used? ______________________________

____

____

Are any formalised validation methods used? ______________________________

____

____

Are candidate sequences evaluated ? ______________________________

____

____

What is your cycle time?______________________________

____

Do you optimise the content in a cycle?______________________________

____

____

Is cost a valid criterion for evaluation? ______________________________

____

____

How is cost calculated? ______________________________

____

____

Any Other Valid Criteria?______________________________

____

____

____

____

____

____

____

____

B

Joining Processes:

Do you have a standard list of joining processes to choose from?____________

Which joining processes should be included ?______________________

C